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The Mechanism of Mine-collapse Deduced from Seismic Observations

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Abstract—On May 2, 1993 more than 200 seismic events from an underground mine in Tyrol/Austria were recorded with short-period seismometers of a local seismic network which was introduced in the late 1980s to monitor the tectonic seismicity in Tyrol in greater detail. The cause of this series of mining-associated events has become the subject of intensive investigations—as it was associated with a subsidence affecting an area of 10.000 m^2. Underground observations revealed a number of discontinuities along which the rock mass was able to move. Seismic recordings of the close-by seismic stations revealed two types of mechanisms: One mechanism seems to be associated with pure block-sliding along several discontinuities, while other signals indicate additional collapse. The consideration and combination of several seismological principles made possible the construction of a model of the mine collapse.

Key words: Mine collapse, seismic signals, long-period wavelet, first motions, collapse model, possible cause.

1. *Introduction*

On Sunday, May 2, 1993 a sequence of seismic events was recorded with short-period seismometers from the area of Schwaz, a town in Tyrol/Austria.

The Department of Geophysics of the Central Institute for Meteorology and Geodynamics in Vienna (Austria) maintains four seismic stations in Tyrol, equipped with Geotech S13 short-period seismometers which can be directly accessed from Vienna. Two of them (station Wattenberg ‘WTTA’ and Walderalm ‘WATA’) are situated 12 km from Schwaz (Fig. 1). It turned out that the observed seismic signals were related to a partial collapse of dolomite-mine workings near this town.

Mining has a long tradition in Schwaz, reaching its peak in production during the 16th century when silver was recovered from numerous galleries in the mining district of ‘Falkenstein’ near Schwaz (EGG *et al.*, 1986). Today’s production concentrates on underground dolomite mining. Mine workings extend over 200 m in a vertical direction, and finally reach a diameter of approximately 80 m (see also Fig. 7).

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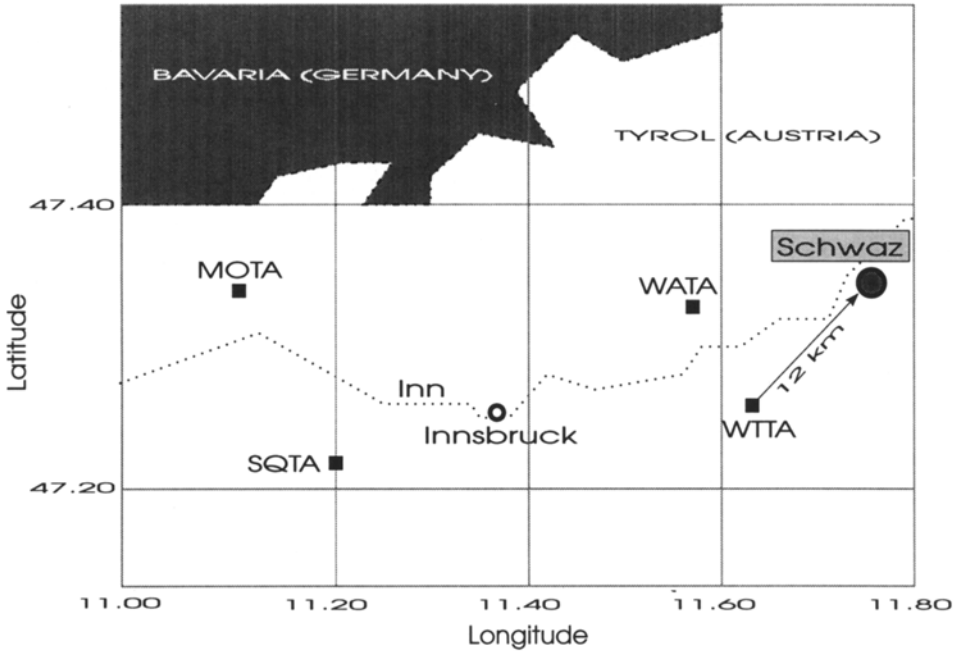

Figure 1
Seismic stations in Tyrol/Austria (solid squares) and the mining district of Schwaz.

The main shock registered a magnitude of M 1.9, which was even observed in Vienna as well as by foreign seismological stations. It constituted the last event of a sequence of events which was associated with a massive subsidence, reaching 8.5 m in places (CZUBIK, 1993), 340 m above the mine workings. The entire process took two hours and affected a surface area of 80 m × 150 m, thus roughly delineated the plan view of one of the involved underground caverns. Underground observations revealed a number of discontinuities along which the rock mass was able to move. The total rock mass, which was involved in the process, amounted to approximately half a million cubic meters.

2. *Seismic Observations*

2.1. *Time Sequence of Collapse*

The seismic activity began on May 2, 1993 at 1 h 15 UTC (=local time − 2 hours) with minor events. At 2 h 15 the first larger event was recorded, registering a magnitude of M 1.4. The next stronger shock occurred at 2 h 57 (M 1.7), and shortly thereafter the main event (M 1.9) at 2 h 59.

The cumulative frequency-magnitude relationship from this 2-hour long sequence can be described by

$$\log N = 1.93 - 0.95\,M, \quad \text{valid for } -0.7 \leq M \leq 2$$

which indicates that more than 390 events ('N') of $M \geq -0.7$ were observed during this period of time. At least half of them could be further evaluated in terms of first motions and wavelets. The remaining signals could not be evaluated, mainly due to insufficient separation in time.

Ths slope (0.95) of this distribution, which is commonly referred to as the 'b-value', obviously does not differ from aftershock sequences of tectonic earthquakes ($b = 0.5-1.0$), thus indicating that the size distribution of the involved slip-planes seems to follow fractal laws, similar to those of earthquake processes (AKI, 1981).

However, two types of seismic signals could be distinguished, which are uncommon in earthquakes of tectonic origin. These signals were also observed in subsequent seismic activities in November/December 1993 and April 1994, which indicated that the process of collapse has not been fully completed.

2.2. *Two Kinds of Seismic Signals*

Based on the shape of the signals, it was possible to distinguish 'collapse' events from tectonic earthquakes. The first kind of signals (1 in Fig. 2) exhibits a long-period wavelet, starting approximately 3 seconds after the arrival of the

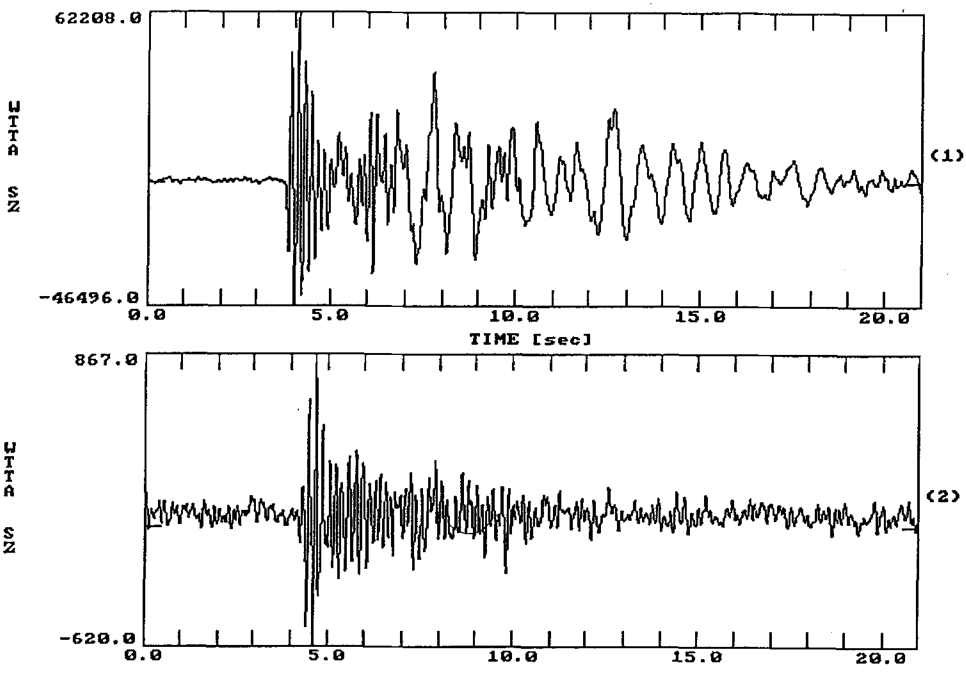

Figure 2
Seismic signals with long (1) and short-period (2) wavelet.

compressional wave. This long-period wavelet is missing in the second type (2 in Fig. 2) of seismic signals. Sometimes both types of signals showed a 'compressional' (movement away from the source), and sometimes a 'dilatational' (movement towards the source) first arrival at the very same station. As it can be reasonably assumed that both signals originated in the mine and were associated with the collapse, we are left with the question, why could two obviously different signals be observed?

A combination of a slip and collapse mechanism seems to explain both types of signals. Type 1 would involve the slip of a rock mass along a plane of weakness, including a free fall of the rock mass, which terminates with an impact pulse, thus creating the long-periodic wavelet. Type 2 events lack these onsets, hence they seem to be caused by pure slip movements.

The process obviously started with events of the 1-type (Fig. 3), indicating the collapse of the roof. At a later stage, events of both types can be observed. At the end of the seismic sequence mainly type 1-events were observed again.

However, the erratic presence of compressional and dilatational onsets indicates the possible involvement of more than one slip-plane, with an opposing sense of movement. Only from the point of mining geometry does this situation actually apply to the real situation. The cavern under consideration is in fact surrounded by more than two discontinuities (see also Fig. 7).

2.3. *Seismological Models*

Three different models were applied to explain the involved mechanisms. The first model resembles the model by Brune (1970, 1971), including Hanks and Kanamori's (1979) relationship between magnitude and seismic moment, which

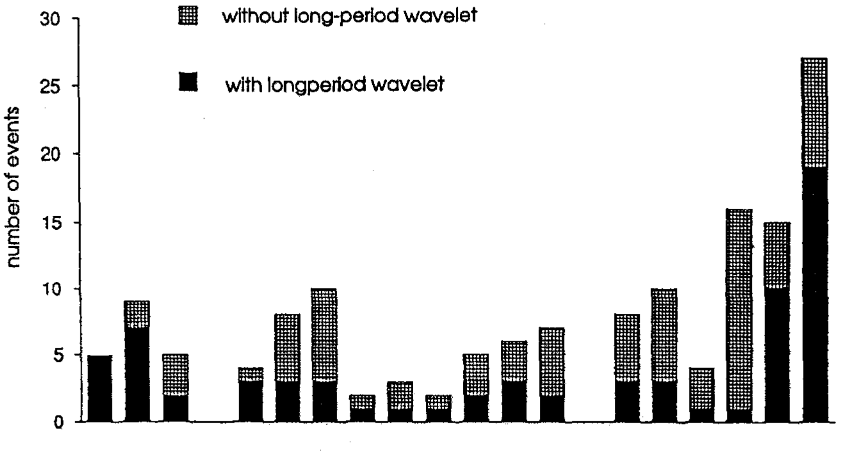

Figure 3
Frequency of type 1 (solid fill) and type 2 wavelets (hatched fill) during the main collapse.

implies a stress drop $\Delta\sigma$ assumption of 0.01% of the shear modulus, when used in connection with GUTENBERG and RICHTER's (1956) relationship between seismic energy and magnitude. The Brune model allows for estimation of the size of the involved rupture area:

$$A = M_0/(d * G)$$

with
A—rupture area (m^2)
M_0—seismic moment (Nm)
d—displacement (m)
G—shear modulus (33 GPa).

Hence, a magnitude $M2$-event is related to a source radius of 35 m, if the displacement is kept at 0.01 m. Larger displacements automatically result in smaller source-radii; hence the size of contact-planes between dislodged blocks and the surrounding rock mass decreases, which ultimately leads to smaller involved volumes of the rock masses.

The second model allows for calculation of the involved volume of rock V in m^3, which moved purely gravitational. The volume can be estimated by relating the potential energy E_{pot} and the released seismic energy E_s in Joule (GUTENBERG and RICHTER, 1956) by

$$E_s = 10^{(1.5 * M + 4.8)}$$

$$E_{\text{pot}} = V * \rho * g * h$$

$$E_s = E_{\text{pot}} * \eta$$

hence

$$V = E_s/(\rho * g * h * \eta)$$

with
ρ—density (2850 kg/m^3)
g—acceleration of gravity (9.81 m/s^2)
h—height of free fall (m)
η—seismic efficiency (E_s/E_{pot}).

Given a height of 25 m and a seismic efficiency η of 0.001 (thus only 0.1% of the potential energy is actually converted into seismic energy), the main event with a magnitude of M 1.9 relates to a volume of 63.000 m^3, which is insufficient when compared with the existing cavern of 500.000 m^3.

The third model regards slip along planes and collapse. Each block is treated as if it would have been sliding along its cylindrical surface for 0.025% of its height. The rupture area A is determined by the radius of the cylinder and its height

$$A = 2 * \pi * r * H$$

with
r—radius of the cylinder (m)
H—height of the cylinder (m).

After sliding, the block is subjected to a free fall. A small volume of rock, with a radius of 4 m and a height of 2 m, would cause an event of $M0$ coupled with a dropping height of 25 m and a seismic efficiency of 1%. A larger block, with a radius of 45 m and a height of 20 m, would cause an event of $M2$. The involved volume totals 127.000 m^3 in the latter case, which is still lower than the available volume of the cavern. It should be noted, however, that a lower seismic efficiency automatically leads to larger volumes in this approach.

Although many assumptions had to be made (consistent slip and stress drop, seismic efficiency of slip event equals the impact event), some conclusions can be drawn from the above estimates:

1) sliding in conjunction with collapse as well as pure sliding dominate the model—and not pure collapse.
2) seismic efficiencies seem to range between 0.1% and 1%.

It should be noted, that the results from the three simple models presumedly serve only as rough estimates, since they necessarily include numerous assumptions.

3. *Interpretation*

Already the time of collapse, early on a Sunday morning indicates that the collapse was not directly triggered by mining activities, such as production blasts, as this is generally the case (see also LENHARDT, 1992). Furthermore, seismicity in November/December 1993 and in April 1994 did not correlate with blasting time either. Figure 4 shows the diurnal distribution of these seismic events, in which the sequence of May 2, 1993 has been excluded for clarity.

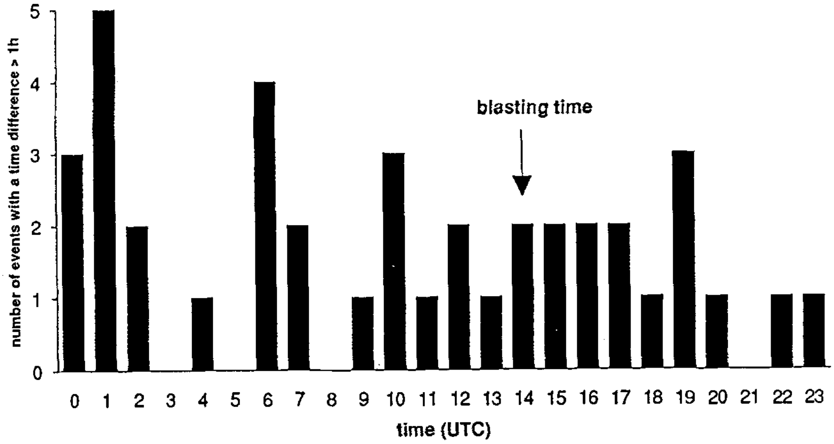

Figure 4
Diurnal distribution of seismic activity.

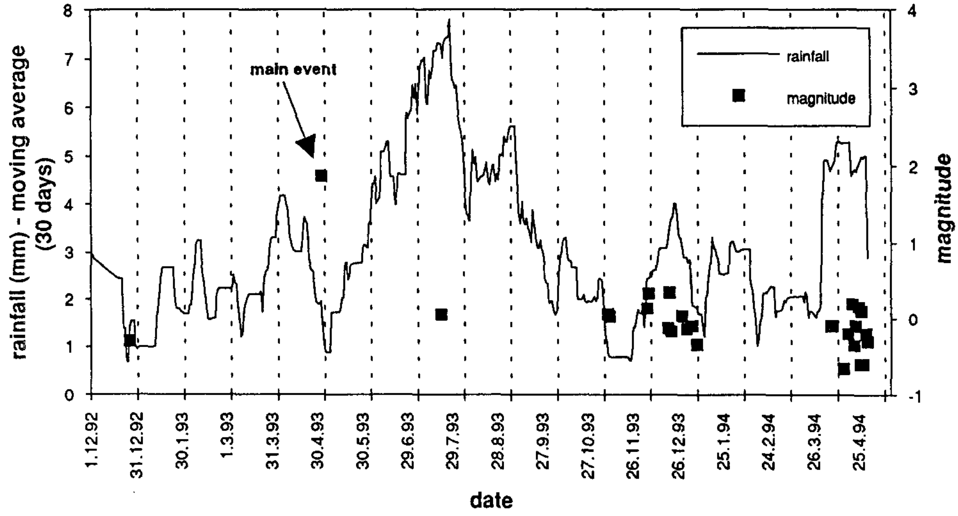

Figure 5
Rain- and snowfall (30 days-moving average).

However, meteorological influences cannot be completely ruled out. As can be seen in Figures 5 and 6, the seismicity in November/December 1993 and April 1994 correlated with peaks of snow- or rainfall. This fact does not apply to the time of the main collapse, which occurred during a period of thaw, after a two-month increase of temperature.

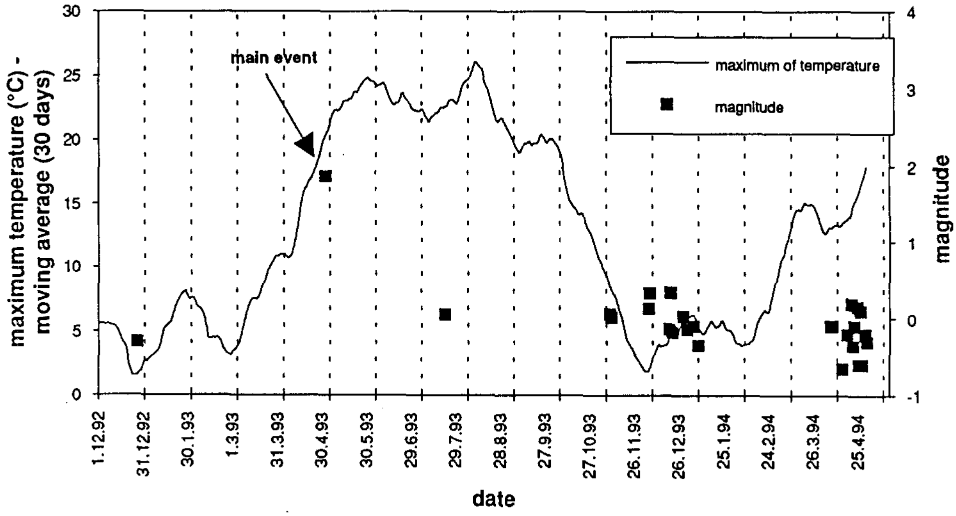

Figure 6
Temperature (30 days-moving average).

The presence of geological discontinuities seems to have a far more important influence on the stability of the cavern under consideration. The subsidence delineates one of the recent mine workings which exist 300 m below surface. Further, the subsidence was clearly limited by outcropping discontinuities (BAUER *et al.*, 1993), which extend down to mining level. Several discontinuities formed a 'pyramidal' roof-block, which was intersected by another discontinuity, thereby dividing the hanging into block 1 (bottom part) and block 2 (top part). At a certain mining-step, the critical block 1 lacked support and started to disintegrate.

According to the seismic records, three phases of the collapse can be distinguished:

Phase 1 (Fig. 7)

Partial roof-collapse at the bottom of block 1 begins at 1 h 15 UTC. Most signals exhibit long-period wavelets thus indicating the impact of the falling rock masses (see Fig. 3).

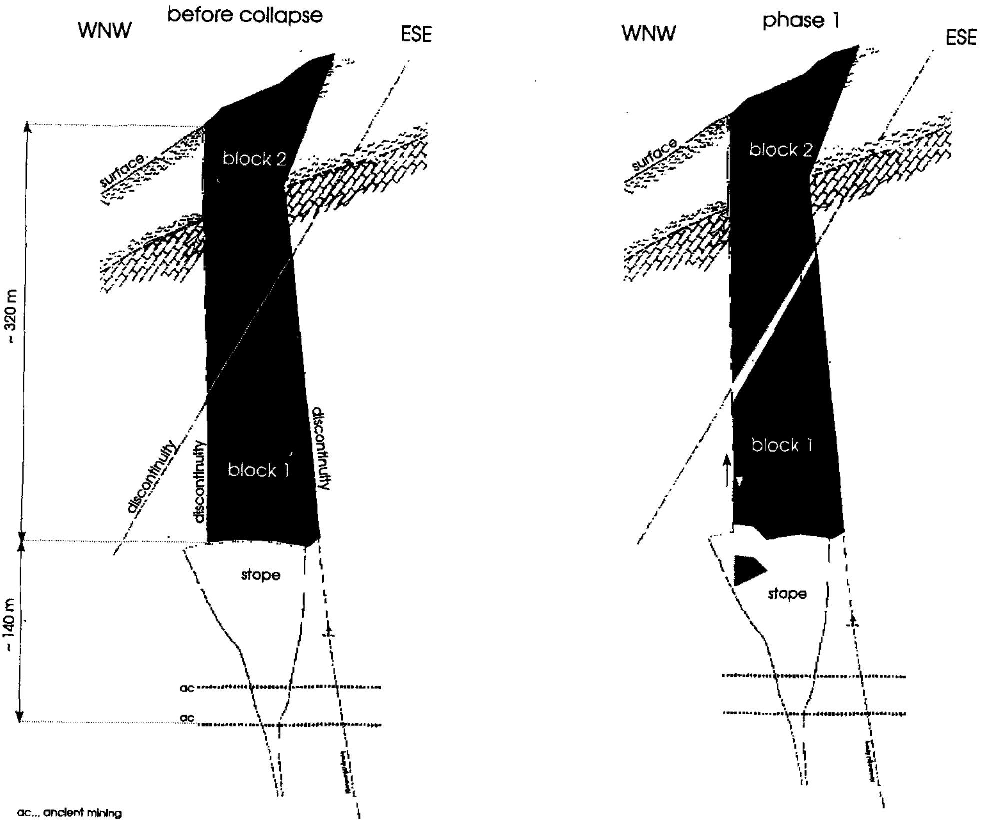

Figure 7
Initial state and proposed mechanism during phase 1.

Phase 2 (Fig. 8)

Due to changed stress conditions, block 1 mainly moves along the existing—almost vertically orientated—discontinuities. This process seems to have started at 1 h 45. Erratic compressional and dilatational onsets at one and the same seismic station indicate the involvement of more than one slip-plane. Finally, block 1 disintegrates. Block 2 starts to move.

Phase 3 (Fig. 8)

Since block 1 has disintegrated, block 2 is able to move due to lack of vertical support. Finally, at 2 h 59, the main part of block 2 seems to have moved at once, thus emitting most of the seismic energy (with long-period wavelets) and causing the subsidence on surface.

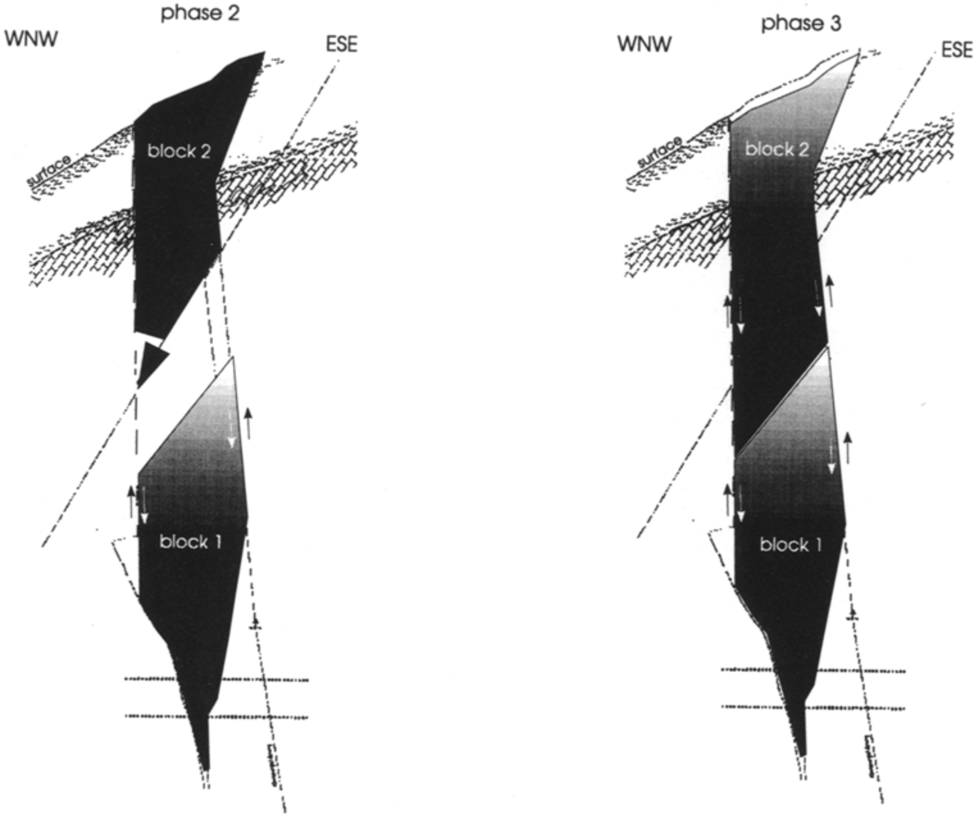

Figure 8
Proposed mechanisms during phase 2 and phase 3.

4. *Summary*

Seismic recordings of nearby seismic stations revealed two types of mechanisms during the collapse: One mechanism seems to be associated with pure block-sliding along several discontinuities, while other signals indicate collapse events.

Three phases of the collapse can be recognized from seismic observations. The first phase seems to be a result of slip movement along one of the adjacent discontinuities and collapse of the roof. During the second phase the lower part of the roof block collapses, fills the mine workings, and the higher part of the block starts to move. The third phase constitutes the final part of the process during which the subsidence on surface took place.

Not only the atypical history of seismic events—numerous foreshocks, culminating in the main shock at the end of the collapse—attracts attention, but also the fact that minor seismic activity continues, thus indicating remaining cavities in the mine workings under consideration.

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