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Developing Tools for the Prediction of Catastrophic Coastal Cliff Collapse

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Abstract

The erosion of coastal cliffs is inevitable. The cliff collapses are a hazard, a problem for coastal land use planners and limit the use of the coastline as an amenity. Techniques to increase our knowledge of coastal cliff failure and provide pre-cursors to impending collapse are presented.

The rock mass cracks before a collapse and the cracking generates high frequency seismic signals. An increase in emitted seismic energy has been recorded on accelerometers, in boreholes within a cliff, during the fifteen hours before a cliff fall. Comparison of the seismic signals with those generated in the laboratory has identified a number of collapse mechanisms that occur during different phases of the fall.

A second technique assumes that in cliffs composed of a highly fractured rock, any sub-vertical fractures will gradually dilate with time before a collapse. The electrical resistance of the rock varies with azimuth reflecting the dominant fracture orientation. A factor of anisotropy, calculated from the measurements, was found to change dramatically due to a cliff fall. Large values of anisotropy prior to the fall were interpreted as evidence of dilating fractures.

In addition, the research has demonstrated the existence of a cliff parallel fracture adjacent to the cliff edge. It is likely that cracking within this fracture set is responsible for the seismicity and the variations in the measured anisotropy. Laboratory analysis has identified a significant weakening of the rock due to salt crystals within the matrix. The integration and implications of these results are discussed.

1. INTRODUCTION

The erosion of hard rock cliffs is inevitable and to-date it has been considered to be relatively unpredictable. A large proportion of the European coastline is subject to erosion and cliff recession. A considerable body of data has been collected on the nature and lithology of coastal cliffs that has enabled geologists and engineers to develop a better understanding of cliff collapse mechanisms and the factors that determine rates of erosion. The only measuring tools commonly implemented are displacement transducers and inclinometers used to detect movements of blocks. However, these techniques cannot be used at large spatial scales because they are too expensive and they monitor only single blocks or a small area. There has been very little research into physical property changes within the rock mass behind a cliff face prior to collapse. If any such changes can be quantified they could be used as pre-cursors to impending collapse.

It is to be expected that in cliffs composed of a highly fractured rock such as chalk, any sub-vertical fractures near the top of the cliff will gradually dilate with time. The downward-developing dilatancy will alter the stress regime within the cliff until a shear is initiated that separates the base of the tension fracture from the cliff face. This fresh crack will generate high frequency seismic signals known as acoustic crack emissions. An increase in emitted seismic energy would be expected as a collapse approaches.

Since fractures often occur in sets with a preferred orientation they impose anisotropic physical properties to the rock mass. It has been shown that the apparent resistivity of the rock will vary with azimuth reflecting the dominant fracture orientation. A factor of anisotropy can be calculated from resistivity measurements collected on the cliff top that would be expected to vary with time if the fractures are dilating.

2. DATA COLLECTION

Developing large scale monitoring tools to predict coastal cliff collapses was the main aim of the current study. It was undertaken by a colloborative project, PROTECT (PRediction Of The Erosion of Cliffed Terrains) that was supported by the European Union 5th Framework Reseach and Development Programme. The project, involved nine partners from five different countries (Busby et al., 2002).

Five test locations were established on chalk sea cliffs in order to collect microseismic and apparent resistivity data over a two-year period. These were at Beachy Head and Birling Gap on the East Sussex coast of the UK, Mesnil-Val on the Normandy coast of France and two locations on the island of Mon, at Mons Klint, on the Baltic coast of Denmark.

2.1 Geological description of the test locations

The cliff at Beachy Head is composed of Seaford Chalk in the upper part of the cliff, underlain by Lewes Nodular Chalk. Seaford Chalk is characterised by sub-vertical fractures with mapped dominant fracture orientations of 70° and 150° (relative to British National Grid co-ordinates) The site is on a westerly facing slope that has undergone deep periglacial weathering that might have created randomly orientated fractures near surface and a variety of dissolution features. The site is on the northerly limb of the Beachy Head Anticline and dips at 15° to 20° to the north-west. The Birling Gap site is approximately 2.5 km west from the Beachy Head site. Due to the north-westerly dip of the chalk the Seaford Chalk that is exposed at the top of Beachy Head is found at about 20 m below the top of the cliff at Birling Gap. The entire cliff is composed of Seaford Chalk and is characterised by sub-vertical fracturing. The strata at Birling Gap are approximately horizontal.

The cliff at Mesnil-Val is composed of Lewes Nodular Chalk. The fracturing is sub-vertical and two conjugate fracture sets have been mapped striking at 30° and 127° (relative to l'Institut Geographique National grid). The south-facing slope of the research site has been subjected to some periglacial weathering. This has resulted in a number of linear cryoturbated lobes filled with silty material that strike at ~150°. Some of the fractures at Mesnil-Val have been observed to be filled with loess.

The chalk of Mons Klint has been highly deformed by glaciotectonics. The chalk originated from the Baltic and was moved by northerly flowing ice before being deformed again by an ice sheet from the east. As a result, thrust sheets of chalk lie over and are intermingled with slabs of glacial till. The cliffs at the test locations contain no till. The glaciotectonics has generated a highly fractured chalk with many fracture sets, but with low persistence and high frequency.

2.2 Microseismic data collection

The emission of a seismic signal when the rock cracks has been efficiently used to detect cracks in deep coal mining (Senfaute et al., 1997; Sato and Fujii, 1988) in abandoned mines (Senfaute et al., 2000) and in hot dry rock geothermal projects (Niitsuma et al., 1987). The challenge in this research was to adapt the microseismic technique to cliffs where the overburden stresses induced by the rock mass are lower than in underground deep mines. The induced crack signals are likely to be weaker than in underground mines and are disturbed by noise.

Acoustic crack emissions are measured with accelerometers and geophones. Since the wavelengths of the seismic signals generated during the rupture of chalk are not known, a broad frequency band-width was selected. A network of five microseismic stations (accelerometer and geophone) was installed in the cliff at Mesnil-Val. Anticipating strong attenuation of the seismic signal in chalk, a maximum spacing of about 50 m was chosen between stations. The network comprised two stations in vertical boreholes, drilled from the top of the cliff, and installed to a depth of 10 m and located 10 m from the cliff edge. And three stations in horizontal boreholes, drilled from the cliff face to a depth of 6 m. Data were recorded continuously from January 2002 to May 2004. In addition the cliff was equipped with temperature and humidity sensors, extensometers and a weather station was established on the cliff top. Due to the cost of the installation, microseismic data were only collected at Mesnil-Val and not from the UK and Danish locations.

2.3 Azimuthal apparent resistivity data collection

An apparent resistivity measurement is made by imposing a low energy direct current between two electrodes implanted into the ground surface. The resultant distribution of ground electrical potential is measured between additional pairs of stainless steel electrodes. Sub-vertical, parallel fractures will often impose anisotropic physical properties that result in a variation of apparent resistivity with the orientation of the resistivity measuring array (Taylor and Fleming, 1988). By rotating the array it is possible to estimate the dominant strike direction of the fracture set and to calculate a coefficicient of anisotropy, λ. For the Square resistivity measuring array used in this study (Habberjam and Watkins, 1967) this is defined as the ratio of the apparent resistivity perpendicular to the fracture set (the maximum value) to the apparent resistivity parallel to the fracture set (the minimum value). If the fractures dilate as a cliff collapse approaches then the value of λ would be expected to be time dependant.

On each cliff top, three sites perpendicular to the cliff face were established and a control site was setup approximately 50 m from the cliff (cf. Figure 1). Those sites near the cliff edge (Sites A, B and C) should sample ground that is likely to be affected by fracture dilatancy. The maximum electrode spacing (referred to as 'a' and equal to the side of the square) for the three sites near the cliff face was set so that the nearest approach of an electrode to the cliff edge was about one to two metres. Some temporal variations are likely to be observed due to influences such as seasonal changes in saturation levels, but these should also be observed at the Control Site. A time series was built up by repeating the measurements every two months for a period of two years at the five test locations.

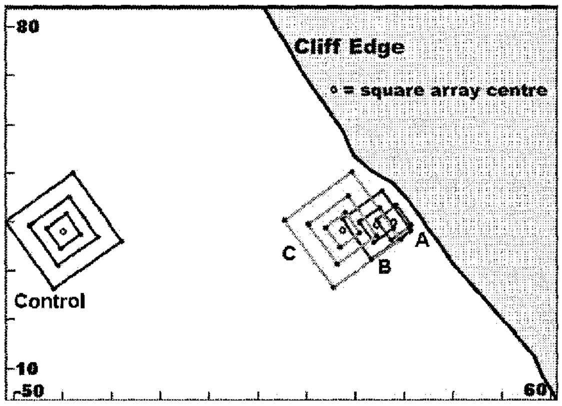

Figure 1: Four centres for azimuthal apparent resistivity measurements on the cliff top. Site A: 'a' = 5 m, Site B: 'a' = 5, 10 m, Site C: 'a' = 5, 10, 20 m, Control: 'a' = 5, 10, 20 m. Where 'a' = the side of the square.

Detailed geological data have been collected from all locations that consists of mapping of the lithology and stratigraphy, mapping of fracture density, fracture orientations and fracture persistence and laboratory strength testing of samples under varying levels of saturation. Topographical surveying grids were also established at each location in order to detect any small ground movements near the cliff edge.

3. RESULTS

3.1 Microseismics

Significant seismic activity was recorded twice per day at Mesnil-Val, at the hours when the sea was highest for periods of 2 to 3 hours. Analysis confirmed a strong correlation between tide and seismic triggering. Hence, it is possible to conclude that these recordings are related to the action of high tide on the face of the cliff. Microseismic events were also recorded at low tide. These events are considered as independent of the action of the sea. Spectral analysis of the signals showed significant differences between these events and those recorded during high tide.

A cliff collapse occurred on 23rd June 2002 at Mesnil-Val. An estimated 2700 m^3 of chalk dropped from a maximum height of around 50 m. It occurred at the center of the monitored zone (cf. Figure 2). In the 15 hours preceding the collapse strong seismic pre-cursors were recorded on one of the accelerometers (cf. Figure 3).

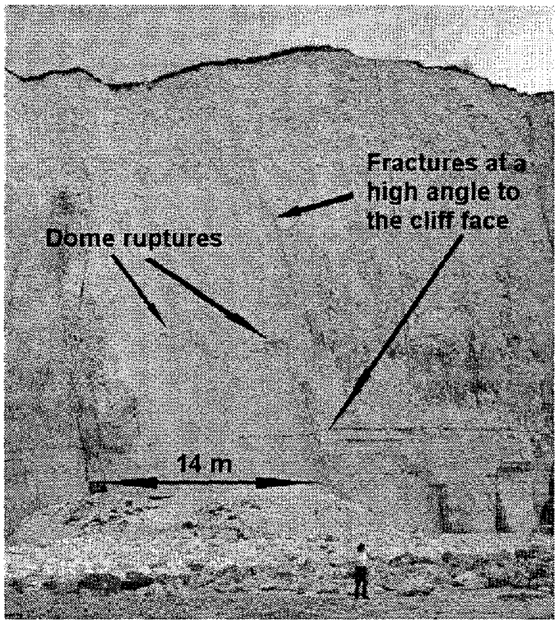

Figure 2: Mesnil-Val cliff collapse that occurred on 23rd June 2002.

This accelerometer (AH4) was damaged by the collapse and ceased to function. The collapse occurred during a low tide, and most of these seismic pre-cursors can therefore be considered to be independent of the action of the sea.

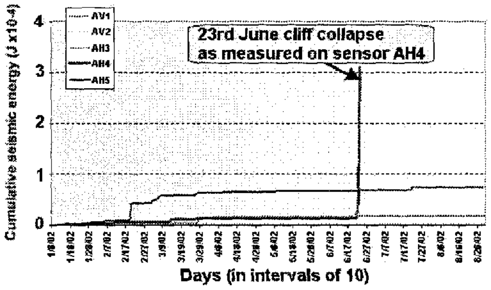

Figure 3: Cumulative seismic energy recorded over eight months at Mesnil-Val. AV are stations in vertical boreholes, AH are in horizontal boreholes.

3.2 Azimuthal apparent resistivity

From the measured apparent resistivity anisotropy, fracture orientations have been estimated. Away from the cliff edge, the derived fracture orientations correspond to the tectonic fractures and are consistent with the mapping of fractures at the cliff face. At the French and UK locations, the fracture orientation obtained adjacent to the cliff is sub-parallel to the cliff face. At Beachy Head and Birling Gap it occurs in a zone about 10 m wide, but at Mesnil-Val it widens to about 20 m. At the Danish locations no consistent fracture orientations were obtained. The chalk here has been highly deformed by glaciotectonics and these results are consistent with the geological mapping that indicates a highly fractured rock mass with many fracture sets at different orientations, but of low persistence.

A plot of the variations of the coefficient of anisotropy (λ) against time at Birling Gap is shown in Figure 4. A cliff fall occurred between 5th March and 23rd April 2002 and is associated with a large decrease in λ at Sites A and B, which are situated adjacent to the cliff edge. There is no associated reduction in λ at the Control Site, away from the cliff. A further cliff fall at Birling Gap occurred on 9th January 2003, but there is no indication of it in the time series of λ.

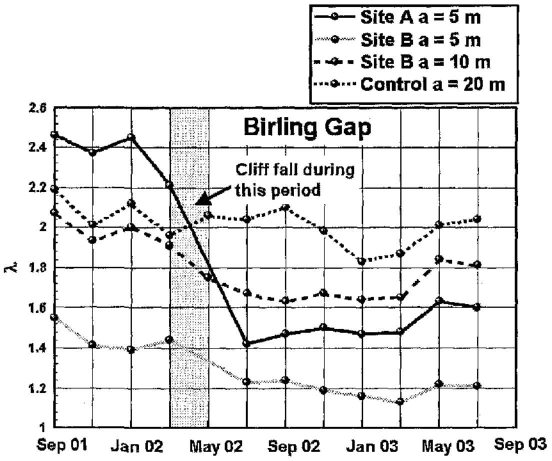

Figure 4: Temporal variation of the coefficient of anisotropy at Birling Gap.

At Beachy Head and Mesnil-Val there is a strong seasonal variation in λ (cf. Figure 5). Values peak in the summer with minimum values in the winter. The cliff fall at Mesnil-Val is not apparent in the variations of λ.

3.3 Laboratory sample testing

Laboratory based investigations have been carried out to better understand the mechanical properties of the chalk cliffs in relation to the effects of sea salt saturation on the strength and stability of the sea cliffs. This will help to better understand the causes, processes and mechanics involved in chalk cliff collapse. The laboratory testing involved a series of undrained triaxial tests to establish stress paths for chalk cliffs in the Cuckmere Bed of the Seaford Chalk Formation. Chalk samples from Birling Gap were compared with samples collected of the same stratigraphy from an inland cement works. The coastal Birling Gap samples were placed in a desiccator and saturated in stages under vacuum with de-aired water for at least 7 days. A set of samples from the chalk quarry were saturated with saline water, whilst another set of identical samples from the quarry were saturated in de-aired water. After saturation the samples were dried in an oven at 60° C, this process was repeated 3 times. The saturated weight of the sample was measured after removing surplus water, and the dimensions were measured with a vernier gauge. The sample was then prepared and tested in the triaxial rig.

The cement works samples in de-aired water had the highest average axial stress peak strength of 4.9 MPa and the Birling Gap coastal samples had the lowest average axial stress peak strength of 2.9 MPa. The salt saturated samples from the cement works had an average axial stress peak strength of only 3.4 MPa. This is evidence that the weakness in the coastal samples is at least partly due to the influence of the salt from the sea on the chalk.

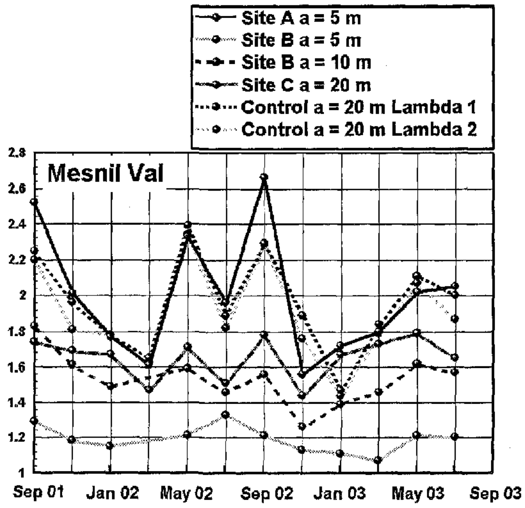

Figure 5: Temporal variation of the coefficient of anisotropy at Mesnil-Val.

4. ANALYSIS AND DISCUSSION

4.1 Microseismics

Frequency analysis of the seismic signals measured before the collapse at Mesnil-Val has identified a number of seismic event families that each contains one specific frequency spectrum. Each family is associated with a different phase of the collapse and thus indicates two phases of failure. This has been investigated further by measuring the acoustic emissions emitted by chalk samples collected from the Mesnil-Val cliff, under laboratoty uniaxial compression tests. The failure strength obtained for each sample was between 3 and 6 MPa. The total porosity of the chalk is very high (42 to 45 %) suggesting a low mechanical strength, which is confirmed by the low values of the failure strength obtained during the tests. The laboratory results show similar changes of the seismic behaviour before the final rupture of the samples, and the collapse of the cliff. There is an exponential increase in the number of seismic events and in the energy released. The frequency spectra evolve towards higher frequencies that are associated with the formation of new cracks. In the hours before the collapse of the cliff, high frequencies were recorded one hour before the collapse and at the time of the collapse itself (cf. Figure 6). Hence, these peaks are most likely associated with the creation of new cracks. Lower frequencies emitted after the first peak are most likely associated with the extension of cracks. The identification of a significant increase in released seismic energy and of high frequencies may be a pre-cursor for the imminent catastrophic failure of the cliff.

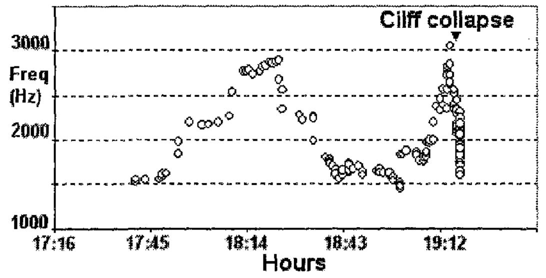

Figure 6: Frequency spectrum of seismic events recorded during the cliff collapse at Mesnil-Val.

4.2 Azimuthal apparent resistivity

Of the three cliff falls that occurred during the period of monitoring, only the one from Birling Gap in the spring of 2002 generated a significant variation in the temporal variation of the coefficient of anisotropy. The interpretation of this result is that considerable fracture dilatancy was occurring in the cliff parallel fracture set prior to the fall. This collapse occurred from the part of the cliff over which the resistivity measurements were made, whilst in the other two collapses the ground lost was several metres from the measurements. Since the lateral extent of the falls is largely constrained by the tectonic fractures, it is likely that these tectonic fractures also constrain the lateral extent of the fracture dilatancy.

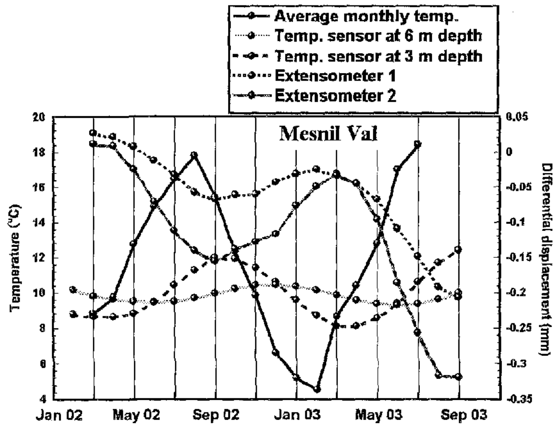

Figure 7: Air temperature, rock temperature and extensometer data from Mesnil-Val. The rock temperature sensors were emplaced in a horizontal borehole drilled into the cliff face.

Temperature and extensometer data collected at Mesnil-Val are shown in Figure 7. The average monthly air temperature shows, as expected, a peak in the summer and a trough in the winter. The temperature sensors within the cliff demonstrate that rock temperature is being driven by the air temperature. It is well known that to depths of around 15 m, rock temperature changes are driven by atmospheric temperatures. There is a phase shift of 1 to 2 months between the temperature variations at the cliff face and those at a depth of 3 m and 4 months between the cliff face and those at a depth of 6 m. From these differences an average thermal diffusivity of 5.98 x 10^{-3} cm^2 s^{-1} has been calculated, which is consistent with fractured chalk. In turn, rock temperature is driving an expansion and contraction of the rock mass that has been measured by the extensometers. The movements are extremely small, but there is a clear maximum expansion in February and minimum contraction in September. Hence, it would appear from the seasonal variations in the coefficient of anisotropy (peak in the summer and trough in the winter) that the expansion of the rock mass is taken up by a contraction of the fractures. The different magnitudes of the seasonal variations observed in λ at different locations are unclear, especially, when as at Beachy Head and Birling Gap, they are on the same Chalk stratigraphy and are only 2 km apart.

5. CONCLUSIONS

The research presented has been successful in identifying changes within the rock mass behind the cliff face prior to a collapse. The joint interpretation of a number of data sets has enabled the following conclusions to be drawn.

- The microseismic data have demonstrated that there is a significant increase in seismic energy emitted from cracks within the rock mass in the hours before a cliff collapse.
- Analysis of the sesismic data indicates that different phases of the failure can be identified by distinct seismic families. Comparisons with laboratory induced acoustic crack emissions has demonstrated that high frequency seismic signals are emitted as the rock cracks and that this might be used as an indicator that a collapse is imminent.
- The high porosity of chalk was found to lead to rapid attenuation of the seismic signals. The distance between accelerometers in a monitoring network on a chalk cliff would have to be less than 30 m.
- Comparisons of the azimuthal apparent resistivity data with geological mapping indicate that tectonic fracture orientations are being measured at the Control sites. Towards the cliff edge at the UK and French locations, the analysis indicates a cliff parallel fracture set that is thought to develop in response to the free face at the cliff. This occurs in a zone adjacent to the cliff

edge, 10 to 20 m in width. In Denmark, at Mons Klint, the results are more uncertain, reflecting the glaciotectonised nature of the chalk. It is likely that acoustic crack emissions are being generated as the cliff parallel fracture set develops.

- The 2002 cliff fall at Birling Gap, where ground from within the circle of measurement was lost, produced a large temporal change in the coefficient of anisotropy. This has been interpreted as a reduction in fracture dilatancy as a result of the cliff fall.
- The Mesnil-Val and Birling Gap 2003 cliff falls did not show temporal changes in the coefficient of anisotropy. Ground outside of the circle of measurement was lost and it is possible that the tectonic fractures limit the extent of both the fall and the dilating fractures.
- Some sites showed seasonal variations in the measures of anisotropy with peaks in the summer and troughs in the winter. The Mesnil-Val temperature monitoring suggests a correlation between these variations and rock temperature. The thermal diffusivity of the rock is such that the maximum expansion of the rock mass occurs six months after the maximum air temperatures. The data indicate that the expansion leads to fracture contraction with associated minimum values of anisotropy in the winter.
- The laboratory testing of chalk samples saturated with saline water has demonstrated a significant weakening of the samples. It has been noted how frequently collapses occur along coastal sections, yet inland quarries of similar chalk appear relatively more stable. Hopefully this study goes some way to proving that salt is a major contributing factor to the weakening of chalk coastal cliffs.

The techniques described here would need to be improved and optimised before they could be used as tools for predicting cliff collapses, especially on lithologies other than chalk. However, cliff failures affect local communities and the wider participation of all groups of people who use the cliffs as an amenity. Planners and local government authorities need to be assured of the safety of the cliffs. With further improvements to these methods, networks could be installed by the appropriate authorities within cliff collapse high-risk zones. These would contribute to preventing risks and decreasing insurance costs of vunerable properties.

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REFERENCES

Busby, J. P., Gourry, J. C., Senfaute, G., Pedersen, S. & Mortimore, R. 2002. Can we predict coastal cliff failure with remote, indirect measurements. In: Instability, planning and management (eds R. McInnis & J. Jakeways), London: Thomas Telford: 203-208.

Habberjam, G. M. & Watkins, G. E., 1967. The use of a square configuration in resistivity prospecting. Geophysical Prospecting 15, 445-467.

Niitsuma, H. Chubachi, N. & Takanohashi, M. 1987. Acoustic analyses of a geothermal reservoir and its application to reservoir control. Geothermics, 16, 47-60.

Sato, K. & Fujii, Y. 1988. Induced Seismicity Associated with Longwall Coal Mining. International Journal of Rock Mechanics and Mining Sciences. 25, 253-262.

Senfaute, G., Abdul-Wahed, M., Piguet J. P. & Josien, J. P. 2000. Qualification of the microseismic monitoring technique applided to the risk of collapse in iron ore mines. EUROCK Symposium, Aachen, 597-602.

Senfaute, G., Chambon, C., Bigarre, P., Guise, Y. & Josien, J. P. 1997. Spatial Distribution of Mining Tremors and the Relationship to Rockburst Hazard. Pure and Applied Geophysics, 150, 451-459.

Taylor, R. W. & Fleming, A. H. 1988. Characterizing jointed systems by azimuthal resistivity surveys. Ground Water. 26, 464-474.