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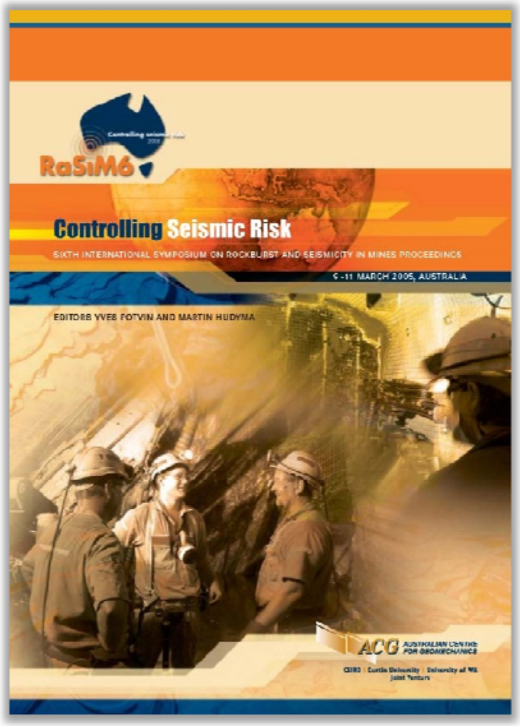

# Fundamental Study of Micro-Fracturing on the Slip Surface of Mine-Induced Dynamic Brittle Shear Zones

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*An important type of severe rockburst in deep, tabular mines results from the sudden eruption of a dynamic brittle shear zone. Earlier studies involving thin-section micrography and scanning electron microscopy of the fault gouge and slip surfaces had shown the existence of unique sub-microscopic particles. These indicated extreme processes accompanying the evolution of the fracture.*

*The genesis of these particles has important implications for the understanding of the large stress-drops and unusually violent damage associated with this particular rockburst type. It thus appeared necessary to confirm the prevalence of these particles and to substantiate, quantitatively, the explanation postulated for their formation*

*This paper shows that the sub-particles are, in fact, characteristic of induced dynamic brittle shears in quartzite. Using an energy balance analysis, it quantitatively supports the hypothesis that the polyhedral sub-particles are the result of a shock un-loading phenomenon. The paper suggests that this has important implications for the mobilisation of frictional resistance on the fault surface.*

## 1 INTRODUCTION

In the deep, laterally extensive South African gold mines severe rockbursts occur relatively frequently, creating a serious safety risk and sometimes causing major damage to mining infrastructure. The larger events associated with these rockbursts range from Richter magnitude $M_L = 2.0$ to extreme values as high as $M_L = 5.0$. These events result from violent shear failure in the critically-stressed portion of the rockmass surrounding the extensive stoping operations.

Usually the failure consists of rejuvenated slip along existing geologically ancient faults. Sometimes the slip movement is clearly visible where the fault plane is intersected by mine tunnels. More often the fault surface is not exposed and the mechanism at source is inferred from seismological data and known geological structure.

Less frequently the rockburst results from a sudden shear fracture through pristine rock where no faults or discernible planar weaknesses existed before. Such fresh *dynamic brittle shear zones* have been observed on several mines and studied fairly closely in a few instances. There are indications that this type of source mechanism has potential for causing damage of greater violence than is usually associated with fault-related events.

The first of these induced brittle shear zones to be studied extensively (Gay and Ortlepp, 1978) revealed scanning electron microscopic (SEM) evidence of unusually-shaped sub-particles of quartz in the fault gouge. It was later suggested (Ortlepp, 1992) that these minute pseudo-crystalline particles resembled rhombic dodecahedra and were formed by 'explosive' self-shattering of quartz grains subjected to sudden isotropic tensile body forces resulting from shock unloading.

Subsequent observations, from a different study on another mine, provided supporting evidence for such extreme processes of compression and rarefaction occurring on a microscopic scale (Ortlepp, 2001). However, the self-shattering mechanism which was proposed for the formation of the dodecahedral fragments seemed implausible to several persons who had given the matter considered thought.

Because there are potentially many serious implications for the genesis of rockbursts and possibly also for the study of earthquakes should such a mechanism reflect physical reality, it seemed desirable and even necessary to explore the process more thoroughly.

It is our intention in this paper to assemble further relevant evidence and to examine it more quantitatively in order to confirm, with greater certainty, the mechanism which was proposed for the extreme processes that accompany the eruption of an induced brittle shear zone.

## 2 BACKGROUND

All rockbursts, by definition, involve sudden and often violent displacement of rock. Occasionally however, larger incidents cause damage of such intense violence that it seems that our knowledge of the mechanism of damage is completely inadequate. McGarr (2001) suggests that strong ground motions are limited to values of a few metres per second governed by a maximum slip velocity of perhaps 4 $ms^{-1}$ at the source. Although high by most standards, it seems, intuitively, that peak particle velocities of this magnitude are not sufficient to produce the explosion-like damage effects in tunnels where the surrounding rock is shattered into fragments (e.g. Ortlepp et al., 2003) or which have been observed in stopes where hydraulic props have been punched deep into the quartzite footwall (Ortlepp, 1993).

The question we pose is whether the extreme failure processes which are minutely-localised on the fault surface, can somehow occur also on a larger (fractal?) scale? These might then impart extremely strong ground motions in the form of localised, directional and focused 'shock' waves into the surrounding wall rock as illustrated in Figure 1. Is it possible that, locally, peak particle velocities higher by one to two orders of magnitude, can result within a few metres of the slip surface of high energy rockbursts?

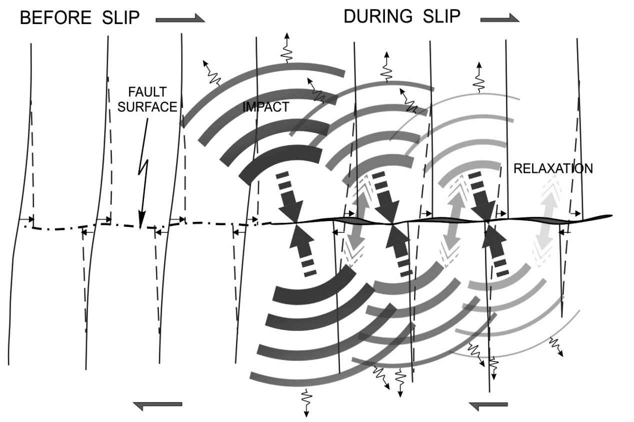


**FIG. 1** **Conceptual illustration of mechanism for creating extreme compressions and instantaneous rarefactions along a non-smooth fault surface and generating localised, focused strong ground motions**

In the field of earthquake mechanics the absence of a marked temperature gradient across major faults that have experienced recent or repeated movement, has been recognised as an important paradox. Theorists attempting to explain this lack of frictional heating have sometimes invoked ingenious hypotheses for reducing the dynamic friction on the slip surface. For example, when the velocity of seismic slip exceeds quite low values, in the order of about 1 $ms^{-1}$, Di Toro et al. (2004) have suggested that friction approaches zero due to the formation of a thin layer of silica gel on the fault surface.

We would submit, instead, that the existence of 'self-shattered' polyhedral quartz sub-particles, on a real life-size scale, specifically and uniquely associated with violent shear slip, offers the possibility of a totally different conceptual approach. Their presence may suggest that frictional resistance may not be able to be mobilised at all. Their mode of origin indicates that near-isotropic compressions co-exist spatially, and nearly simultaneously, with instantaneous rarefactions of near-shock intensity. The rapid pulsating repetition of compression/rarefaction across the surface of on-going slippage effectively represents a 'blanket' of high-frequency vibration of minute amplitude and high intensity. This high energy interface is self-generated – an inherent part of the brittle fracture process. We argue therefore that rapid shear slip under high confining stress is thus necessarily accompanied by a high-frequency, high-intensity vibration that would intrinsically not permit friction to establish itself from the outset.

Under the resulting conditions of dynamically-lowered frictional resistance, slipping would occur at considerably higher velocity. In the case of a severe rockburst this would cause stronger ground motion than previously believed possible, in the immediate vicinity of the fault surface.

In the earthquake slip process, we tentatively suggest that the same self-exited, high frequency, high intensity vibration might take place. It would occur as a consequence of the very process of shear slip propagating through a strong brittle rock crust. Such vibrations would intrinsically inhibit the mobilisation of resistance due to friction (see foot-note on final page).

It is in the context of this background that we diffidently offer the notion that similar extreme failure processes may occur on large dry fault surfaces in the earths crust in the same way as they appear to occur on the smaller fault surfaces that cause major rock bursting on deep South African gold mines. It is therefore not necessary to postulate the presence of very low friction materials on such a dry slip surface. Rather, the essentially vibrational character of the rupture process itself inhibits the onset of frictional resistance from the very start of fracture propagation.

We believe that these unique quartz sub-particles and the intense causal processes that they imply, should be brought to the attention of other disciplines such as fracture mechanics and earthquake physics. Their authoritative consideration may throw more light on an intriguing and potentially important matter.

**TABLE 1** **List of observed brittle shear zones**

| Mine | | Level/ Area | Date | Photographs | Microscope Study | SEM Study | Publication Observer |
|---|---|---|---|---|---|---|---|
| ERPM | #1 | 49 Level West Claims | 1974 to 1980 | ✓ | ✓ | ✓ | Gay and Ortlepp (1978) Ortlepp (1992) (2001) |
| ERPM | #2 | 70 level | 2002 | ✓ | ✓ | ✓ | Harvey |
| Mponeng | #1 | 84W | 1995 | ✓ | ? | ✓ | Grodner |
| | #2 | 87W64 | 1997 | ✓ | ? | ✓ | Grodner |
| | #3 | 89W49 | 1997 | ✓ | ? | ✓ | Armstrong |
| | #4 | 87W50 | 1999 | ✓ | ✓ | - | Ortlepp (2001), Stewart |
| Blyvooruitzicht | #1 | 24W4 | 1982 | ✓ | - | - | Ortlepp, Spottiswoode |
| Blyvooruitzicht | #2 | 17W24 | 1997 | ✓ | ? | ✓ | Ortlepp (2001) Grodner, Armstrong |
| Hartebeesfontein | #1 | Shaft #2 | 1999 | ✓ | - | - | Bosman *et al.* (2003) |
| Hartebeesfontein | #2 | Shaft #4 | 1999 | ✓ | ? | ✓ | Armstrong |
| Crown Mines | | Shaft #5 | 1976 | ✓ | - | - | Ortlepp |
| City Deep | | Shaft #5 | 1966 | ✓ | - | - | McGarr (1970), Ortlepp |

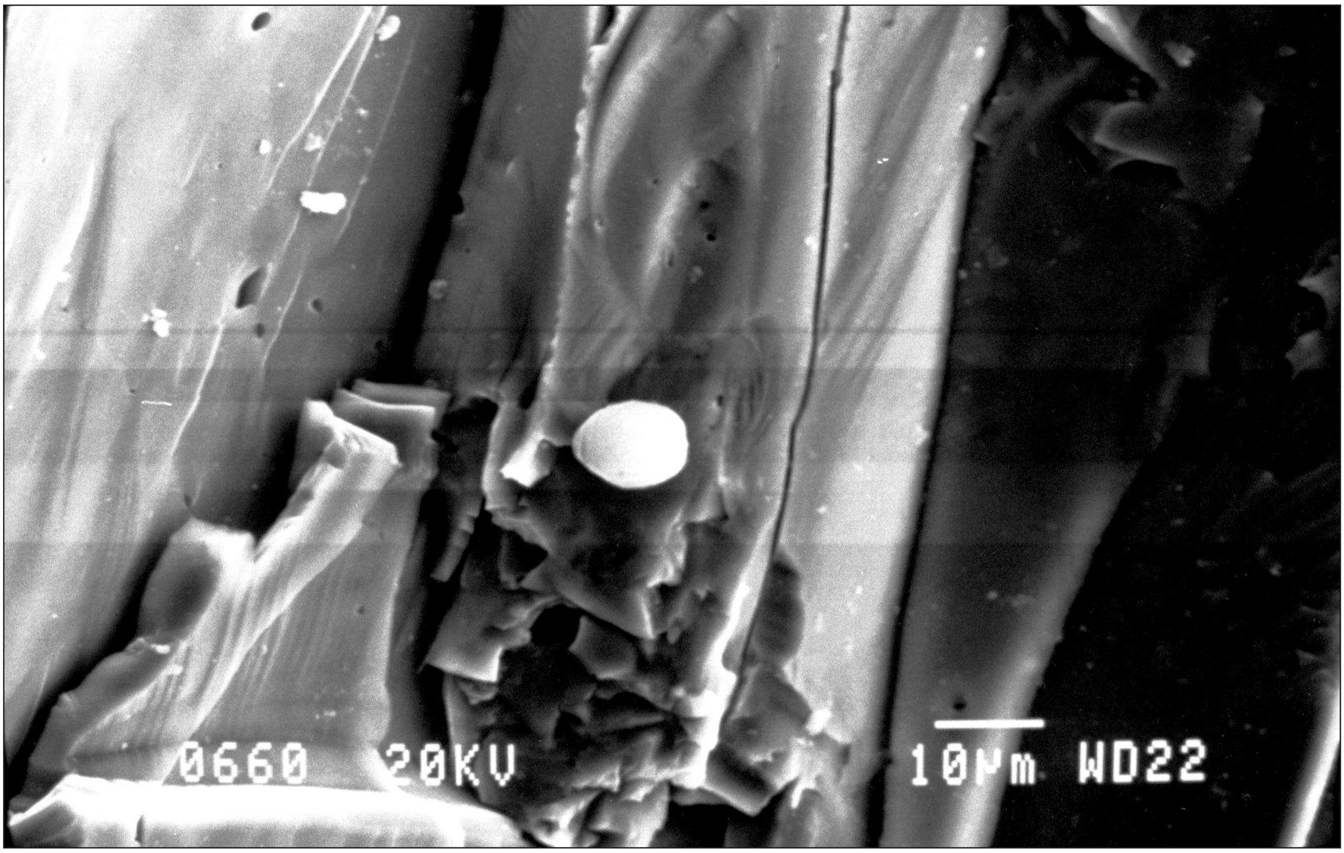


**FIG. 2** SEM photograph of fault gouge from an induced brittle shear (Blyvooruitzicht #2) which resulted in a rockburst of $M_L$ = 2.4 on 30.01.96. Sample by M Grodner. SEM study by R Armstrong

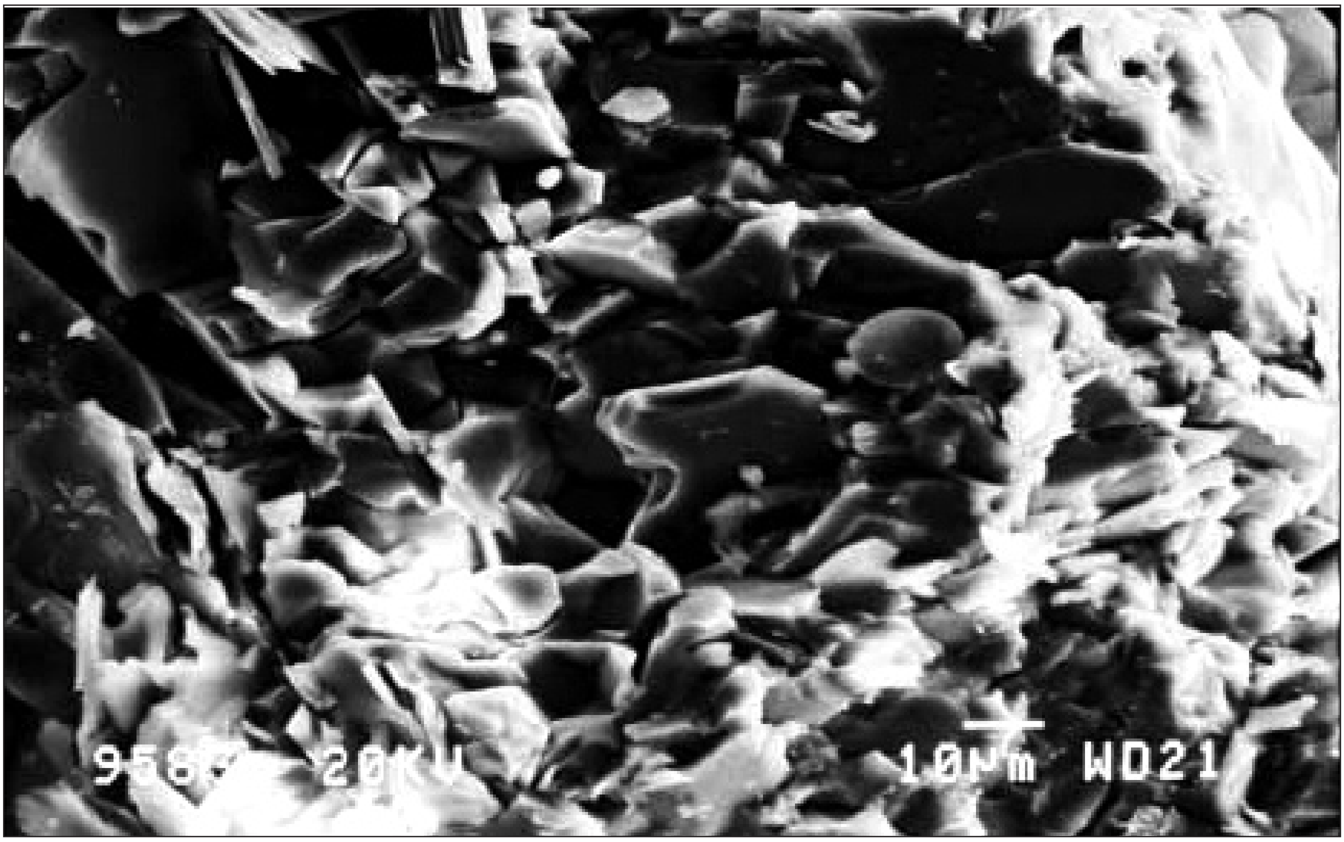


**FIG. 3** View of prolate silicate spheroid (right of centre) in the same SEM field as polyhedral sub-particles from ERPM #2. Brittle shear discovered by F Harvey, attributed to $M_L$ = 2.2 event of 17.10.98. SEM study by R Armstrong

## 3 RANGE OF OCCURRENCES

The induced brittle shear zones which are the principal focus of this study have been observed on many of the deeper South African gold mines. The mines where these structures have been recognised and clearly photographed, are listed in Table 1.

To date eight shears from four mines have been studied with varying degrees of thoroughness. The macro-structure of some of these features has been described previously e.g. Bosman and van Aswegen (2003), Ortlepp (1992) etc. Only structures traversing quartzitic rocks have been explored.

Specific studies of the microscopic features in the fault gouge and the general morphology of the host structures have been carried out on six different brittle shears from three of these mines.

The diagnostic feature of the slip surface is that it is strongly 'hackled' with a marked lineation perpendicular to the direction of slip. It is on this surface, the interface between finely-ground rock flour and relatively undamaged quartzite, that the polyhedral sub-particles are localised. Within a few millimetres of this surface individual quartz grains are totally undamaged – see p 47 in Ortlepp (2001).

Polyhedral sub-particles showing easily recognisable characteristic features have been identified in four of these structures so far. In sample 8 from ERPM#2 the presence of spheroids of silicate material has been observed in the same SEM field as the quartz polyhedra. Similar small spheroids have been observed in two other structures, Mponeng1 (photograph in Ortlepp, 2001) and Blyvoor#2 (Figure 2) – where no polyhedra were seen. The SEM search was rather superficial in these latter two instances so it is not impossible that the 'self-shattering' process also occurred there and polyhedra particles did exist.

The spheroids, although rarer and less conspicuous, are believed to originate from the same 'shock' compression/ rarefaction process that created the polyhedral sub-particles. These small spherical particles were first described by Ortlepp (2001) and their postulated origin and relationship to the polyhedral silica sub-particles were discussed briefly.

Based on a single electron dispersion spectrometric (EDS) analysis it appears that a spheroid from sample #8, ERPM(2) (see Figure 3) is not quartz but a mineral rich in potassium, silica and lithium, probably with a significantly lower melting point than that of silica. These silicate spheroids are deserving of closer study particularly in the context that they co-exist with the quartz sub-particles. Here it is sufficient to emphasise that we believe that they firmly substantiate the mechanism proposed for the genesis of the minute polyhedra. Too little is known at this stage to warrant further discussion of the detailed role that the silicate spheroids might play in the total dynamic process.

## 4 THE NATURE OF THE SUB-PARTICLES

The most striking features of the quartz sub-particles, which were evident in all four cases, are the following:

- They display a sharp-edged, pseudo-crystalline appearance due to each sub-particle being enveloped by nearly regular facets, often of recognisable polygonal shape such as rhombs, pentagons and hexagons - Figure 4, from ERPM #1.
- Most of the sub-particles within a particular SEM field tend to be quite closely similar in size and equidimensional in shape – Figure 5, from Mponeng #3.
- Polyhedral sub-particles often seem to constitute the whole of a single quartz grain, flanked by unshattered, less-broken grains – Figures 5 and 7.
- The number of facets often appears to be about twelve but is frequently more – e.g. photo 6, from Mponeng #3.
- Planes separating facing pairs of facets of three neighbouring grains frequently intersect at approximately 120$^{o}$ – particularly clear in Figures 4 and 6.
- Whatever their particular shape or size, individual sub-particles rest against one another in such a tight arrangement, without voids or interstices, as to leave no doubt that they were originally part of a continuous space.

It is this last attribute which we feel is the most convincing demonstration that some of the original intact quartz grains comprising the quartzite host rock have been, selectively, 'exploded' apart by some extreme internal dynamic process.

## 5 MECHANISM OF FORMATION OF SUB-PARTICLES

Arising from discussion between two of the present co-authors several years ago in the early 1990's, a possible mechanism for the development, on a small scale, of pervasively isotropic and uniform, tensile body forces was postulated. The complete failure hypothesis was described in some detail by Ortlepp (1992) and is illustrated in Figure 8.

Very briefly, the essential requirements of the process can be described as follows. A small portion of the incipiently failing rock comprising of a quartz grain, or several adjoining grains, is momentarily over-compressed hydrostatically, accumulating elastic strain energy. The stress-strain curve would increase linearly to some considerably elevated value. If allowed suddenly to relax instantaneously and completely, the internal fabric of the grain would experience a uniform, isotropic tensile 'shock' due to elastic re-bound. Small volume elements (illustrated as incipient dodecahedra in Figure 8) would tend to expand and acquire some inertial momentum away from one another. The stress-strain response at potential interfaces would rapidly decrease (along the linear portion of the graph), overshoot the zero-strain point and continue into the tensile domain. The 'rebound' would extend beyond the critical tensile strain limit for quartz and direct tensile fracturing would ensue simultaneously along planes perpendicular to each of the isotropic tensile stress vectors.

In a perfect material (i.e. one with no defects even on a molecular scale), there would be sets of twelve stress vectors, uniformly distributed and directed outwards from nuclei uniformly spaced in a 3-D lattice grid. These geometrical requirements are logically inferred from the fact that the twelve perpendicular planes along which the tensile fracturing would extend, must necessarily form the twelve facets of a rhombic dodecahedron. This condition follows from the fact that this particular geometric form is the one that uniquely fills space completely with the smallest surface area. In other words such a configuration is the most energy-efficient way of dividing three-dimensional space – Figure 9 from Aste and Weaire (2000) p 48.

A distinguishing feature of the rhombic dodecahedron is that its facets intersect to form edges that connect at three-edged and four-edged vertices – Figure 9(b). Aste and Weaire state that "….vertex connectivity three…. is present in a very large class of natural packings and patterns". On the other hand, a four-connected vertex is possible only in a perfect rectangular configuration of centres. The slightest departure from perfection causes the four-connected vertex to break down into a couple of three-connected vertices (pages 49-50). This is illustrated in Figure 9(d).

In all of the SEM fields of polyhedra e.g. in Figures 3 to 7 it is clear that three-edged vertices are common while four-

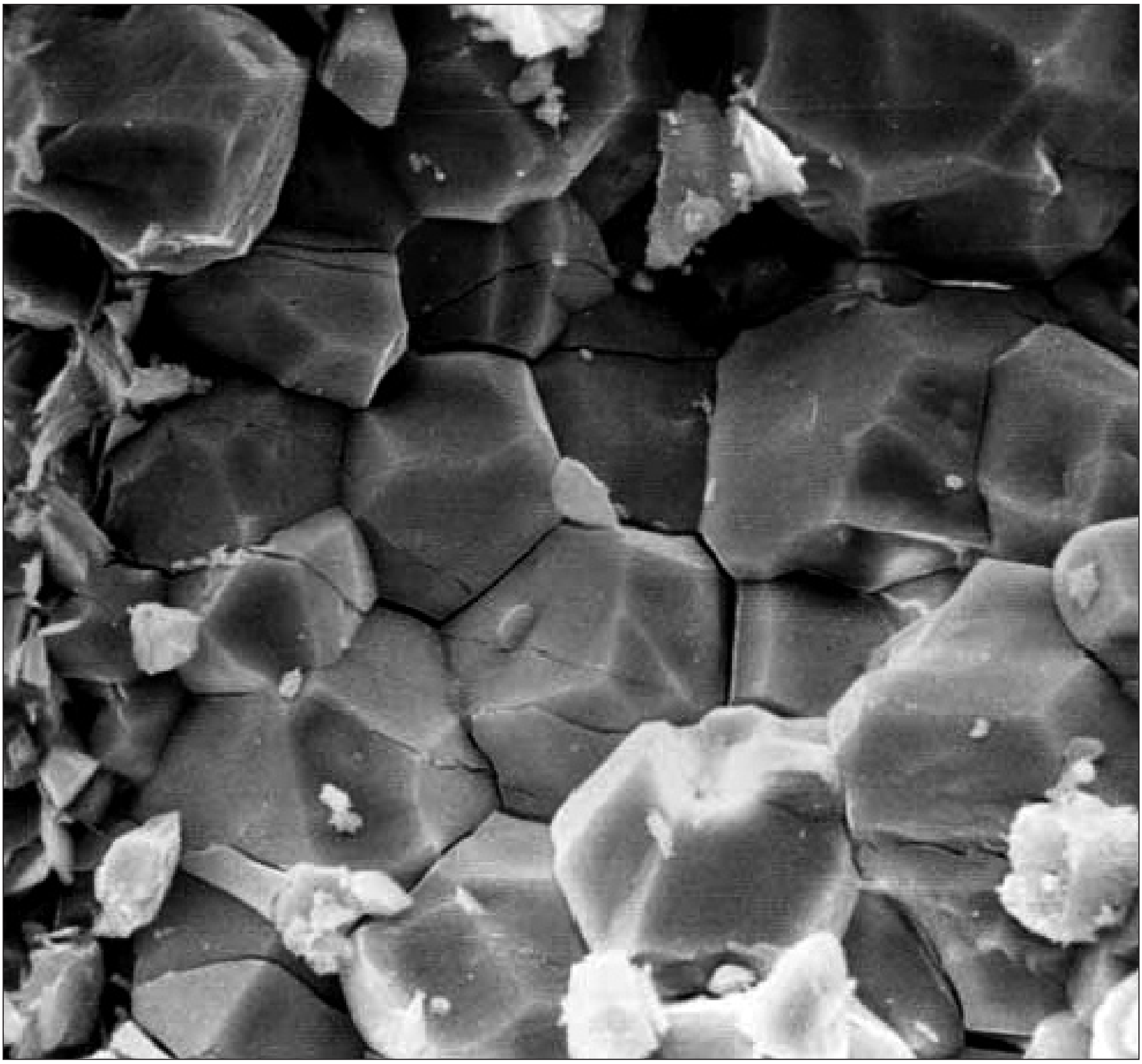

**FIG. 4** SEM micrograph of internal structure of a quartz grain from fault gouge from 1974 ERPM #1 brittle shear showing disruption into elemental polyhedral sub-particles by tensile shock-unloading. SEM study by N Gay. Shear zone was associated with $M_L = 2.1$ rockburst of 23 September 1970 (Ortlepp, 1992)

edged vertices are very rare or absent. We suggest that the lack of vertex connectivity four is simply due to the reason given above.

We believe therefore that there is a strong tendency for the polyhedral sub-particles to take the form of rhombic dodecahedra in order to minimize the total new surface area created. However the existence of imperfections, even on a molecular lattice scale, will override the requirement of idealised geometry. According to Aste and Weaire p 52, "… when the packing is disordered… the structures have polyhedral cells with faces that vary from triangles to octagons with the great majority being pentagons and less abundantly, squares and hexagons".

## 6 SIZES OF SUB-PARTICLES

While the spread of particle sizes in any one SEM field appeared to be quite limited, there seemed to be a wider range of sizes between different fields, different samples and different host structures. Working from the SEM photographs, sizes were estimated for sub-particles from five different samples – see Figure 10. Combining the data from the two most-studied sets of photographs i.e. the original ERPM #1 (Figure 4) and Mponeng #3 (Figure 5) yielded a slightly skewed distribution with a mean of 25 μm and a standard deviation of 9%.

## 7 ENERGY BALANCE

Fairhurst (2003) suggested that the postulated mechanism for self-shattering of the quartz grains could be substantiated by an analysis based on the energy balance implied in the minimum surface area concept.

Conceptually the argument would require fracture to occur at a dodecahedral size at which the elastic strain energy, contained within the incipient volume (at the fracture stress limit), would equal the surface energy of the newly-formed dodecahedral surface.

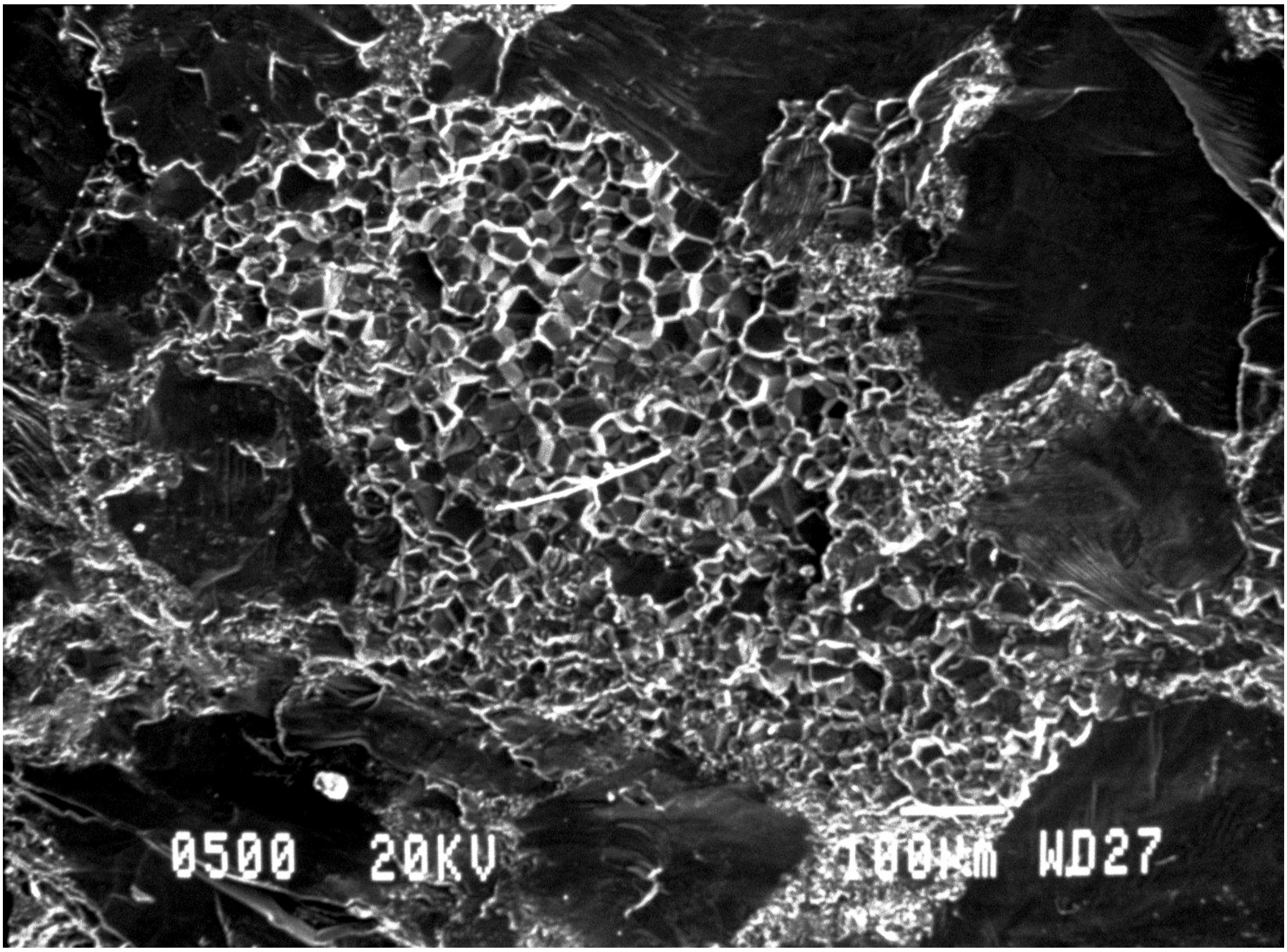


**FIG. 5** SEM view of pervasively-shattered quartz grain with roughly uniformly-sized polyhedral sub-particles flanked by less fractured grains

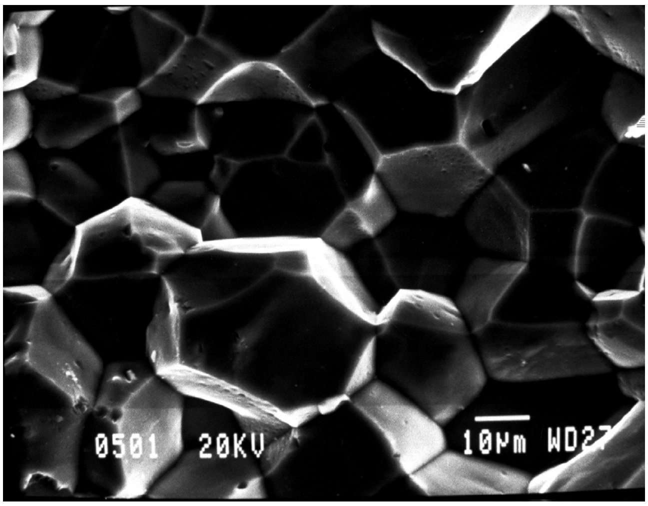


**FIG. 6** Details of upper portion of Figure 5 slightly left of centre showing multi-facetted 'sockets' and a 40 $\mu$m polyhedron with truncated 4-edged vertex. Brittle shear Mponeng #3

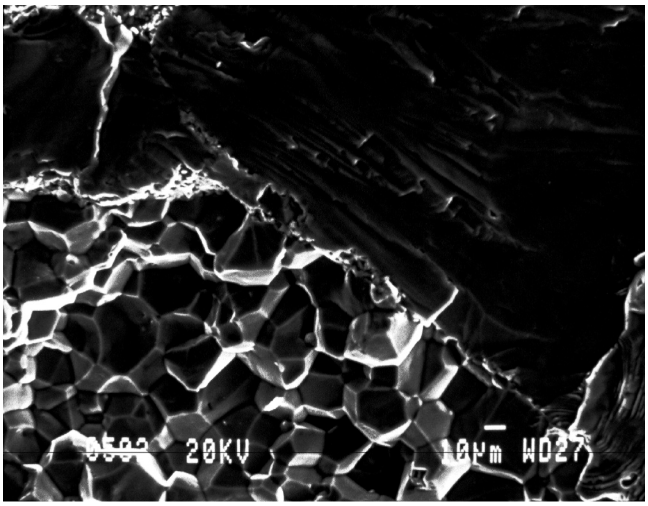


**FIG. 7** Detail of interface at top centre of Figure 5 showing shattered portion of quartz grain abutting a conchoidally broken surface

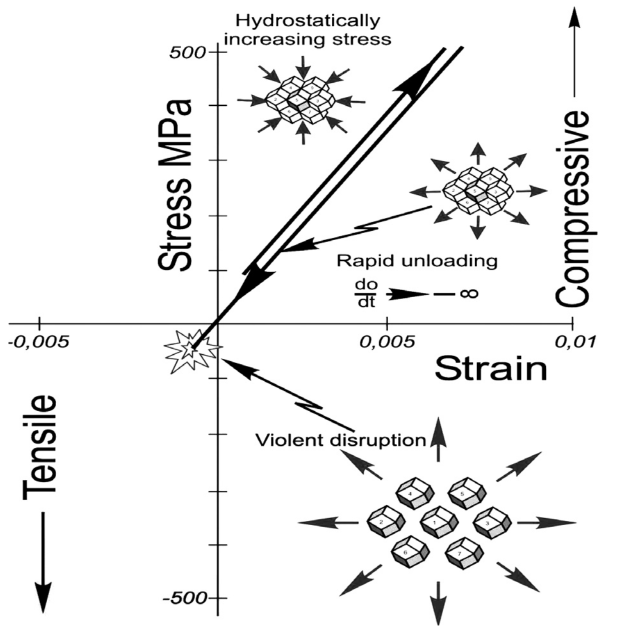


**FIG. 8** Stress-strain graph illustrating dynamic overloading followed by instantaneous 'shock' unloading leading to violent disruption of quartz grain

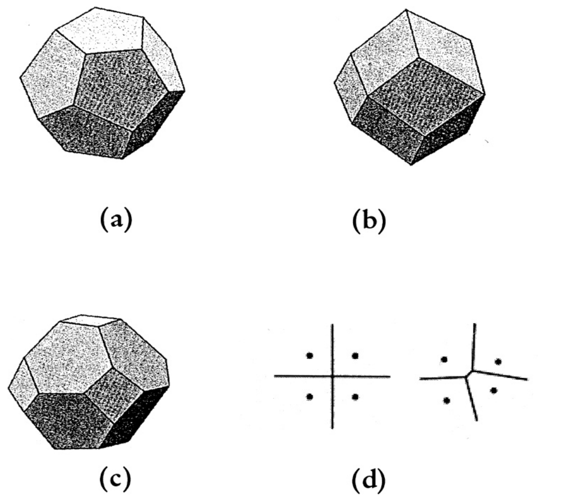


**FIG. 9** (a) pentagonal dodecahedron; (b) rhombic dodecahedron; (c) tetrakaidecahedron; (d) four-connected vertex degenerates to couple of three-connected vertices

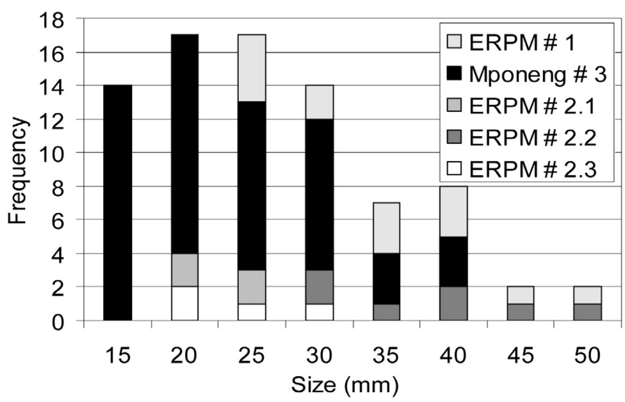


**FIG. 10** Grain size histogram for quartz polyhedral sub-particles from various dynamic shears

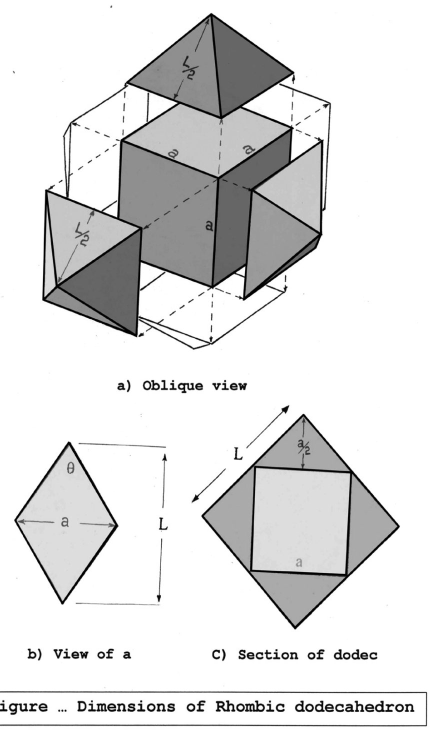


**FIG. 11** Dimensions of rhombic dodecahedron

### i) Area and Volume of the Rhombic Dodecahdron

The essential geometry of the rhombic dodecahedron is outlined in Figure 11 and its general appearance is illustrated in Figure 9(b). Figure 11 shows that it can be considered to be made up of a central cube of side **a** with each cube face surmounted by a pyramid of base **a** and height **a/2**. With their apices pointing inward and located at a common point, the flanking pyramids would make up a second cube of side **a**. Adjoining triangular faces of each pyramid form a rhomb of width **a** and length L.

The dodec has 12 rhombic faces, so the surface area A is

$$A = \frac{12 \cdot 2}{2} \cdot \left( a \cdot \frac{L}{2} \right) = 6 \cdot a \cdot L = 3\sqrt{2} \cdot L^2 \qquad [1]$$

The volume V is equal to two cubes of side, **a**, i.e.:

$$V = 2 \cdot a^3 = \frac{L^3}{\sqrt{2}} \qquad [2]$$

It follows that $\frac{V}{A} = \frac{L}{6}$ (similar to a sphere where $\frac{V}{A} = \frac{D}{6}$)

### ii) Energy Equivalence

The *strain energy* $W_{Strain}$ in a volume V subject to hydrostatic stress σ is

$$W_{strain} = \frac{3}{2} \cdot \frac{1-2\nu}{E} \cdot \sigma^2 \cdot V \qquad [3]$$

The *surface energy* $W_{surf}$ is equal to the product of the dodecahedral area and the specific surface energy for quartz

$$W_{surf} = \gamma \cdot A \qquad [4]$$

When σ is at the critical limit in tension, fracture will occur such that $W_{strain} = W_{surf}$. Equating and using $\frac{V}{A} = \frac{L}{6}$, one gets $L = \frac{4 \cdot \gamma \cdot E}{\sigma^2 \cdot (1 - 2 \cdot \nu)}$ or, in terms of σ,

$$\sigma = \sqrt{\frac{4 \cdot \gamma \cdot E}{L(1 - 2 \cdot \nu)}} \qquad [5]$$

### iii) Determination of σ

It seems reasonable, in the extreme fracture process postulated, that E and ν should be 'dynamic' elastic constants. Values of E = 100 GPa and ν = 0.15 are consistent with known seismic wave velocities in quartzite (Green, 2004).

At this initial stage, we are uncertain as to whether there is a 'dynamic' value for the specific surface energy γ. The value we accepted is 0.7 J/m$^2$ (Brace and Olgaard, 1983) which is consistent with the values quoted by J E Gordon (1976) p 70.

Substituting these values into equation [5] gives a value for σ, at the instant of fracture, of 126 MPa when L = 25 μm, the mean size of the sub-particles determined from Figure 4 and 5.

A range of L = 10 μm to L = 50 μm would probably include 95% of the thousands of polyhedra that have been fleetingly scanned without attempting to estimate size. The corresponding tensile strengths i.e. the limiting values of σ from equation [5], indicated by these sizes would be 200 MPa and 89 MPa respectively.

For direct comparison with other strength determinations on glass and silicon fibres, these strength values are plotted against the diameter of a circular area equal to the area of a single facet of the dodecahedron, in Figure 12.

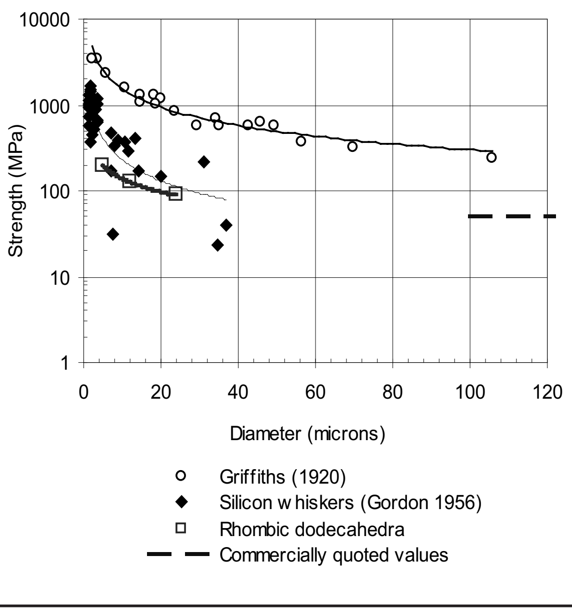


**FIG. 12 Tensile strength of quartz inferred from the dodecahedral dimensions, compared with other experimental data**

## 8 DISCUSSION AND CONCLUSION

We feel that the main implication of the suggestion by Professor Fairhurst is a profound one. Essentially, if the mechanism we postulate for the failure process is plausible, then the energy balance should yield estimates for the stress, at the critical instant of 'self-shattering' of the expanding elastic continuum, that have reasonable values.

It is not a simple matter, however, to decide what may be regarded as a reasonable value for the tensile strength of pure quartz at these very small dimensions.

Values of tensile strength of 48 to 55 MPa and 55 MPa were obtained from the web-sites of two commercial suppliers of high quality quartz products. These are presumably for normal sized samples. It has been known for a long time that very small sized test specimens show a very large increase in strength. J E Gordon (1976) presents strengths measured by A A Griffiths on glass fibres across a range of diameters from 100 μm down to about 2 μm, and results of his own on silicon whiskers between 35 μm and about 1 μm. Figure 12 shows that tensile strengths inferred from the sizes of the polyhedral quartz sub-particles correspond reasonably with Gordon's data but are, somewhat surprisingly, considerably weaker than Griffiths (1920) data.

It is very evident that there are other uncertainties and imponderables obscuring adequate understanding of how and why the observed sub-particles came into existence. On the other hand it is now abundantly clear that the phenomenon is not an isolated one.

In fact it would seem that nearly uniformly-sized, minute polyhedral sub-particles of quartz are characteristic features to be expected on the abraded slip surface of a rockburst brittle shear. Importantly, the previously suspected co-existence of melt spheroids and quartz polydedra in the same gouge sample has been proven.

As often happens in fundamental research, the study outlined in our paper has revealed more intriguing unknowns than satisfactory answers. We suggest the following questions should be among those most urgently requiring further attention:

i) For theoretical physics and fracture mechanics: How does the micro-fracturing sub-division, from a continuum of nearly uniformly-sized polyhedra, nucleate with similar spacing between the vertices?

ii) For the mine seismologist and crustal seismologist: Can the 'vibration' produced by nearly simultaneous, juxtaposed extreme compression and rarefaction prevent the mobilization of frictional resistance?

iii) For the rock mechanics engineer concerned with the design of rockburst-resistant support: Does the extreme process of localization and focusing of pulses of energy on a microscopic scale happen also on the much larger scale of tunnel dimensions? If it does, the extreme violence sometimes seen in the most severe rockbursts would be more easily understood.

These matters, we suggest, are seriously problematic and of very considerable importance. Therefore any acceptable explanations of any aspects of the process will significantly improve understanding of the genesis of shear-type rockbursts and perhaps also of earthquake mechanism.

## ACKNOWLEDGMENTS

The search for new brittle shear zones on other mines and the cost of specimen preparation and microscopy was funded by Safety in Mines Research Advisory Committee (SIMRAC). We are grateful for their permission to present this paper. Access to the SEM facility of Witwatersrand University is gratefully acknowledged. The interest and guidance of Professor Frank Nabarro of the Physics Department and Professor Dick Stacey of the Mining Department is much appreciated.

It was the suggestion of Professor Charles Fairhurst of Minneapolis University that inspired the revival of our interest in this problem so we owe him a considerable debt of gratitude.

We are grateful to Koos Bosman of Open House for continued interest and provision of samples and to Johan Wesseloo and Mike Harley of SRK Consulting for help and advice.

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## Footnote

Subsequent to the submission of the final draft of this paper, I read an article on the heat paradox in the February 1996 issue of the New Scientist, entitled *Inside the San Andreas*. It referred, inter alia, to work by Jay Melosh of University of Arizona that suggested that intense vibration would eliminate friction on faults. His argument is expounded in *Dynamical weakening of faults by acoustic fluidization*, in Nature, Vol. 379 of February 1996. Had I seen this article sooner, the notion of a 'blanket' of friction would have been differently phrased and would certainly have acknowledged Prof. Melosh's original concepts.

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