consistent, which can be explained by a number of differing features such as foundation material, building geometry, constructional methods, design and materials as well as the problem of the enhancement of the particle velocity at the particular site. Tempesthof flats was a prime example of these additional effects. This six storey block of flats collapsed completely with the floors and roof layered like a pack of cards (Plates 5 and 6), while at distances of not more than 500 meters away, a seven storey block of flats (Plate 5) and the five storey central post office with microwave tower (Plate 6) were virtually undamaged. The damage in the lower level isoseismal regions consisted of fallen masonry, particularly from bell towers (Plate 7), tall embraced walls (Plate 8) and parapets and both external and internal wall and plaster cracks. The plaster cracks would, in some instances, show compressional strains as well as the more common tensional strains.

The underground damage was reported in detail by the Anglo American Corporation (1977) for their mines. Resurveys after the main event had shown them that the maximum displacement which had occurred since previous surveys a number of years earlier, was of the order of 22 cm and situated on the Dagbreek fault. However, from displacements on a recent drill hole and fresh fractures in concrete structures the movement during the event was considered to be between 9.5 and 15 cms. The overall damage was mostly in the form of severe shaking rather than rockburst conditions and was concentrated to the east of Dagbreek fault on Western Holdings (Figure A1 - 5). There was also little or no closure in the old stopes east of the Enkeldoorn dykes. Thus, confining the damage to the Enkeldoorn block between the Dagbreek fault and the Enkeldoorn dyke.

9.2 Subsequent Seismicity and Structural Damage

If a large number of events after and in the same locality as a main event are considered as representing a positive aftershock sequence, then the seismicity subsequent to the main event at Welkom showed a negative aftershock region, or more correctly this region became an aseismic zone, which progressively showed more seismicity. The evidence for this was that in the region of the underground damage virtually no events occurred during December and January whereas during July there was a definite return to a positive level of seismic activity. Geological section + X1000 shows that this recurrent activity was mainly located along the Dagbreek fault and Enkeldoorn dyke. The mechanism for this behaviour, could be ascribed to complete and rapid destressing of that zone and then gradual build-up of stress due to the mining and or tectonic disturbances. In the previous discussion concerning the frequency of events at different magnitudes, this aspect of strain increase between December and July was also demonstrated.

Some conclusion can also be derived about the proposed source mechanism of the main event from the nature of the damage. The isoseismals for Welkom combined with the predominant orientation of the surface strains, suggested that the maximum horizontal shear stress was perpendicular to the strike or the major geological structures. However, this direction contradicts the direction of a horizontal NE-SW principal stress obtained from the assumed focal mechanism for the main event. The implications of this are that the assumed focal mechanism is incorrect which is supported by the observation that the eastern side of the fault had been upthrown (Anglo American Corporation, 1977).

Certain of the evidence could have been unreliable. Isoseismals are known to generally depart from a radial symmetry even for nuclear explosions, because they are controlled by the geology and geography of a region, apart from being confined by the seismic radiation (Gordon, Black and Bates, 1965). An example where elongation of isoseismals correlated with the depth of overburden was reported for the Ceres earthquake (S.A.G.S., 1974). Elongation of the isoseismals for the Welkom event do not agree with a north-south thickening of the Karoo system (Figures 2.4 and 2.5) while agreement with the overburden thickness cannot be demonstrated due to the lack of information. An interesting feature occurs on the geological section + X1000. The Daagbreek fault and Enkeldoorn dyke virtually converge at a localized Karoo-Witwatersrand contact (Figure 2.4), just beneath the city centre. This geological anomaly could result in some irregular coupling effects during the transmission of seismic energy which in turn may cause some of the trends observed in the isoseismals. Finally, the underground damage appears to have an elongate north-south distribution which is more appropriate to a strike-slip focal mechanism. (Figure A1 - 5)

9.3 Enhancement and Site Variation of Seismic Energy

Beside the differences associated with the construction and geometry of the buildings, variations in the surface damage could also be attributed to anisotropy in the surface energy frequencies, attenuation and energy enhancement.

Discussions about the magnitude and amplification factors (Chapter 5) has already shown that magnification of the ground motion at the surface stations was about five times. Verification of this was also available from a comparison of energy and magnitude for different events. The energy estimation of the digitized events from Church Street, was obtained from the accumulative squared velocity by applying the formula -

$$E_c = 4\pi\rho c r^2 \int_0^t Vc^2 \, dt$$

where the density ρ = 2.67 gm/cc; the phase velocities 'c' = 5.9 km/sec and 3.6 km/sec for P and S waves respectively and r was the hypocentral distances (Peret, 1972). The condition $r >> {}^c/w$ was not violated since ${}^c/w$ = 94 meters for C = 5.9 km/sec and $w = 2\pi \cdot 10$ Hz. Using the relationship log E = 11.8 + 1.5 M_L (Gutenberg and Richter, 1956) as a reference line, the log energy and magnitude data plotted on the upper side of this line but maintained the same slope (Figure 9.1). It could therefore be concluded that, although the data satisfied this relationship in principle there was once again evidence of surface energy enhancement and an associated over-estimate of the magnitudes.

As shear waves are identified as the source of the maximum ground motions, only horizontal component S waves were examined in the following analysis. Consideration of the seismic stations situated at the sites of structures which were severely damaged during the main event, revealed that individually these stations showed a relative variation in the ground magnification of between 2 and 8 (Table 7).

It was also noticed that the ground displacement obtained from the digitized records was consistent for the surface stations in a range of 10^{-2} to 10^{-3} micron. These displacements were usually a factor of ten higher than at the underground stations. The cause of the inhomogeneity between surface sites was therefore not entirely in the amplitudes but it also appears to be related to the variation in the peak freqencies

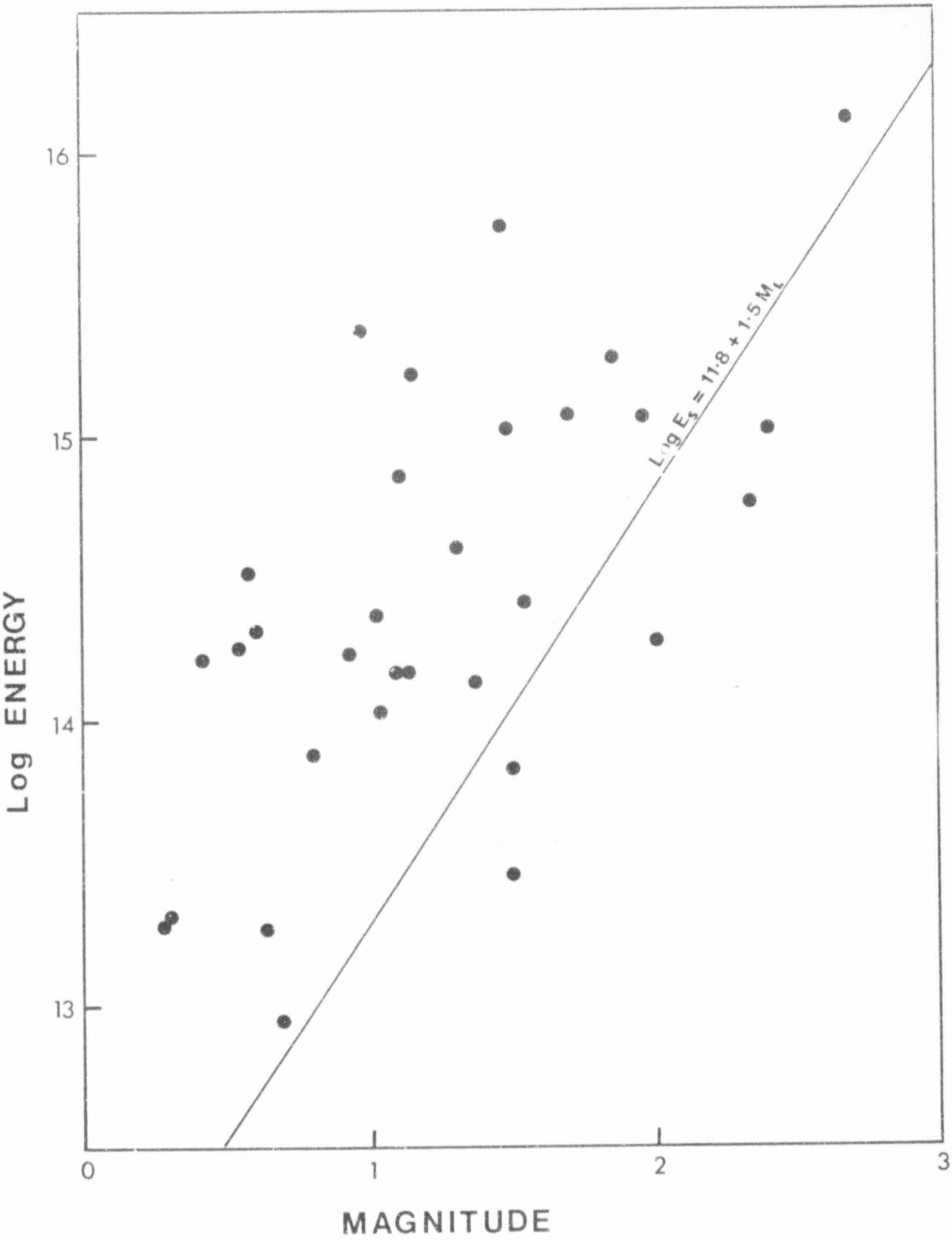

Figure 9.1 Log energy as a function of magnitude

of ground motion (Table 7). Although it was not apparent that this was a linear relationship.

TABLE 7

Site	Mean Increase in Magnitude above underground value	Standard Deviation	Equivalent Magnification	Range in maximum Shear Wave Frequency (Hz)
Tempesthof	+ 0.4	0.4	2.5	20 - 30
Romeo	+ 0.6	0.4	4	25 - 30
U.B.S.	+ 0.4	0.5	2.5	8 - 12
Anmercosa*	+ 0.6	0.3	4	15 - 18
St Andrews*	+ 0.9	0.3	8	-
Utopia*	-	-	-	20 - 30
Church	-	-	-	8 - 12
All	+ 0.7	0.3	5	-

* These values were obtained from a seismometer that was located on a concrete basement floor and the readings include the magnification effects of the lower portion of the building.

The relationship of frequency site magnification and structural damage can be understood in terms of the ground particle velocity V. Ground particle velocity is related to ground displacement A through the angular frequency ($V = 2\pi fA$) and various studies have confirmed that V^2 provides the best criterion for formulation of damage limits (Langefors et al 1958). In this way it is seen that the Welkom building sites that experienced the most significant damage were those that were subjected to the higher frequency shear waves. Assuming that the buildings were invariant to constructional properties and distance attenuation, the critical sites would be Romeo Street, Tempesthof, Utopia and possibly the St. Andrews School. Situated 3 km from the assumed epicentre in a region of intensity IV, St. Andrews School suffered small wall and plaster cracks, this offering support for the higher magnifications of ground motion. Although the simple concept of damage being related to the square of the particle velocity is good for mid frequencies, the detailed picture is more complicated. Normally structures have resonant frequencies that are low (> 1 Hz) and vibrations above 5 Hz represent overtone frequencies. At these frequencies the damping is more effective and as the resonant frequency is approached the situation becomes more dangerous.

Richter (1958) reported that the ground motions on alluvium can be a factor of ten greater than that on competent rock. More recently in the San Francisco Bay region it was found that the spectral amplitudes for the frequency range 0,25 to 3 Hz increased from the normalized values on granite to 3 to 4 for alluvium and 4 to 11 for bay mud (Borcherdt and Gibbs, 1976). This was also demonstrated at Welkom from the contrast in ground motion amplitude between underground stations on consolidated quartzites and the surface stations on unconsolidated, weathered mudstones. Beside the type of surface material its thickness has also been observed to play an important role. At Seattle in the Puget Sound, USA, a 1 km thickness of unconsolidated sediment caused a rapid attenuation of strong motion spectrum above 1 to 2 Hz. in comparison to the lower rate for spectra from Olympia situated on only o.1 kms of the same sediment (Shakal and Tokosz, 1979). Similar results reported by Moharz (1976) showed that it was the presence and depth of a velocity of impedance contrast that was the critical factor; not just the thickness of the alluvium. Alluvium considered to be continuous with depth gave spectrum amplitudes that were 40% less than for alluvium situated on bedrock at a depth of 10 meters.

By application of these observations the unusual variations in the degree of structural damage at Welkom can be better assessed. Assuming continuity for seismic energy across a seismic boundary such as a petrological change, the impedance or velocity contrast can be considered proportional to the ratio of the two adjacent densities. Therefore for clays with an average density of 1.4 gm/cc and sandstones with an average of 2.5 gm/cc, the impedance contrast is in the proportion of 1.0 to 1.8, which is adequate for the formation of surface waves. The predominant frequency of these waves would then be a function of the thickness of the clay overburden. Convincing evidence on the effect of the overburden was provided by the absence of damage in the Civic Centre, including the 50 meter clock tower (Brink 1979). This large building is located between the U.B.S. and Anmercosa House, both badly damaged during the main event. Credit for the stability of the Civic Centre is due to the fact that 6 meters depth of claysoil was removed and replaced by compacted waste rock from the mines before building operations commenced.

10 DISCUSSION

The influence of both tectonic stresses and mining disturbances on the seismicity at Welkom for the two recording periods is clearly in evidence from this study. One good example is the region of seismicity that was noted at depth below the mining activity, particularly in the region around 1 km below stoping. This particular region being associated with major geological structures. Smaller structures may also have been implicated but it is not possible to identify them because of their size, position uncertainty and the location tolerances. Reports of large events associated with geological structures have been provided for the Witwatersrand mining districts (Cooke, 1975; McGarr and Gay, 1978) but this seismicity has not occurred at any significant distances below the mining levels except at the Klerksdorp mines (van der Heever, 1978). Other mining districts have reported seismicity beneath and deeper than the mining levels. At both the Sunnyside Coal Mine, Utah (Smith et al., 1974) and Wappingers Falls Limestone quarry (Pomeroy et al., 1976) the maximum level of seismicity occurred at depths in the region of 1.0 km below mining. the major tectonic features in both cases were thrust faulting and the seismic evidence supported the premise of a maximum horizontal principal stress. At Sunnyside this was also in agreement with the regional tectonic stress pattern. It was concluded in both these studies that the seismicity was caused by unloading or reduction in vertical stress by mine activity which then induced small stress perturbations onto the critically pre-stressed rocks at depth. At Welkom a similar situation seems to exist. For the deeper events the strike-slip source mechanisms suggested horizontal maximum stresses with a north-east south-west orientation which could be accounted for by either a residual or tectonic stress field or a combination of both. The normal faulting source mechanisms from the mining environs provided evidence of unloading through mining and a resultant decrease in the vertical stress field. The variation of stress drop with depth also supported the existence of relatively higher stress release at these two respective depths while correspondence between these higher stress zones was provided by the time variation and frequency of events (Chapter 7). These studies suggested evidence of stress transfer taking place aseismically, following the stress pertubations resulting from mine blasting, to deeper and higher stressed localities. This aseismic deformation occurring as edge dislocations and not plastic deformation (McGarr 1971a), or alternatively lubricated fault movement.

Not all the active mining during December, January and July could be identified with high levels of seismicity, particilarly on the western side of the Dagbreek fault. It was probable, therefore, that residual stresses confined to specific fault blocks played a more significant role than the regional tectonic stresses. Field evidence of high residual stresses has been reported for dykes, sills and the Witwatersrand sediments within the mines (McGarr et al. 1975). Gay (1979) demonstrated that Ventersdorp age dykes at ERPM were capable of storing large components of residual stress which could be released by transfer of stress inbalances created by mine activity. At Welkom the Enkeldoorn dyke, also of Ventersdorp age, is a prime candidate for storing a high residual stress. This argument is supported by the level of seismicity that was noted in close proximity to the dyke and, in addition, the burst prone behaviour of mining pillars in the vicinity of the dyke on Western Holdings and President Brand (Patchet pers com., Anglo American Report 1977). Some conflict is in evidence as to the source mechanism of the 8 December event and as a consequence the existence of a maximum horizontal stress for this event. However, a consideration of the regional tectonic stress patterns helps to clarify this.

Residual stress is primarily a result of the palaeo-stress fields during formation of a geological feature. In the O.F.S. goldfields the final stage of tectonic deformation of the Witwatersrand basin resulted from a north-south horizontal maximum stress (Chapter 3) which is in agreement with the expected orientation of the residual stresses. The present regional stress field appears to have a predominant maximum vertical component (Gay 1975), however maximum horizontal components have been observed. At the Evander mine in the eastern Witwatersrand Basin the horizontal stress became greater than the vertical by 500 to 700 bars at depths of 2 to 3 kms (McGarr and Gay 1978). Similarly in the western Witwatersrand Basin a north-south orientated, maximum horizontal stress was reported from Durban Roodepoort Deep and at West Rand Consolidated a north-south striking normal fault, the Violet fault, displayed a strike slip displacement in association with a large event at the beginning of 1980 (Gay pers. comm.)

CONCLUSIONS

The two periods recorded seismicity at Welkom have provided evidence which implicates the natural geological conditions as having a control over the stress releases and resultant seismic distribution in this region. Two of the O.F.S. principle results contributed to this assessment. A large percentage of the hypocentres occurred below mining down to depths of 3 and 4 kms while the majority were typically at depths of 1 km. In addition a number of these deeper events exhibited strike slip focal mechanisms which were in keeping with natural tectonic stress conditions and which was in contrast to the mine associated events. The mine tremors displayed the more typical normal source mechanism that had been observed at ERPM and which is caused by unloading, this process resulting in an increase in the maximum vertical stress.

These results, however, did not exclude the influence of the mining activity. In some very active mining regions such as in the Enkeldoorn block, higher rates of seismicity were observed; but not all these active mining regions were associated with high rates of seismicity which was further evidence of influence from inter-tectonic conditions. Consideration of the hourly distribution further confirmed the close correspondence of seismicity with the period of maximum stress disturbance during mine blasting times. This correspondence was not direct, for the larger events appeared to be the more isolated events, occurring in isolation and associated with the major tectonic features at depth. Such a delay was evidence of a natural tectonic influence indicative that the deeper events were in response to the small stress adjustments occurring in the mining environs. The accompanying strain adjustments taking place aseismically because of the time lag behind the assumed mine disturbances. The small stress releases of the order of 0.01 bars did not contradict the existence of tectonic activity because micro-earthquake studies have revealed similar stress drops. The small stress drops at Welkom were more a reflection of the incompetency of the sedimentary rocks due to a high fractive content; further support being provided by the relatively large source dimensions. The occurrence of large enough releases such as the 8 December event was probably due to the reaction of a pocket of residual stress stored by a dyke or in isolation due to a fault system, been perturbed by the mining induced stresses. The location of this main event could not be concluded from any aftershock sequence, however an absence followed up by a small build-up of seismicity in a volume of rock in the region of both maximum surface and underground damage suggested this position as being the epicentre. Particularly if the suggestion made by McGarr et al (1975) is applicable; ie. that the strain energy consumed in creating a fracture system is drawn from a region much broader than the system itself. To identify either of the Enkeldoorn dyke or Dagbreek fault as the actual source structure would therefore be misleading and in this case especially more so because of the close proximity to each other of the two structures just below the maximum surface isoseismal.

The study also supports the view that mine tremors are directly analogous to natural events as no distinction was evident between the deeper and shallower events except for the controlling stressfields. Agreeing with observations for induced activity at geysers, Peppin and Buff (1980). Further, this was another example of small stress perturbations generated by mining activity inducing tectonic controlled events below mining as has been reported by Smith et al (1974) for a coal mine in Eastern Utah and Pomeroy et al (1976) for a quarry at Wappingers Falls, New York.

Finally, the observation that an enhancement by a factor of 5, the shear displacements at surface, due to the existence of clay and unconsolidated overburden, needs further emphasis. Anticipating that a large event could occur again in this region it is important that consideration should be given to earthquake resistant building design. Adaption of such methods employed for the foundation of the Welkom Civic Centre would greatly reduce the possibility of a reccurrence of the situation at Tempesthof Flats.

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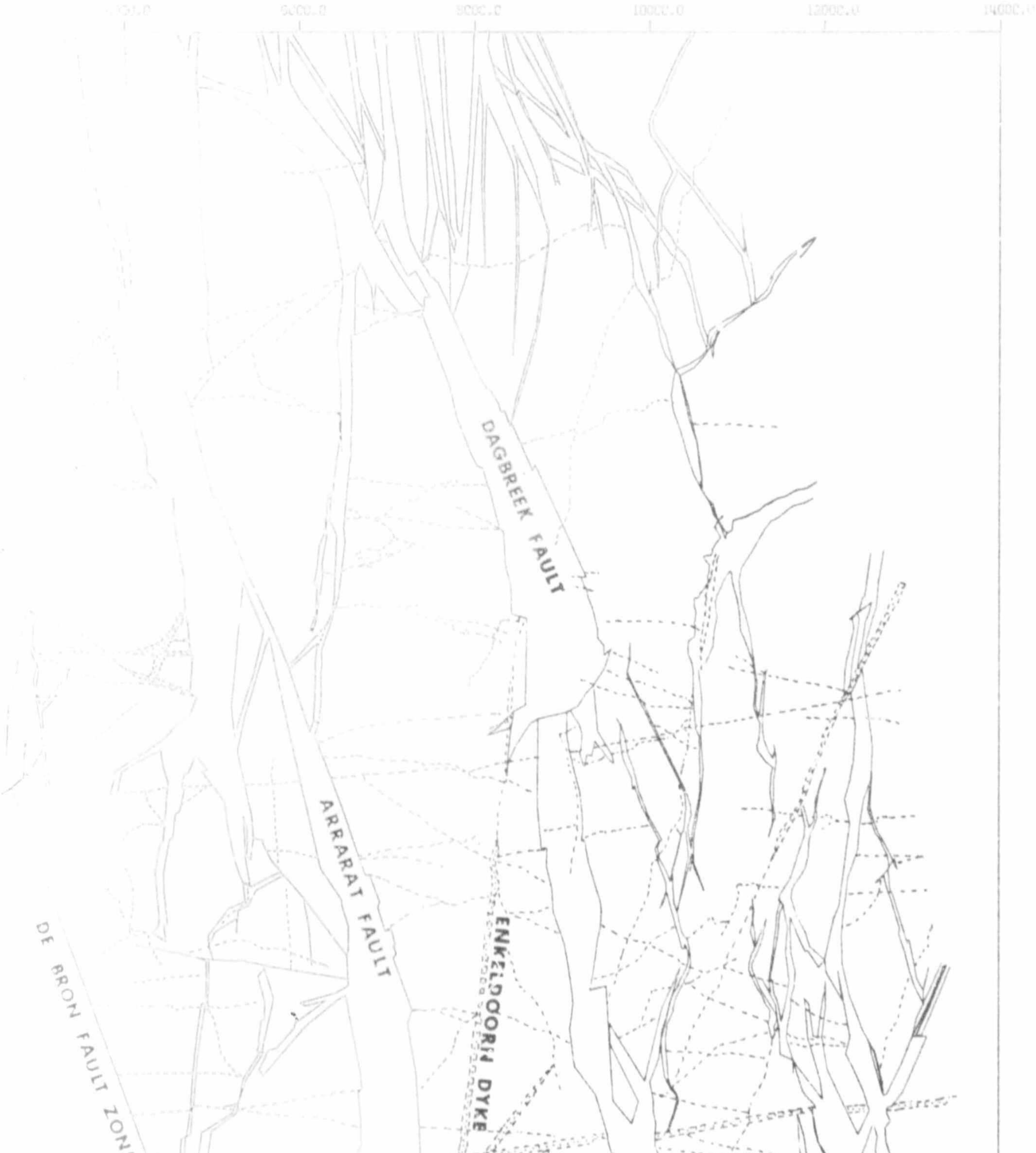
APPENDIX 1

Figure A1-1 Simplified structural geology in plane of Basal Reef, solid lines: faults, dashed lines: dykes
scale: 1:666.7

South



source: Anglo American Corporation

Figure A1-2 Station distribution showing region of confidence for the located events. Details of stations in Table 3. Scale 1:666.7

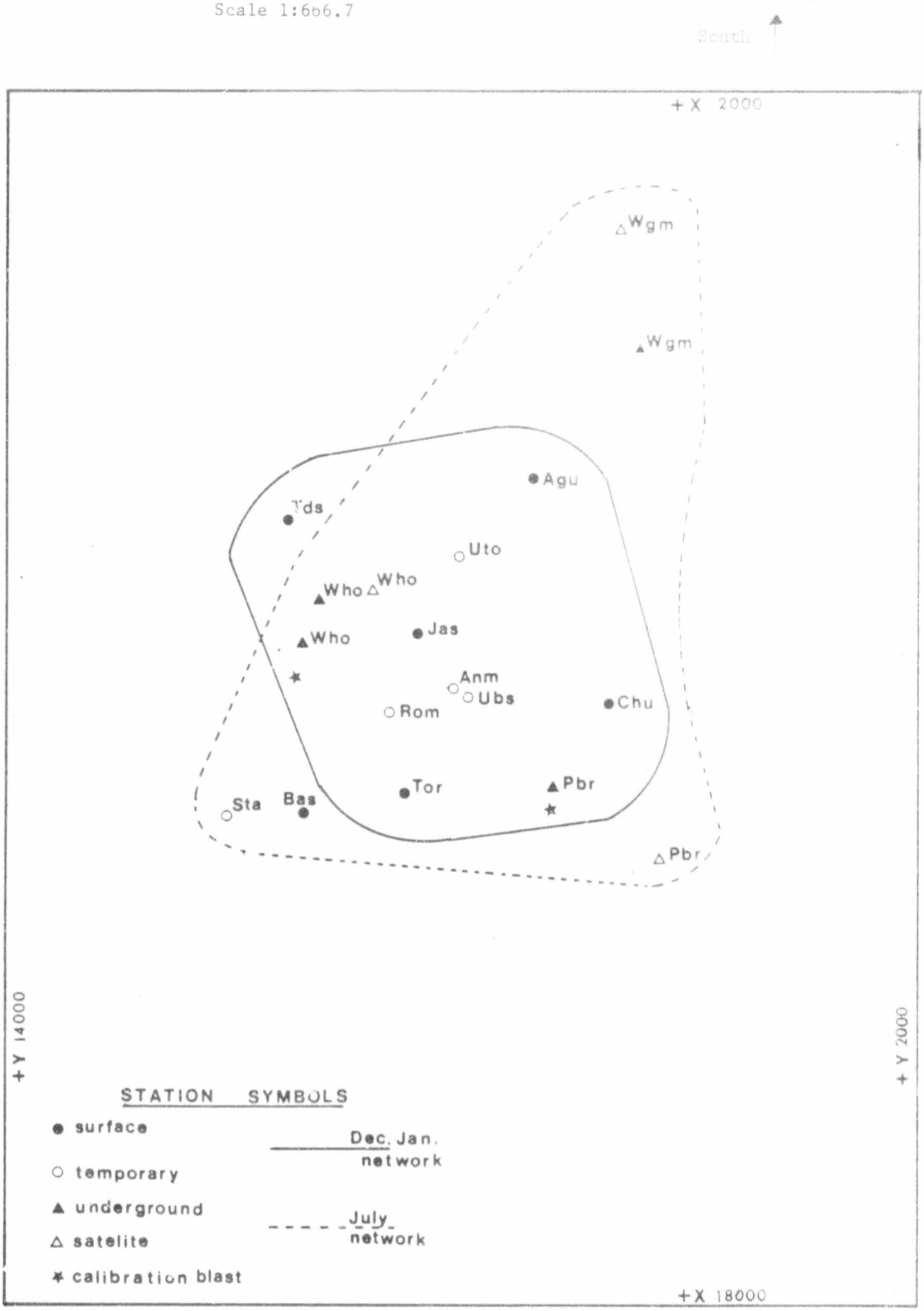
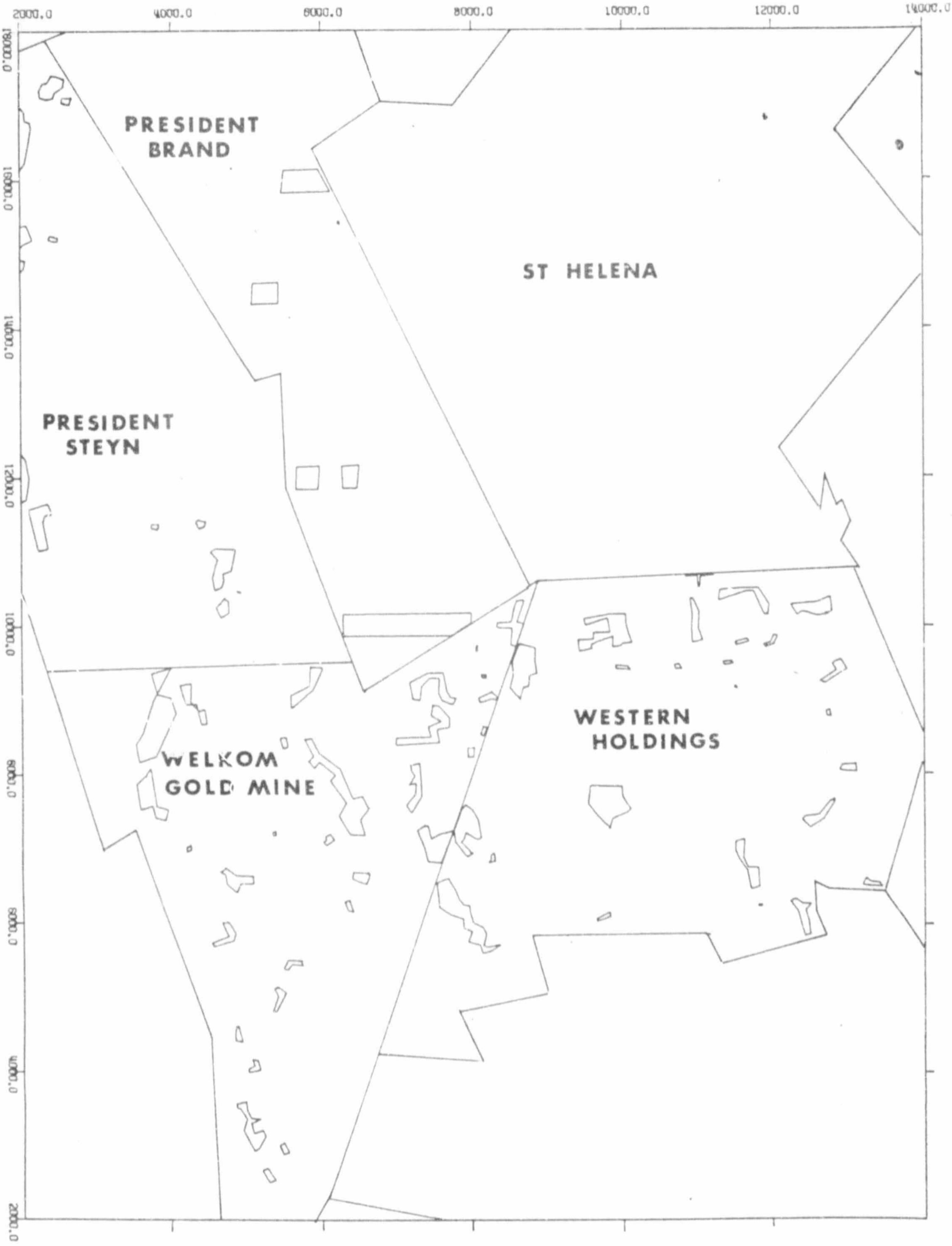


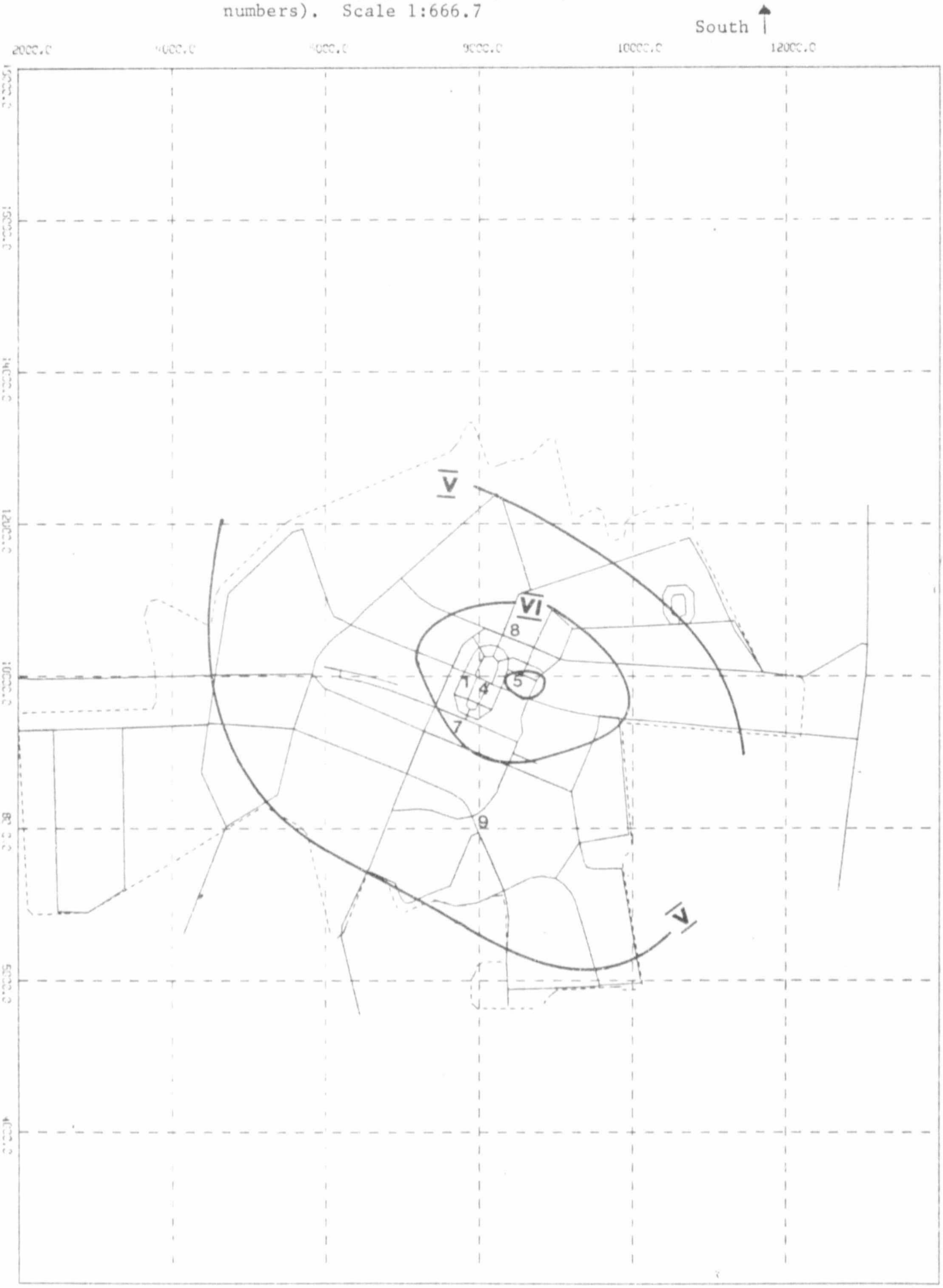
Figure A1-3 Mine Boundaries showing combined mining activity for periods of recorded seismicity. Distribution of mines stopes was similar for both periods.
Scale 1:666.7

South ↑



source : Anglo American Corporation

Figure A1-4 Outline of Welkom town (dashed line) and major roads (light solid lines). Also shown are the isoseismals (heavy solid lines) for the December 8, 1976 event, and the locality of the photographs in Chapter 9, (numbers relate to the Plate numbers). Scale 1:666.7



source: Anglo American Corporation

Figure A1-5 Distribution of underground damage resulting from the December 8, 1976 event. Scale 1:666.7 (Plan view)

South ↑

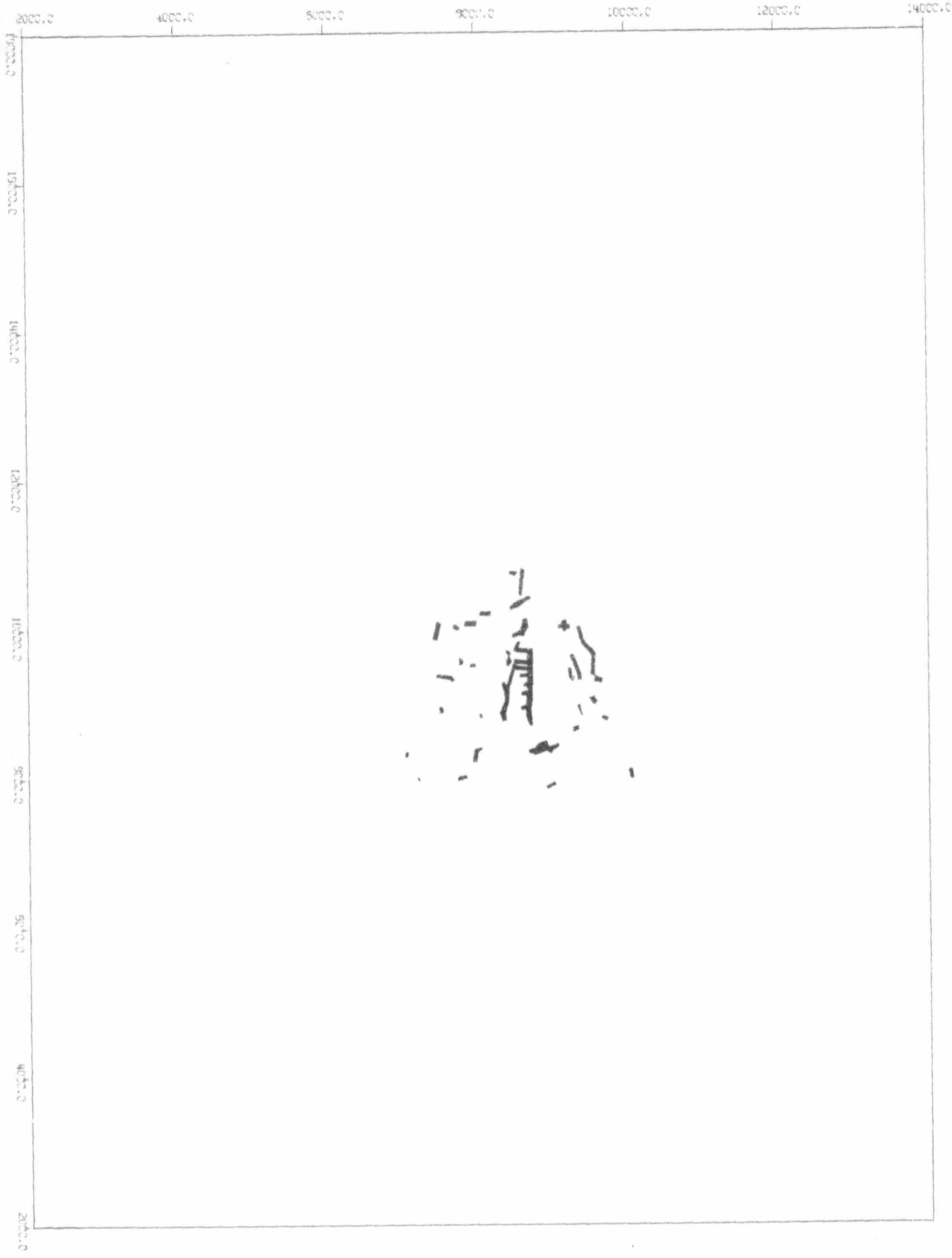


Figure A1-6 O.F.S. Goldfields Seismicity Dec. 1976/Jan.1977 (Plan view)

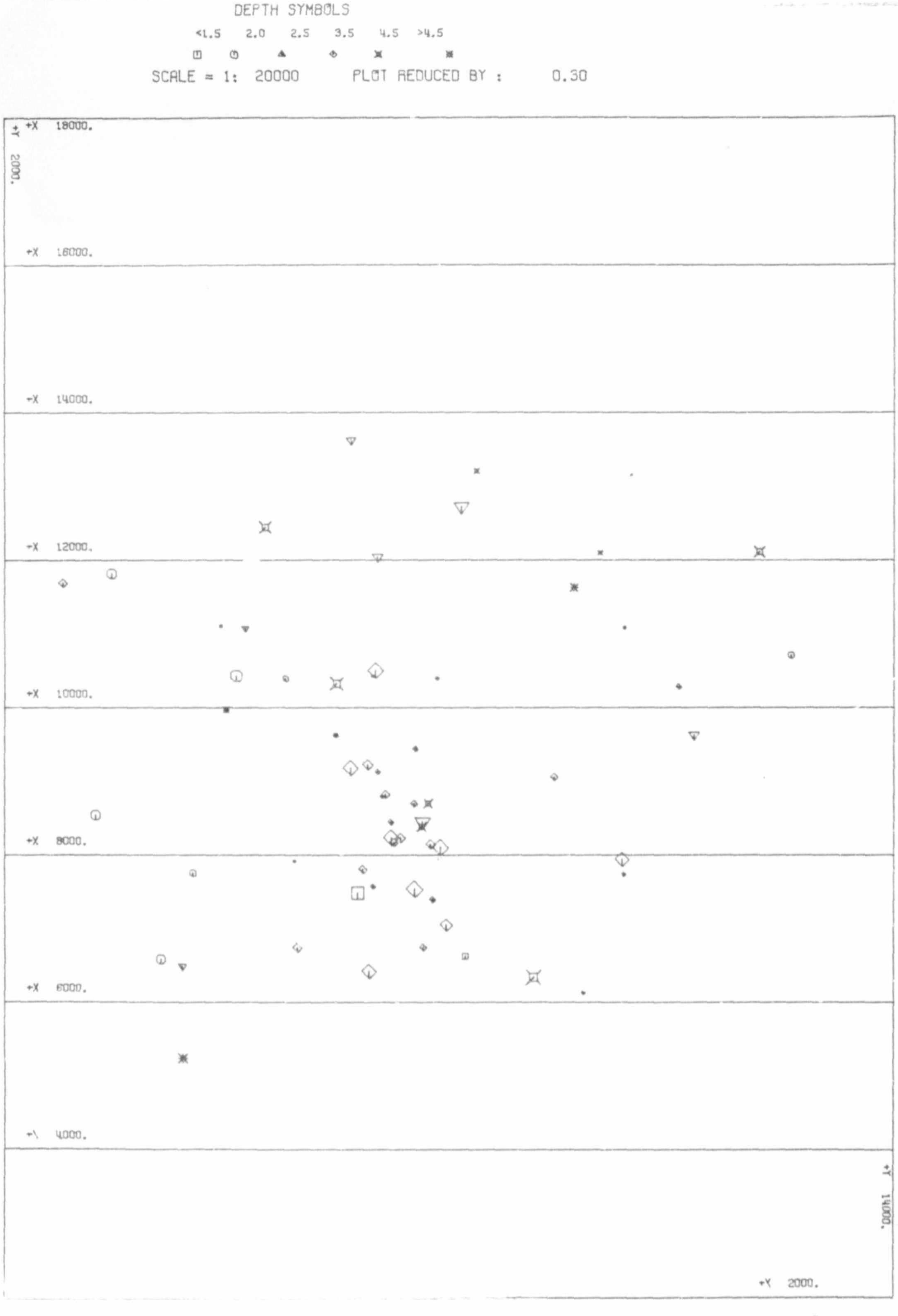
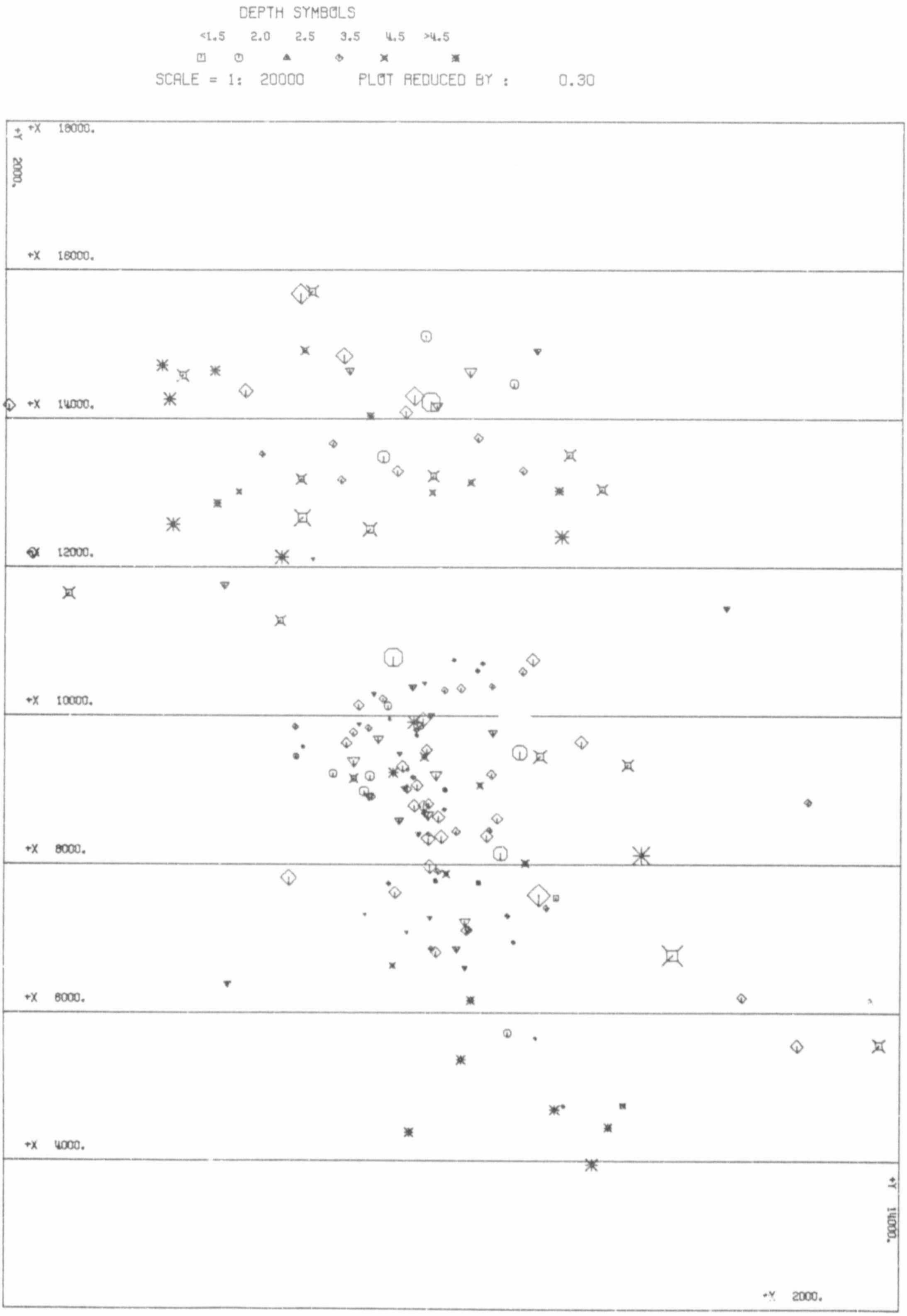


Figure A1-7 O.F.S. Goldfields Seismicity July 1977 (Plan view)



KEY FOR FIGURES A1-8 to A1-13

December/January events on Figures A1 -8, A1-10, A1-12. July events on Figures A1-9, A1-11, A1-13. Event symbol size is proportional to its magnitude. Depths in Kilometers.

GEOLOGICAL KEY AND ABBREVIATIONS

KAROO SUPERGROUP

LOWER VEBTERSDORP SUPERGROUP

...... BASAL REEF

INTRUSIVES

FAULTS AND FAULT ZONES

DB De Bron fault zone
W Welkome fault
A Arrarat fault
D Daagbreek fault
E Enkeldoorn dyke
Eu Eureka fault

GEOGRAPHICAL KEY AND ABBREVIATIONS

MINE boundaries
Welkom city centre buildings
UBS United Building Society
CC Civic Centre
Anm Anmercosa House
Temp Tempesthof
Rom Romeo Street

Figure A1-8

Section +X6000 Dec.

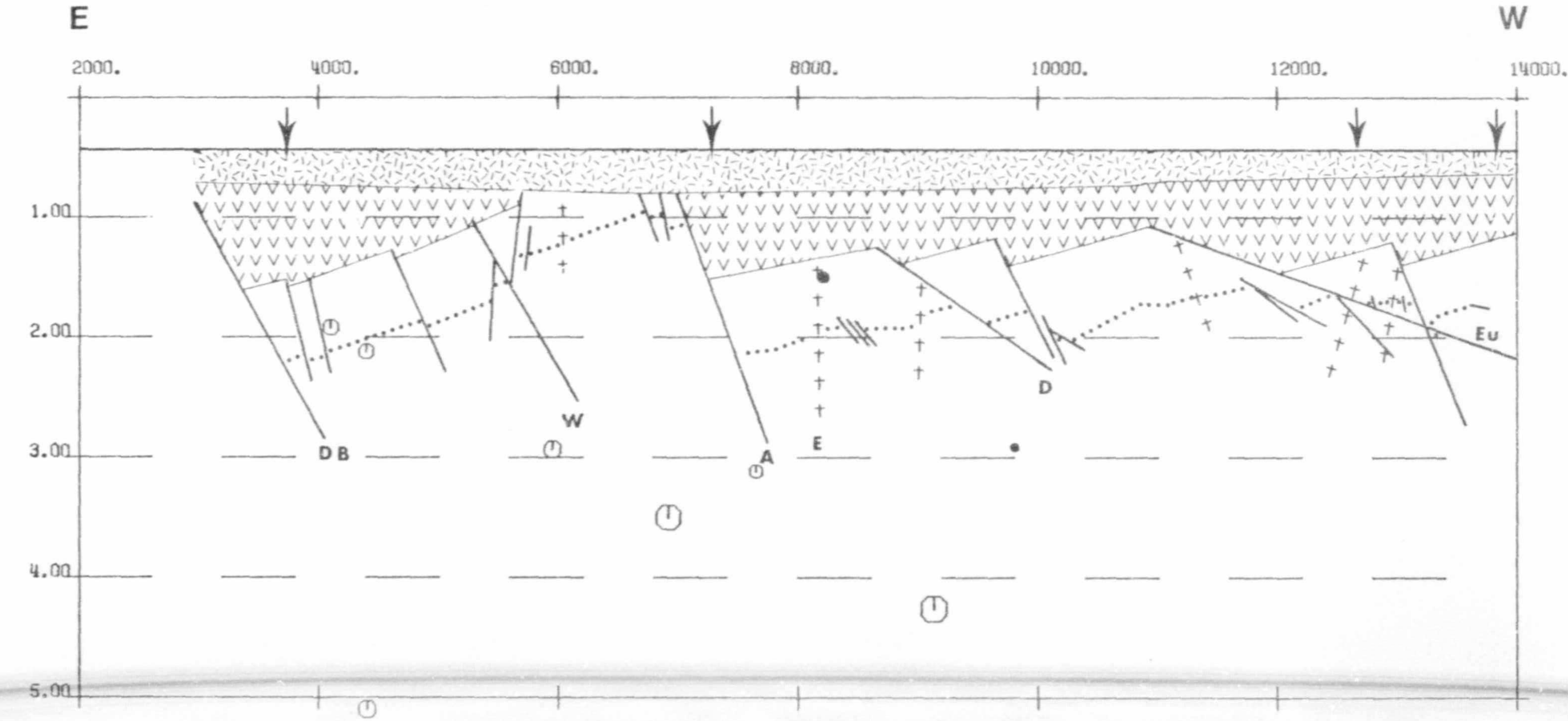


Figure A1-9

Section +X6000 July

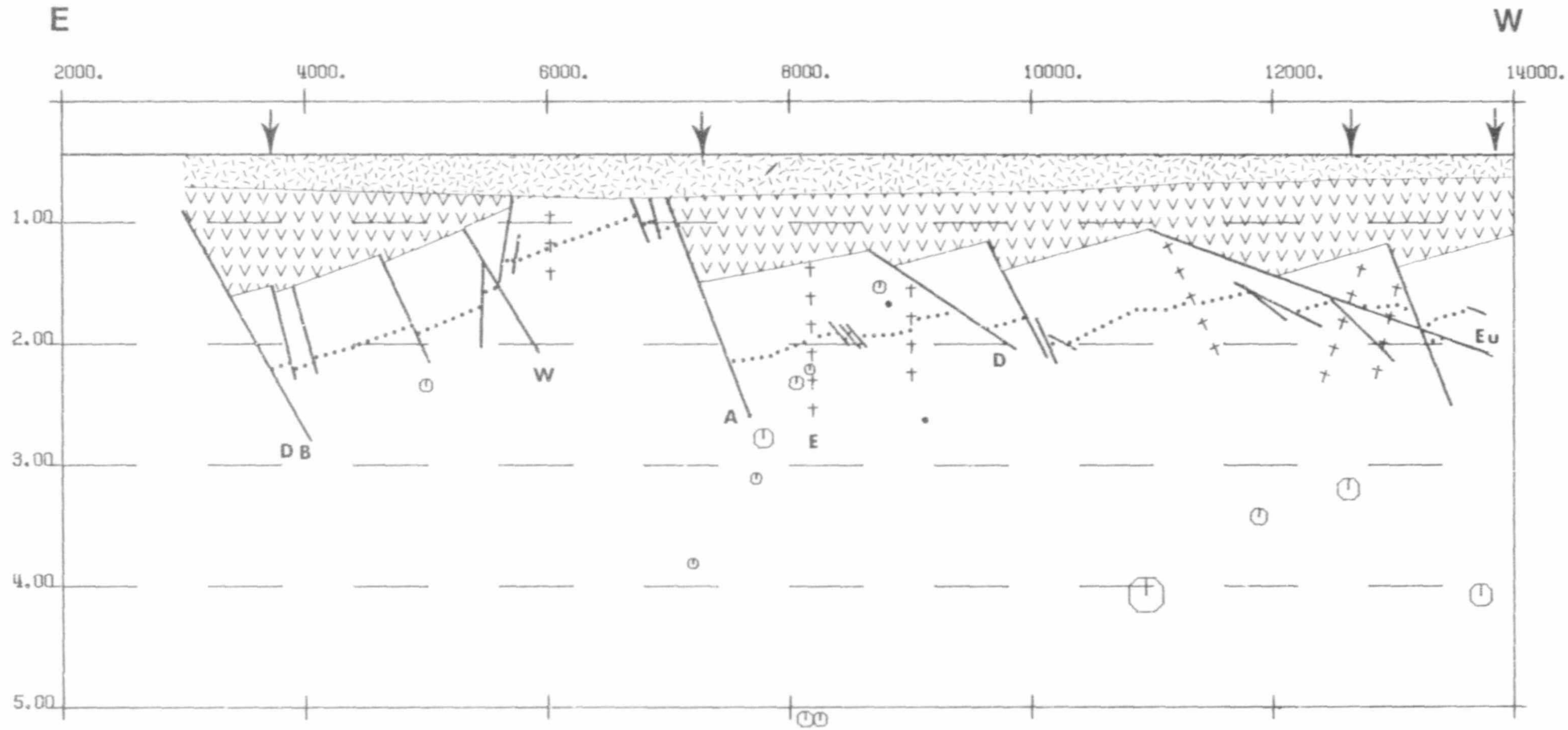


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Figure A1-10

Section +X8000 Dec.

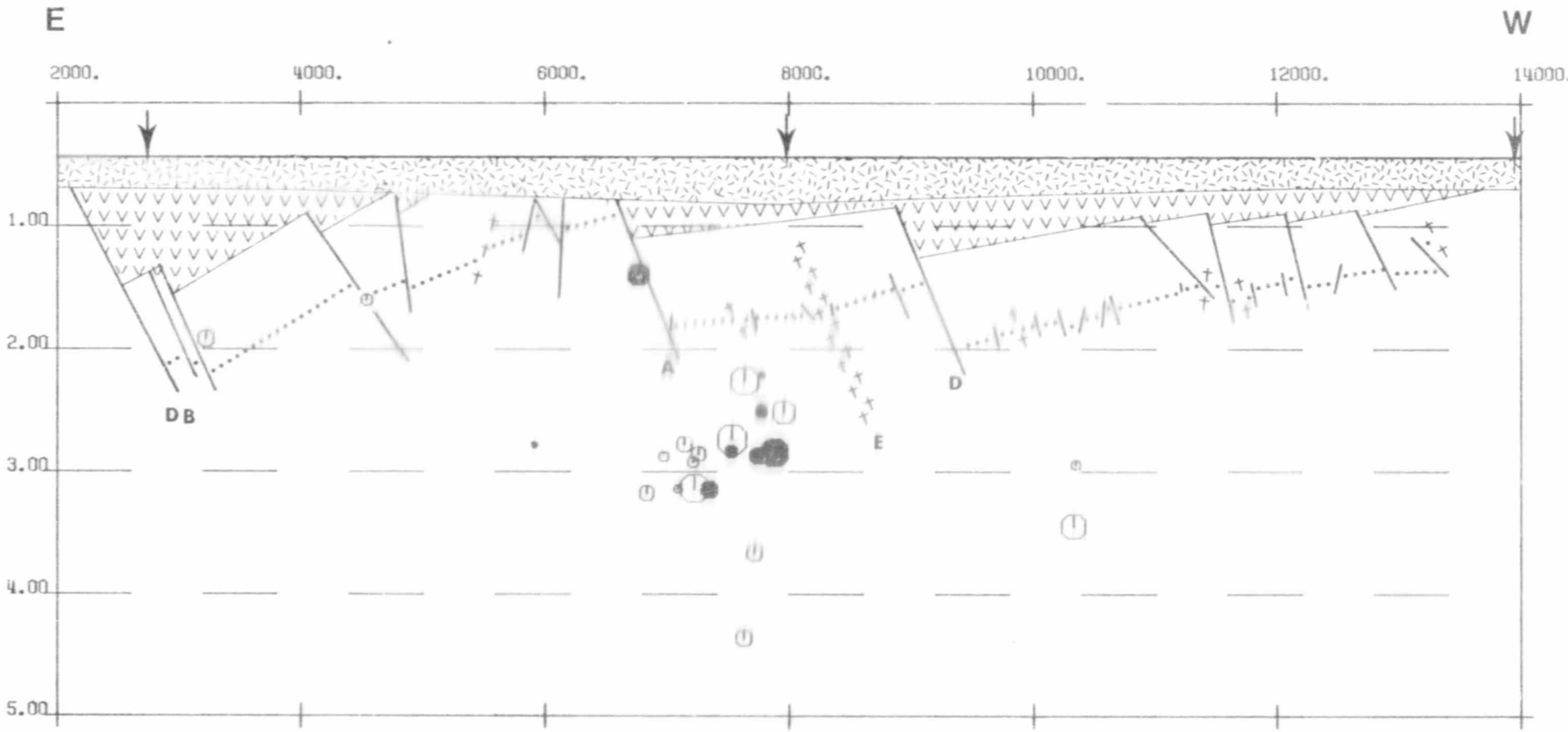
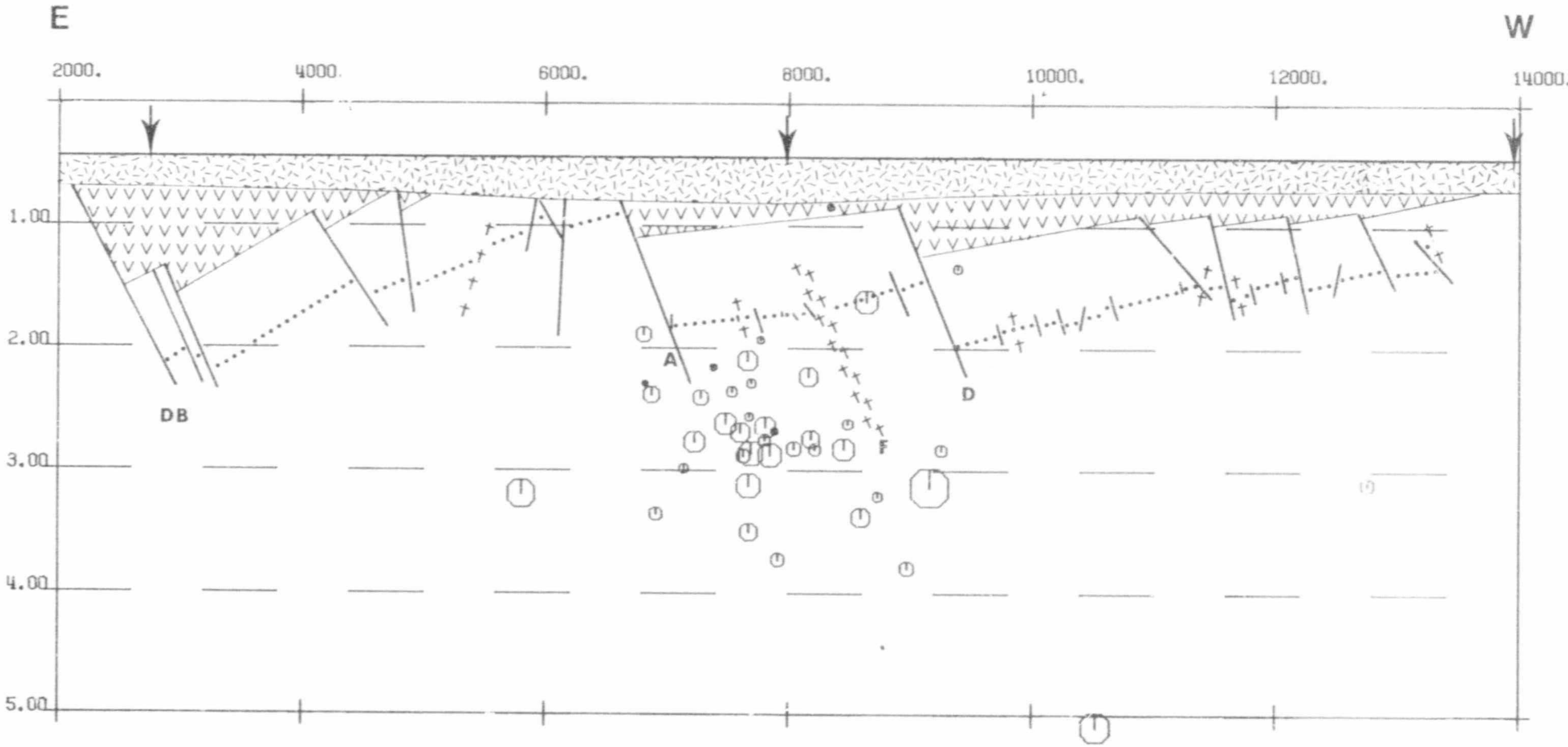
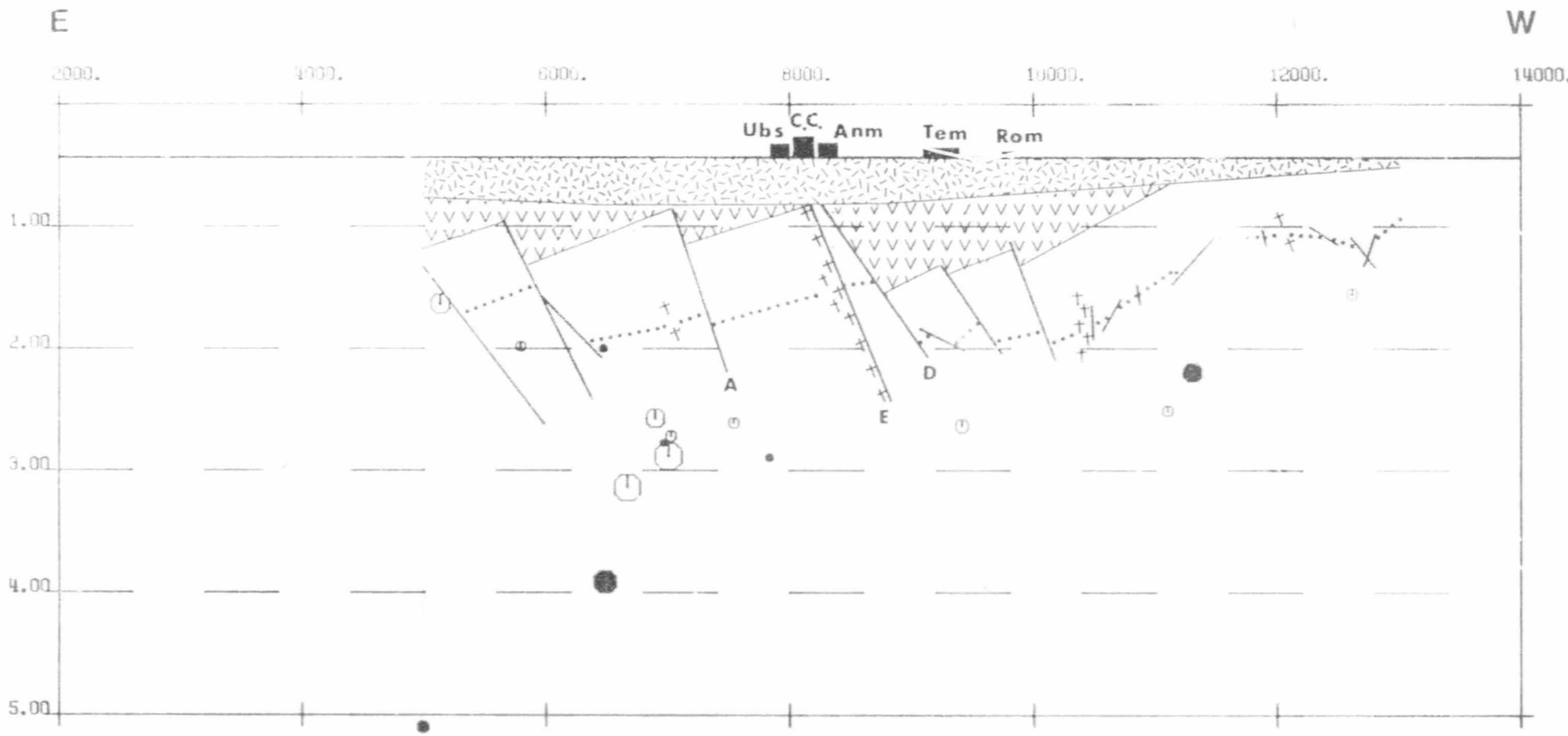


Figure A1-11

Section +X8000 July



143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