MASTER JOINT FORMATION IN THE WESTERN COALFIELD OF NEW SOUTH WALES:
ANALYSIS OF SOME INITIAL MATHEMATICAL MODELS

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SUMMARY

Three preliminary models have been investigated by finite element analysis to test the hypothesis that master joint formation in flat-lying Permo-Triassic strata of the Western Coalfield of New South Wales near Lithgow may have occurred in different ways. The models are two-dimensional cross-sections of hydrostatic unloading, basement uplift and horizontal 'pull-apart', assuming that 0.5 km of post-Triassic rocks formed a cover during joint formation.

The models are based on the currently accepted views of the origin of joints (which are briefly reviewed) and the post-Triassic tectonic history of the Sydney Basin. All three models formed joints: hydrostatic unloading and the horizontal 'pull-apart' formed vertical extension joints and the basement uplift formed extension and shear joints. Evidence of burial, uplifts and consequent erosional unloading and rifting of the eastern margin of the Australian Plate suggests that such mechanisms may have operated in the Sydney Basin since Triassic times.
1. INTRODUCTION

The Western Coalfield, situated near Lithgow in the Blue Mountains region (Fig.1), is an important source of steaming coal in New South Wales. The coal is won by underground mining of the Lithgow and Katoomba seams in the Upper Permian, Illawarra Coal Measures (Morris 1975). Although several collieries have had excellent mining conditions in most areas, recent mining geological studies (Shepherd et al., in preparation) have shown the importance of systematic master joint sets in the coal measures because some are associated with localized zones of roof failure.

Branagan (1960) first documented the fracture system of the Western Coalfield and commented on the possible effects of basement folds on structures in the Lithgow Seam. Powell et al. (1976) have delineated the regional structures in the Lower Palaeozoic rocks to the west of the coalfield and some elements of these structures appear to be reflected in the structural patterns of the flat-lying Permo-Triassic cover.

2. JOINTS IN FLAT-LYING SEDIMENTS

In contrast to their presence in folded regions, the presence of systematic joint sets in flat-lying and gently warped sediments such as those in the Western Coalfield has puzzled geologists and they have provided explanations (Parker 1942; Muehlberger 1961; Secor 1965; Hobbs 1967; Hancock 1968; Price 1966, 1974, 1975; Attewell and Taylor 1971) using the Griffith and Coulomb-Mohr theories of failure. All these writers have discussed extensively the evidence for extension versus shear mechanisms. Gramberg (1966) and Lajtai (1977) favour the theory that joints are load-parallel tensile fractures in a régime where \( \sigma_3 \), they presumed, was of low magnitude or stress conditions were hydrostatic. Price (1966), Attewell and Taylor (1971) and Lajtai (1977) have postulated that decompressional release of residual strain energy at sites of stress concentration in rocks would have been needed. Price (1966, 1974) has put forward a model of crustal uplift which would achieve this release of energy and most workers have accepted this theory, possibly to the exclusion of other feasible models. The most widely held view is that joints are formed later than faults (Hancock 1968). The models discussed in this report are based on this theory.
Cook and Johnson (1970) however, have described joints from a sandstone horizon in the Southern Coalfield (N.S.W.) which they suggested were formed soon after the sediments were deposited. The timing of joint formation is therefore uncertain and it seems likely that joints may be formed at different times during the history of the sediments.

The present study arose from observations of regionally-developed systematic master joints that persist vertically downwards from surface outcrops to coal seam levels and probably deeper, in and around the Western Coalfield (Fig.2). The approach we adopt in this study is reported because, despite possible flaws in our models, the general concept of theoretical models based on field observations is a sound one which can be explored much more fully by subsequent work on extended and refined models.

3. THE MODELS AND FINITE ELEMENT ANALYSIS

Three rudimentary models, based on the widely held views of the tectonic history of the Sydney Basin and offshore Tasman Sea basin, have been analysed for master joint formation. It is considered that the models analysed represent the most basic mechanisms, which may have operated independently but which probably interacted (Fig.3). The models do not account for rock fluids and the consequent pressures almost certainly present in nature.

The ages of the various joint systems in the Permo-Triassic of the Sydney Basin are unknown, partly because fieldwork has only recently been started and partly because of the inherent difficulty of determining relative ages from cross-cutting fractures where no movement has occurred. The period from post-Triassic time to the Pleistocene was a long one for joint formation.

3.1 Hydrostatic Unloading

This mechanism represents the erosional stripping of overlying sediments without tectonic horizontal compression (Fig. 3a). Unloading has been a consequence of uplift (discussed below), but the total thickness of sediment removed is not precisely known. There is evidence, based on
coal reflectance measurements (Shibaoka et al. 1973), that considerable thicknesses of post-Triassic sediments once covered the present rocks of the Sydney Basin. Browne (1969) has concluded that "vigorous erosion" has occurred since the late Pliocene, which may have been a factor in joint formation.

3.2 Basement Uplift

A simple form of basement uplift has been modelled by differential basement movement to form a gentle arch-type structure (Fig. 3b). An obvious drawback with this model is that the basement was not included and no account has been taken of structures within the basement which might have propagated upwards in a manner suggested by Attewell and Taylor (1971) and Moseley and Ahmed (1967).

However, there is ample evidence for the uplift of eastern Australia which has resulted in the denuded form of the Great Dividing Range and deeply incised drainage systems. Browne (1969) has recognized three stages of uplift since Tertiary time; firstly the 'Kiandra epoch' in Oligocene-Eocene times, secondly a 'Macleay epoch' at the close of the Miocene, and thirdly the 'Kosciusko epoch' of late Pliocene to early Pleistocene time. The last he considers to be a stage of repeated differential uplifts.

David (1950) considered that "the uplift of the Eastern Highlands was accomplished mainly by gentle warping" and remarked that the mechanism was a matter of controversy. The uplift model analysed in this paper could apply to any one of these uplift stages.

3.3 Horizontal 'Pull-apart'

This mechanism consists of horizontal tectonic forces acting on the complete strata sequence (Fig. 3c). Such tensile forces may have developed during the rifting caused by the spreading of the sea-floor and consequent detachment of the Lord Howe Rise from the Australian Plate during Cretaceous to Tertiary time. According to Weissel and Hayes (1977) the Tasman Sea basin opened up between approximately 82 and 60 m.y. B.P. Controversial aspects of this process are the possibilities that some subduction beneath the edge of the Australian Plate may have caused compression (Hayes and Ringis 1973), and that transform faults in the Tasman basin may link up with structures on the present Australian continental margin (Ringis 1975).
4. CONSTRUCTION OF THE MODELS

The strata sequence is based on the Permo-Triassic succession of the Wallerawang district (Morris 1975) and includes the Lithgow Coal seam and 0.5 km of overlying post-Triassic sediments believed to have formerly existed.

Coal reflectance measurements on the Lithgow Coal seam around Wallerawang suggest that the seam was once buried to a maximum depth of approximately 1.5 km (A.J.R. Bennett, pers. comm.). However, the rates of burial, subsequent uplift and erosion of post-Triassic cover are unknown. The 0.5 km of cover was selected as realistic for initial models.

The study assumes that joints were formed in the sediments when their material properties were either closely similar to or identical with those of the present day. The properties used are based on ACIRL (Australian Coal Industry Research Laboratories) experimental data from typical N.S.W. coal measure strata and shown in Table 1. Each model analyses homogeneous, unfractured rocks by applying loading in multiple stages to allow for load redistribution around failed areas.

To date, little attention has been paid to the finite element method in the mathematical analysis of natural fracture systems in structural geology (Voight and Samuelson 1969, Stephansson and Berner 1971, Bock 1971).

The ACIRL finite element program is a non-linear, two-dimensional program incorporating triaxial compressive and limited tension failure criteria and subsequent post-failure material behaviour (Phillips 1978). The program has been primarily developed for use in analysing the stability of underground excavations. Consequently, for those analyses where no excavation was present, it was necessary to modify the program to enable external loading to be applied to the boundary of the mesh. The mesh is now capable of being loaded according to externally applied nodal forces in various ratios for each cycle of the analysis.

In each analysis, a condition of plane strain was assumed and six loading cycles were applied to the mesh. Each cycle represents an additional load on the boundary of the model and is an attempt to simulate progressive geological conditions.
The following stresses were applied to the mesh, represented by loads along the relevant boundaries (tension is positive).

4.1 Hydrostatic Unloading

Virgin stress field over entire mesh,

$$\sigma_x = -50 \text{ MPa}, \sigma_y = -50 \text{ MPa}.$$ 

Additional cycle loading after cycle 1,

$$\sigma_x = +10 \text{ MPa/cycle to right-hand boundary},$$ 

$$\sigma_y = +10 \text{ MPa/cycle to top boundary}.$$ 

In this model it has been assumed, for simplicity, that the horizontal virgin stress field is uniform along the full extent of the model boundary.

It was necessary to reduce the horizontal stress in proportion to the vertical stress reduction in order to provide a mechanism for horizontal tension to develop. Otherwise such a mechanism would never create joint failure since, from a hydrostatic condition of $-50 \text{ MPa}, -50 \text{ MPa}$, for example, the induced horizontal tension could never exceed the maximum vertical unloading stress for typical Poisson's ratio values. As a result, horizontal compression would occur throughout the model: for example, if a vertical unloading of 50 MPa applied, then induced horizontal tension would probably be about 20 MPa, giving a net stress field of $-30 \text{ MPa}$ horizontally and 0 MPa vertically.

However, by unloading both the vertical and the horizontal virgin stress, the model can produce horizontal tension. The vertical sides of the model are restricted to vertical deformation only, in order to represent an infinite width medium, resistant to horizontal shrinkage. This situation could apply to the edge of an erosional stripping zone.

4.2 Basement Uplift

Virgin stress field over entire mesh ($-20 \text{ MPa}, -50 \text{ MPa}$).

Additional cycle loading after cycle 1,

$$\sigma_y = -20 \text{ MPa/cycle to bottom left-hand corner, and progressively less across lower boundary}.$$
This loading is not intended to represent a realistic phenomenon where strain rate would be an important factor during uplift. Since the time effect is not modelled, then a strain profile across the base of the model can quite justifiably be modelled in terms of a stress profile, although the magnitudes used here are arbitrary. In order to produce any planes of failure, it is necessary to pin the right-hand bottom corner node in a fixed position for the uplift to pivot about. In reality, this configuration would be equivalent to a point sufficiently remote from the uplift zone and therefore it would resist both horizontal and vertical deformation.

4.3 Horizontal 'Pull-apart'

Virgin stress field over entire mesh (-20 MPa, -50 MPa).
Additional cycle loading after cycle 1,

\[ \sigma_x = +10 \text{ MPa/cycle to right-hand boundary}. \]

In all three models the stresses and horizontal dimensions are not specifically related in magnitude to any physical phenomenon represented by the model, but were chosen simply to indicate the type of failure likely to occur.

5. RESULTS

The results of each analysis performed have been presented graphically (Figs. 4, 5 and 6). In Figures 5 and 6 the failure zones are indicated by a number representing the loading cycle in which the particular element failed.

The hydrostatic unloading model remained stable until the last cycle, in which every element simultaneously failed in horizontal tension. In cycle 5, many elemental stresses had become tensile in the horizontal direction representing an induced horizontal stress of approximately 10 MPa, owing to the 40 MPa vertical unloading stress applied. The results of this analysis are shown for cycle 6 in Figure 4. Since all elements failed in cycle 6, failure cycle numbers have been omitted.
The basement uplift analysis caused progressive failure from cycle 2 onwards, the entire mesh becoming unstable by cycle 4. Failure was due to a combination of tension and shear, the failure zone emanating from the fixed lower right-hand corner (Fig. 5).

The horizontal 'pull-apart' process produced the beginning of failure in cycle 3 and total instability in cycle 6. The failure zones occurred within the zones of stratification and were essentially horizontal and tensile (Fig. 6).

6. DISCUSSION AND CONCLUSIONS

The most likely joint system to result from the mechanisms analysed are sketched in Figs. 4, 5 and 6. The essential features of these are as follows:

1. The process of hydrostatic unloading results in a uniform set of vertical joints formed simultaneously by horizontal tension throughout the strata. In actual fact, these joints would form initially at the top and extend downwards as the horizontal stress field became more tensile. This would occur progressively during the unloading process.

2. Basement uplift results in curved tensile joints on the edge of the uplift zone, concentric about the fixed point. These become more vertical and linear above the uplift zone and range through purely shear joints (formed first) to a combination of tension and shear (formed later).

3. The horizontal 'pull-apart' mechanism results in a uniform set of vertical joints which formed sequentially, subject to the material properties of the strata. The joints are tensile and form in the most brittle material first. This is shown in Fig. 6 by the correspondence between the cycle number in which failure occurs and the magnitude of tensile failure strain (inversely proportional to brittleness).

We have attempted to simulate joint formation in the uppermost layers of the earth’s crust using simple models. These models are believed to be feasible in mechanical terms; the geological and geomorphological
histories indicate that processes such as erosional unloading, differential uplift and plate tectonic rifting have all affected the eastern part of the Australian continent. Locked-in strain energy or strain rates have not been accounted for. Price (1975) has suggested that geological strain rates for uplift may be in the range $10^{-16}$ to $10^{-18}$/sec over tens of millions of years. It may be imprudent, therefore, to attempt to assign joint formation to a single phase of Browne's (1969) epochs of uplift. We suggest that some joints may have formed by the sum of the three uplifts relatively late in Pliocene-Pleistocene time. The possible effects of unloading and of plate tectonic rifting cannot be discounted and these processes may have interacted with the stresses caused by uplifts. Alternatively, there may have been more than one joint-forming event.

We prefer an uplift model because shear joints can possibly be formed and the existence of shear joints cannot be ruled out (Shepherd, Huntington and Creasey, in prep.). The differential uplift model analysed predicts three zones of joints (Fig. 5): extension and shear joints close to basement in the Permian Coal Measures; shear joints above in the Triassic Grose Sandstone; and extension and shear joints in the post-Triassic cover. Such predictions may be capable of being tested by field observation. Clearly, the relative distribution of joint types is dependent upon the position (vertically and horizontally) of the fixed rock mass in the model at the margin of the uplift zone.

7. ACKNOWLEDGEMENTS

The early ideas for this study were a result of discussions with Professor K.L. Burns now at the Heroy Geological Laboratory of Syracuse University, New York. Mr F. Jaggar of Broken Hill Prioprietary Limited (formerly of ACIRL) helped us to design the computer models. One of us (J.S.) benefited from discussions with CSIRO colleagues Dr Jon Huntington, Mr John Creasey and Dr Brian Embleton.
8. REFERENCES


<table>
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<tr>
<th>Strati-graphic unit no. (see Figs. 4-6)</th>
<th>Material</th>
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<th>Poisson's ratio</th>
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<th>Mohr envelope shear strength (MPa)</th>
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FIG. 1 LOCATION OF WESTERN COALFIELD AND PRINCIPAL GEOLOGICAL STRUCTURES OF THE SYDNEY BASIN
FIG. 2  OBLIQUE, LOW-ALTITUDE AERIAL VIEW OF NORTHWEST-TRENDING REGIONAL JOINT SYSTEM IN GROSE SANDSTONE

A  Blue Mountains Plateau level (approximately 1000 m)
B  vertical cliff
C  trace of master joint to depth in cliff wall
D  trace of master joint across sandstone outcrop
E  junction of cliff and plateau
F  aircraft wing strut
FIG. 3   SCHEMATIC PROFILES MODELLLED FOR JOINT FORMATION

(a) HYDROSTATIC UNLOADING  (b) DIFFERENTIAL
BASEMENT UPLIFT    (c) HORIZONTAL 'PULL-APART'

PTC  Post-Triassic cover
TGS Triassic Grose Sandstone
PCM Permian coal measures
LS Lithgow coal seam
LPB Lower Palaeozoic basement

Arrows show direction of forces
FIG. 4 JOINT SYSTEM RESULTING FROM HYDROSTATIC UNLOADING
FIG. 5 JOINT SYSTEM RESULTING FROM DIFFERENTIAL BASEMENT UPLIFT

--- cycle 2 joints
--- cycle 3 joints
--- cycle 4 joints

Failure mode:

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<tr>
<td>Tensile and shear</td>
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FIG. 6 JOINT SYSTEM RESULTING FROM HORIZONTAL 'PULL-APART'

Numbers on mesh indicate cycle in which the various elements failed. Histogram indicates diagrammatically, tensile strain leading to failure.

→ indicates effect of horizontal loading