Low permeability coals: towards an exploration model based on macroscopic features of calcite mineralisation and a knowledge of tectonic history.

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Summary.

At Tahmoor Colliery, mining has encountered several local zones of coal up to several hundred metres wide that have been extremely difficult to drain gas from. They are characterized by calcite mineralisation. At a macroscopic scale, mineralisation is dominated by fractures with fibrous calcite; the formation of fractures and precipitation of calcite was essentially synchronous. Cementation of pre-existing fractures also occurs. Simple infill of cleat is subordinate though it may be more pervasive at the microscopic level. Mineralised fractures and veins are both horizontal and vertical. Fibrous calcite often exhibits median lines comprising coal particles.

The distribution of carbonate mineralisation in the vicinity of LW19, Tahmoor Colliery, has a general NW-SE orientation, and is several hundred metres from a major fault of similar orientation. Local zones of coal with carbonate mineralisation at Westcliff Colliery, also appear to be associated with major NW-SE trending faults.

Various origins have been proposed for fibrous veins in sedimentary (and metamorphic) rocks. These include crack and seal mechanisms originating from high fluid pressures, and crystallisation pressure. In the Bulli Seam, it is likely high fluid pressures were a major factor. It is also inferred that the origin of high fluid pressure was primarily due to a fluctuating NE-SW tensional – compressive stress field that was present during the burial phase of the Southern Sydney Basin. During the phase(s) of extension, fluids had access to the coal in the vicinity of the NW-SE trending faults. In compression, the fluids were trapped by the closed nature of the faults and the presence of impermeable roof and floor lithologies. Continued burial caused the entrapped fluids to become "overpressured", and fracturing and mineralisation ensued.

A comparison of the general characteristics of carbonate mineralisation at Tahmoor Colliery with Tower Colliery, and elsewhere, indicates there is a broad relationship between the lateral extent and intensity of mineralisation, and mechanism of mineralisation. It is possible to formulate a spectrum of models that can be applied in exploration. It would be beneficial for the coal mining industry to integrate existing exploration methods, with models of calcite mineralisation, and locate and complete reservoir characterization of zones of difficult drainage well advance of mining.

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Introduction.

In the last five years several underground coal mines in the Southern Sydney Basin have had planned production seriously affected by zones of difficult drainage. With the potential for outburst in un-drained or poorly drained coal, remote mining is the only option to keep moving forward. At Tahmoor Colliery (Figs. 1 and 2), the response to the problem, and probably the only choice available, when these conditions occur as a "geological surprise", is to "grunch" (ie. form roadways with explosives). Whilst this form of remote mining keeps development moving forward, it is very slow (and may result in subsequent longwall delays). It is also expensive, and has its own set of problems (eg. the management and handling of large amounts of explosives). Clearly it would be beneficial to know of the location and severity of conditions of difficult drainage in advance, and to plan accordingly. A comprehensive review of gas drainage at Tahmoor is given by Wynne, 2002.

The basis for trying to predict the location of areas of difficult drainage is the assumption that there is an underlying geological control, and that exploration can be targeted; the alternative is that the distribution of carbonate mineralisation is random and unpredictable. Calcite (carbonate) mineralisation of cleat and fractures exhibits a range of characteristics which may influence gas drainage (Table 1). Opening of cleat and/or formation of fractures, and subsequent mineralisation, may be ultimately related to tectonic events of extension, compression and shear during the burial and uplift history of the sedimentary basin. The formation of calcite is dependent on the presence of bicarbonate ion derived from the dissociation of CO_2 in water. The source of CO_2 includes thermogenic alteration of coal during burial, bacterial fermentation or reduction during early burial or uplift. CO_2 of magmatic origin may enter the sedimentary system during any stage of burial or uplift.

With such a diversity of occurrence and origin of calcite mineralisation, and consequences for gas drainage, it is convenient to distill the essence of differences into several 'models'.

The following sections are concerned with the macroscopic features of calcite mineralisation at Tahmoor Colliery and a model encompassing both the descriptive attributes of mineralisation and genesis. This model is compared with models that can be constructed from information on other mineralized coals. This comparison provides some insight into the reasons why gas drainage at Tahmoor have been so difficult in comparison with other areas with calcite (and /or other carbonate) mineralisation.

The synthesis that is presented below is based on relatively little data and is interim in nature. It is in the category of "idea"/ "working hypothesis" and an extension of an earlier outline (Titheridge, 2003). The aim of ongoing work will be to gather sufficient data to reject or refine these tentative models, and to produce some final models that are sufficiently robust to have a useful predictive capacity for exploration for coals affected by carbonate mineralisation in the Southern Coalfield, and perhaps beyond.

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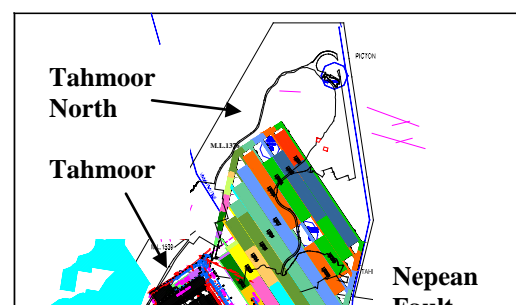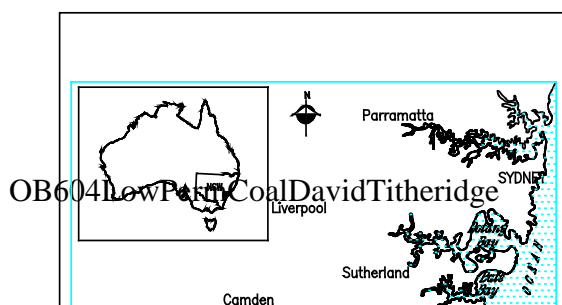
* Effect on permeability and gas drainage

Table 1.   *The range in characteristics associated with calcite mineralisation in coal that may*

Calcite mineralisation characteristics	**Range in characteristics**
Lateral Extent	Hundreds of metres…………………….… Several to tens of metres
Vertical extent	Whole seam……………..……………………….… …Part of seam
Opening type	Cleat…….….…Filling of macropores (cell lumens)… …….……Fracture
Scale	Macroscopic………………………………………….…Microscopic
Abundance	Pervasive……………………….… ………………… ……Sparse
Origin (of CO_2)	Coal (maturation)…… Bacterial (early, late stage) …………Magmatic
Phases	Multiple (additional vs. replacement)……………… …… ……Single
Timing	Burial……………………………… …………………… ……Uplift
Form/origin	Blocky(void filling) Fibrous (crack, precipitation synchronous)
* ...gas drainage	Severe………………………………………………………Minor

have an impact on local and bulk permeability and gas drainage.

Characterstics of calcite mineralisation at Tahmoor Colliery.

Fig. 3 illustrates a generalized profile of the distribution of macroscopic calcite mineralisation from coals that are very difficult to drain at Tahmoor Colliery. It is matched with a brightness log (LHS of Fig 3.) that indicates the vertical location of coal with the highest proportion of bright bands (telovitrinite).
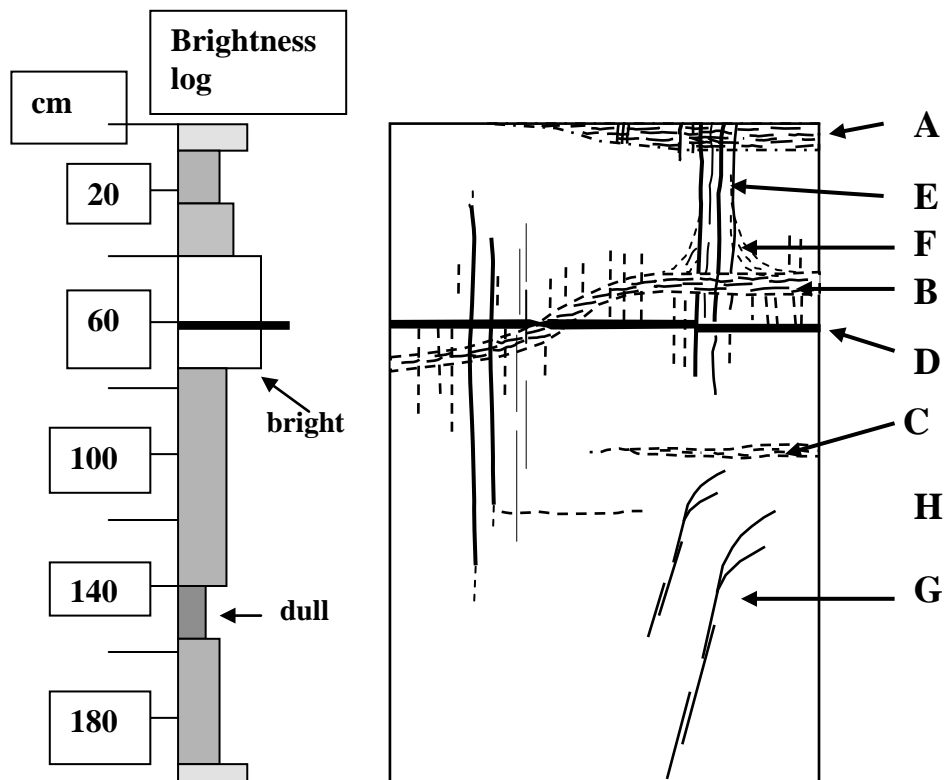
Fig 3. *Generalised profile of the distribution of calcite mineralisation in coals that are difficult to drain at Tahmoor Colliery. Simplified brightness log at left.*

(A)   very dense concentration of horizontal veins near the roof (2-10cm;)
(B)   dense concentration of horizontal veins above mid-seam level (5-10cm);
(C)   one to several horizontal veins at and below mid-seam level;
(D)   sideritic mudstone) band (1-2cm at about 60cm from the roof, locally absent;
(E)   vertical veins (2-5cm) that extend from the roof to near or below the sideritic mudstone band;
(F)   'curved' vein system with veinlets that 'connect' (B) and (E)
(G)   inclined veins in the lower part of the seam that bifurcate at top; and
(H)   mineralized cleat and major cleat near the center of the seam

The diagram does not show the distribution of mineralisation that is only observable at a microscopic level.

i)   Description of selected types of macroscopic calcite mineralisation.

        The characteristic feature of the majority of calcite mineralisation of Tahmoor coals is the fibrous nature of the calcite and the presence of median lines that divide veins.   In most cases the thickness of calcite on either side of the median line of the vein is approximately equal. The "fibres" are perpendicular to the vein walls and the median line.   The median lines exhibit very thin slivers of coal that are parallel to the vein walls, or a slightly dark discoloration, which is due to extremely fine coal particles.   The veins are typically in the range of 0.2 to 1 millimetre thickness and one to several cm in length (Fig. 4). Some veins are up to 3-5mm thick and are of the order of 15cm long.   Thickness of veins is proportional to length. On planes that approximate bedding, these veins are distinctive as white overlapping lamina. The median lines can be observed with a hand lens in veins that are small as 0.3 mm wide.   Termination of the veins varies.   Some exhibit simple termination with tapering of the veins, whilst others terminate abruptly.   Others bifurcate; the ends of the bifurcated veins are invariably tapered.   Some terminate abruptly against cross-cutting veins (Titheridge, 2003).

        (a) Horizontal vein systems at mid –upper seam (B, Figs. 3 and 4).

        Dense concentrations of overlapping horizontal veins (or veinlets), and minor sub-vertical to inclined veins, often occur at the mid-upper seam level, and are a dominant feature of coal that is difficult to drain.   They may also occur in the periphery of zones of difficult drainage but tend to be less well developed.   The density of veins (depending on vein thickness) ranges from several to about ten per vertical centimeter (for veins that are approximately 0.2mm thick).

        These horizontal vein systems range in thickness from about one to five to ten centimeters. They are best developed in coal characterized by relatively abundant telovitrinite (bright bands) immediately above and below the thin sideritic mudstone (D, Fig 3).   Whilst generally horizontal and tabular in extent, the vein system may migrate from ply to ply and is locally not tabular.   In some cases the vein systems dip steeply from one ply to another over vertical distances of up to 50cm.

        This vein system is associated with the highest proportion of calcite in cleat (from the largest to the smallest mineralised cleat that is visible macroscopically, and presumably micro-cleat).   In combination with the sideritic mudstone, this vein system imposes a significant permeability barrier between the upper third and lower two-thirds of the seam.
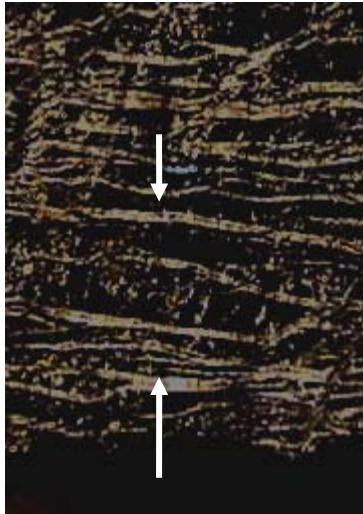
Approximately 1cm

White arrows show median lines with fine coal particles that are discernible by hand lens. To the left of the lower arrow vein bifurcates around large coal shard. Fibrous nature of calcite also visible with hand lens.

Fig 4. Horizontal veins with fibrous calcite.

(b) Horizontal vein systems at seam roof (A, Fig 3).

The roof of the seam at Tahmoor, both in, and proximal to, zones of difficult drainage is characterized by a dense system of predominantly horizontal veins up to 10cm thick. At some localities, these horizontal calcite vein systems are estimated to comprise more than 85% of the coal volume. It is possible that some of the calcite present near the roof is of replacement origin (AC Cook pers. comm.).

The horizontal vein system near the roof is characterised by the presence of cross-cutting vertical and planar, to inclined and curved fractures, with 'black" veins of calcite that also contain kaolinite. These secondary mineralized fractures do not extend down from the roof more than 10-15cm. Kaolinite on fractures near the roof appears to be present across the Tahmoor lease; it appears as a pinkish brown film on cleat and fractures.

The horizontal veins near the roof are often locally thick (up to 1cm), and unlike the mid to upper seam veins with single median lines, display several or multiple lines of coal shards or other fine detritus. The appearance of thick calcite ranges from distinctively white and fibrous in character, to clear and blocky.

Although the horizontal veins at the roof may constitute an impervious barrier to gas and water, the location of this feature at the roof means they have little consequence for gas drainage.

In addition to the fractures and cleat with dark calcite veins and kaolinite, the veins at the roof are cut by fracture zones with calcite that extend to the upper-mid to mid seam level (section d below).

(c) Horizontal vein systems mid-lower seam (C, Fig 3).

Single horizontal veins, or horizontal vein systems with a low density of veins occur in the mid-seam to mid-lower seam interval.   They appear to be associated with the occasional thicker telovitrinite bands.   They are not as laterally extensive as the horizontal vein systems described above.   These features are probably relatively insignificant contributors to difficult drainage.

(d) Vertical vein systems at seam roof to mid-upper seam (E, Fig 3).

Vertical vein systems that occur near the roof to mid-upper seam level are of the order of 2-5cm wide.   The density of veins is up to 7-10 veins per lateral cm.   The vein systems range from simple to complex.

Simple vertical vein systems comprise veins of the order of 0.2-0.5mm with fibrous calcite and median lines with the same or similar orientation.

In addition to the features described above, complex vertical vein systems comprise an additional set(s) of calcite filled fractures, that are oblique to the simple fractures.   They tend not to have median lines and if present the fibrous nature of calcite is difficult to detect. Cemented micro-breccias are also present.

ii)   <u>Interpretation of calcite mineralisation dominated by veinlets of fibrous calcite with median lines</u> .

Calcite veins are characterized crystals with either blocky or fibrous habit (Figs.4 and 5).

Blocky crystals form when there is a pre-existing opening.   Crystals nucleate on the vein walls and grow inwards toward the center.   In contrast fibrous crystals grow where there is no pre-existing opening; opinion is divided on their origin.

There are several views on the processes involved in formation of fibrous crystals. It is easily possible that different processes operate in different situations, and it also possible that a hybrid of processes may function one setting.

Later stage fill

voids

Ol **Blocky calcite with crystal faces**   ier **open fracture**   **coal**
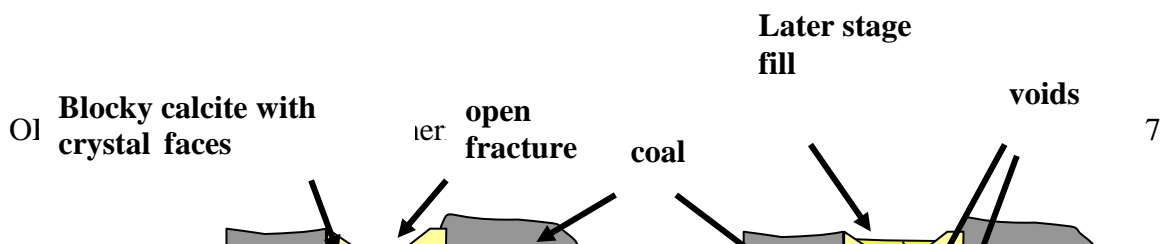
Fig. 5. *Diagrammatic representation of blocky(A) and fibrous calcite(B).*

       The 'crack and seal' mechanism involves formation of a crack by high fluid pressure. The drop in fluid pressure associated with fluid moving into a crack is inferred to cause precipitation.   A vein is formed by countless repetitions of this process (van der Pluijm and Marshak). In essence, the process, and in particular fracture formation, is driven by overpressure, and there many examples of these features in mudstone rocks that have been attributed to this process (eg Parnell et al, 2000, and references cited by these authors).

       A second process involves diffusion of solute along grain boundaries and precipitation at the tips of fibres with grain walls gradually moving apart.   There is no development of open cracks (van der Pluijm and Marshak).
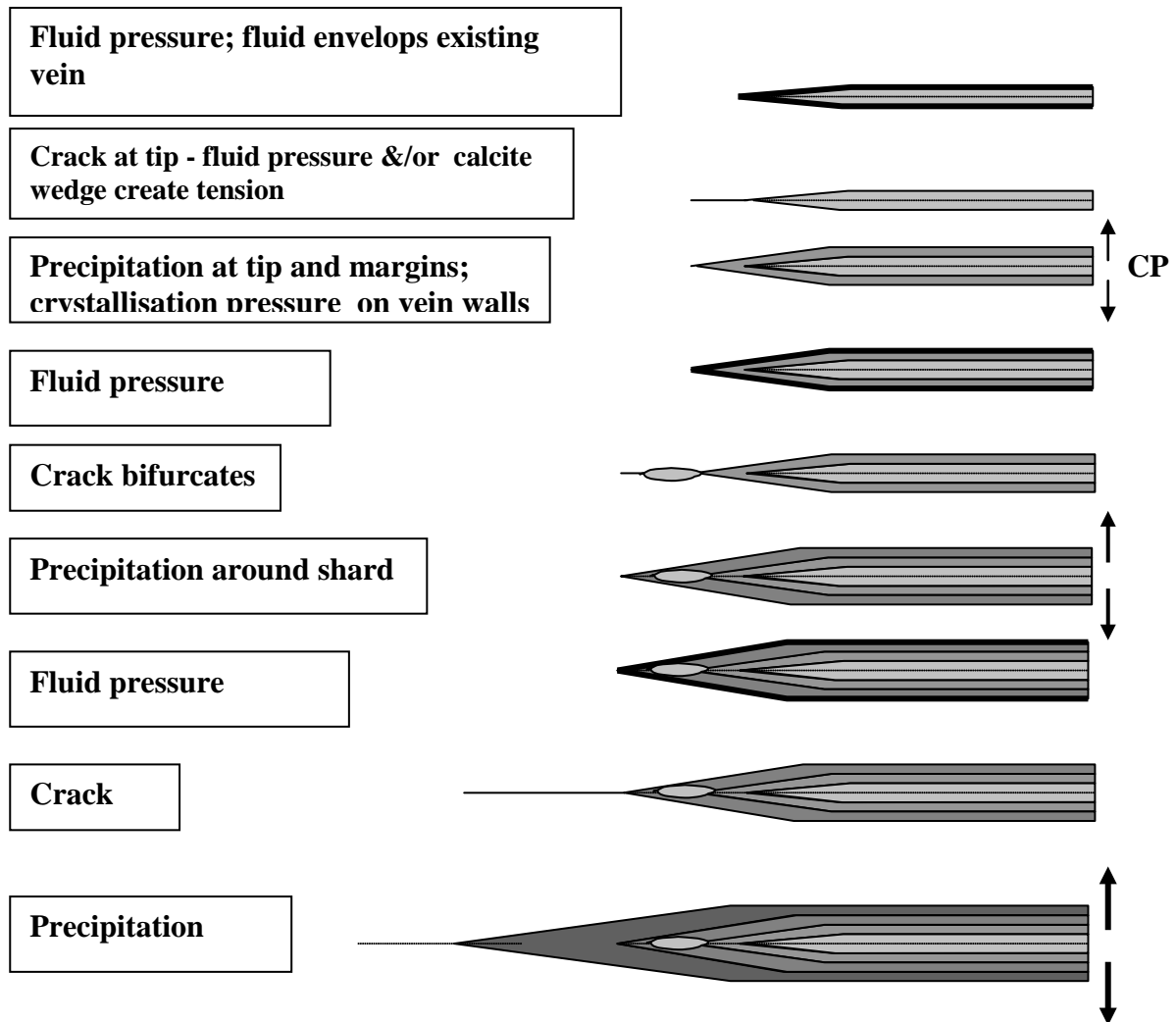
The third process involves crystallization pressure due to crystal growth. In this process the vein walls are pushed apart. In comparison with the crack and seal mechanism, the process is driven by factors that cause super-saturation of pore fluid; the only influence of tectonism is on the orientation of the veins (Wiltschko and Morse, 2001, Li 2000).

There are several questions to resolve regarding the existence of fibrous vein systems at Tahmoor. Resolution is complicated by considerable complexity; the horizontal veins systems near the roof and near mid-seam as well as the vertical veins near the roof have differences in character. The first question to be asked is: could the veins be purely tectonic fractures that have been filled subsequently (as appears to be the case at Tower Colliery; discussed below), or has the formation of veins been dependent on the presence of fluids . The second question is: has fracture formation been an integral part of mineralisation (crack and seal) or are the veins a product of supersaturation and crystallization pressure, or are both mechanisms involved. Mechanisms involving displacement or crystallization pressure might have consequences for permeability (discussed below).

The mineralized horizontal fracture system in the mid-upper seam consists of a locally dense concentration of overlapping micro-cracks. This contrasts with tectonic fabrics where although there may be fracturing, there is a dominant feature (fault or bedding plane shear) that is characterised by some offset. The overall appearance of the veins is one of mineral filled cracks of simple geometry rather than cementation of a very fine breccia with complex fracture. The local high steep dips and random migration of the fracture system from one ply to another in the mid-upper seam of Tahmoor coals excludes a tectonic origin for these fractures. As far as is known to the author, there are no un-mineralised fracture systems that have these characteristics at Tahmoor or elsewhere. In other words this system of fractures only occurs where mineralisation is present and their formation is clearly dependant on the presence of fluids.

The preference for horizontal vein systems in the mid-upper seam to be associated with vitrinite rich plies in the mid to upper seam level is consistent with high pressure fluids creating a migration pathway along the weakest plies.

The marked tendency for thickness of veins to be proportional to length suggests simultaneous precipitation at the ends and margins of veins. The abrupt tapering at the ends of veins suggests it is possible that crack formation at the tip of veins could also be driven by the "wedge" of precipitated carbonate causing tensional cracking; this is yet another possible variation to those mechanisms suggested above to explain both initiation and propagation of fractures. It may be unique to coal. It is illustrated schematically in Fig. 6.
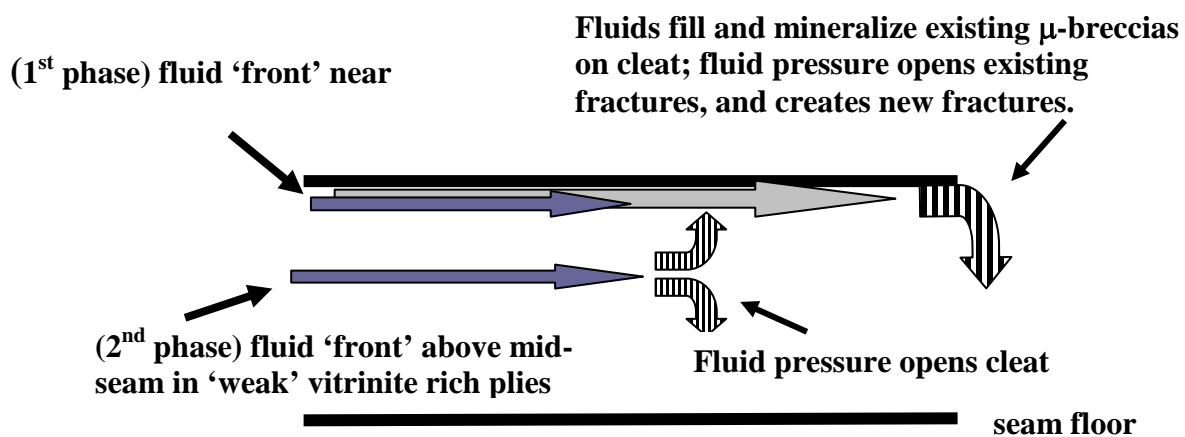
Fluid pressure; fluid envelops existing vein

Crack at tip - fluid pressure &/or calcite wedge create tension

Precipitation at tip and margins; crystallisation pressure on vein walls

CP

Fluid pressure

Crack bifurcates

Precipitation around shard

Fluid pressure

Crack

Precipitation

Fig 6. Possible hybrid crack-crystallisation pressure process for fibrous veins in coal. CP = crystallization pressure.   The evidence to support this is very general (see text).

It is difficult to conceive that in Tahmoor coals or other geological (coal) environment where there is no evidence of mass transfer via mechanisms of pressure solution/overgrowth, or dissolution/ cementation, that the formation of fibrous veins did not involve crystallization pressure and/or displacement force acting on the host coal; the volume is constant but the mass has increased with introduction of calcite. Without microscopy or other investigation that is dedicated to the purpose of seeking out evidence of a mechanism, it is not yet possible to support or reject a mechanism such as is illustrated in Fig 6.

Although there is no evidence of a tectonic cause of fracturing at the mid-upper seam level, this may not be the case at the roof where some horizontal veins might reflect the existence of bedding plane shear in the immediate vicinity of the coal/roof contact prior to mineralisation. Some indication of this is provided by the local presence of very thick calcite veins that have a blocky habit suggesting the presence of cavities at the time of mineralisation. (Calcite of similar appearance and vein thickness has been observed in fault planes at Tahmoor Colliery; in this instance some of the calcite crystal faces have been observed to terminate in small voids) Some of the slivers and fragments of coal in other thick calcite veins could be interpreted as the result of shear whereas others appear to be the product of two or more episodes of fracturing by fluids. It appears that the coal roof may have been a site of mineralisation of both pre-existing tectonic fractures and new fractures (natural hydrofracs) that were created by the invading fluids.

The vertical fracture zones are more complex than those described above. Some are certainly associated with brecciation of cleat prior to mineralisation. It is anticipated that the veins that curve and connect the horizontal and vertical vein systems will provide insight into the way stress can change direction (flip) over a short distance (tens of cm); this might provide insights into rapid changes in stress direction at a mine scale.

In summary, whilst it is not yet possible to convincingly demonstrate a mechanism for the formation of fibrous veins (crack and seal versus crystallization or a possible hybrid as illustrated in Fig. 6), it appears that mineralizing fluids found migration pathways in the weak plies in the mid-upper roof and along the roof/coal where there may have been had been some pre-existing shear. These horizontal pathways provided access to cleat in the middle-upper seam level and vertical fractures near the roof of the seam. Cleat was opened and mineralized, wheras in the vertical fracture

(1st phase) fluid 'front' near

Fluids fill and mineralize existing μ-breccias on cleat; fluid pressure opens existing fractures, and creates new fractures.

(2nd phase) fluid 'front' above mid-seam in 'weak' vitrinite rich plies

Fluid pressure opens cleat

seam floor

Fig. 7. *Mineralisation mechanism for coals at Tahmoor Colliery with difficult drainage.*

zones pre-existing fractures were cemented and fluids mineralized cleat in their immediate vicinity.   This mechanism is summarized in Fig.7.

iii) Why are local zones of coal at Tahmoor and elsewhere in the Southern Sydney Basin so difficult to drain ?

It is generally known that coals with moderate amounts of telovitrinite, have relatively low permeability.   Laboaratory permeabilities for the Bulli seam at Tahmoor coal are in the range 0.1(high stress) to 0.7mD (low stress) whilst field permeabilities of 1.5-2.5mD have been quoted (Lama, 1996). It is also generally known that coals with mineralised cleat have relatively low permeability and are more difficult to drain.

In zones of difficult drainage at Tahmoor, not only is there mineralisation of cleat at the macroscopic to microscopic level but mineralized vertical and horizontal vein systems of the order of 2-5cm thick are present.   These mineralized zones constitute a very effective and additional permeability barrier for lateral and vertical migration of gas.
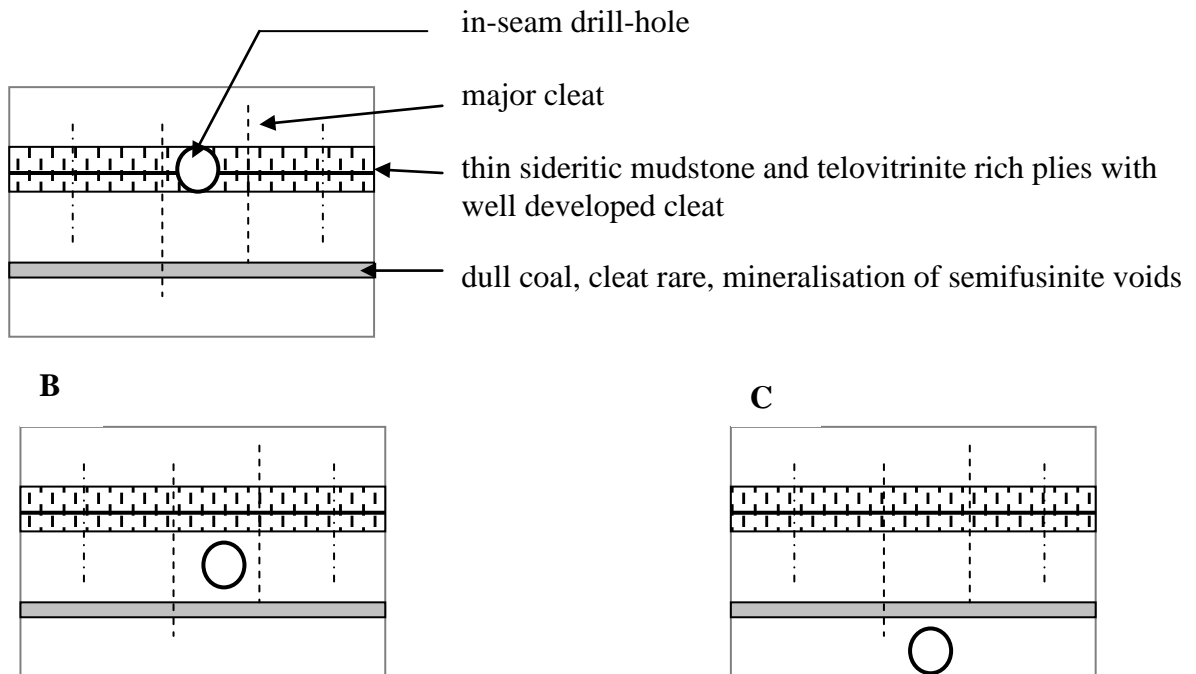
In areas of coal that have not been mineralized, the highest permeability at Tahmoor probably occurs in the mid-upper seam level in plies with relatively high telovitrinite. Mineralisation by calcite has substantially closed off what would otherwise be the most permeable plies of the seam. The influence of in-seam drainage hole position, coal type and vertical location of mineralisation and major cleat is presented in Fig. 8.

Does the mechanism of mineralisation, in addition to its extent, influence the permeability of coal ?

Permeability of coal via cleat is not constant. It can change over geological time and as more importantly over the course of gas drainage. The opening of cleat is the major factor in development of permeability of coal and is dependent on effective stress and matrix shrinkage (Gray, 1995).   On the one hand tectonic stress acts to close cleat whilst on the other, fluid pressure acts to open it; effective stress is the resultant of these opposing forces.

In un-mineralised coals, for gas to flow, and to continue to flow after the formation pressure is lowered below desorption pressure, the impact of matrix shrinkage as a result of initial desorption of gas must exceed the impact of effective stress on cleat openings.

In mineralized coal, the presence of calcite (or other minerals) in cleat or fractures adds an additional factor to the initial and subsequent drainage process outlined above. Mineralisation blocks cleat and fracture permeability routes that would otherwise transport gas. It is reasonable to postulate that the greater the extent of mineralisation, the greater the blockage of permeability pathways, and the more likely it will be that both initial desorption and shrinkage, and subsequent desorption and shrinkage, and hence gas flow will be impeded.

in-seam drill-hole

major cleat

thin sideritic mudstone and telovitrinite rich plies with well developed cleat

dull coal, cleat rare, mineralisation of semifusinite voids

B

C

i) Drainage scenarios in relation to coal type and major cleat for un-mineralised coals at Tahmoor Colliery.

> ***A.*** *Hole in bright coal plies with highest permeability mid –upper seam connected to lower seam via major cleat.* ***B****. Hole in plies of intermediate brightness mid-seam.* ***C****. Hole below prominent dull band with low permeability; limited connection to mid-seam via major cleat.*

D

vertical veins calcite

E

Horizontal veins calcite

mineralized major cleat
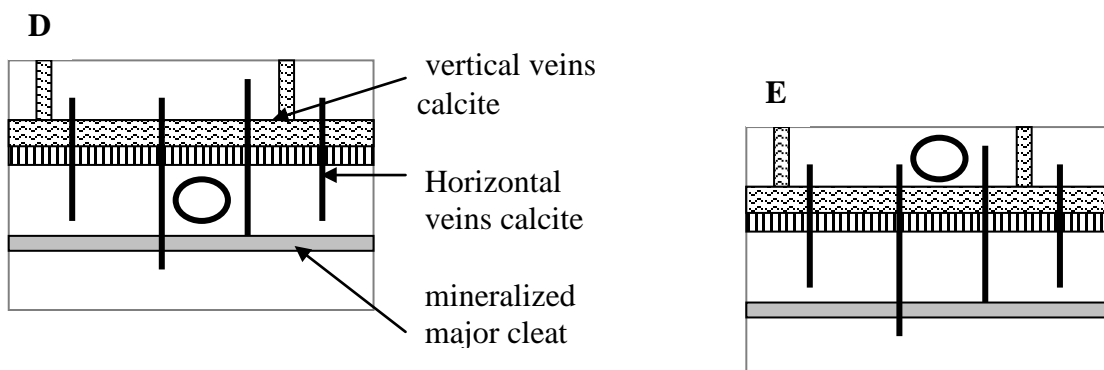
ii) Drainage scenarios in relation to coal type for mineralised coals at Tahmoor.

> ***D****. Permeability route to upper seam blocked by horizontal veins; permeability route to lower part of seam impeded by calcite in major cleat; lateral permeability reduced by mineralised major cleat .*
> ***E****. Permeability route to middle and lower seam blocked by horizontal veins; lateral permeability impeded by vertical vein zones.*

Fig 8 *. Influence of macroscopic calcite mineralisation on gas drainage***.**

This author suggests that the crystallization pressure of minerals that displace coal might also influence effective stress and hence initial and subsequent gas desorption. If fibrous calcite or other minerals are present in some cleat or fractures, then the crystallization pressure will add to the effective stress acting on un-mineralised cleats in close proximity (and further afield ?). This contrasts with the filling of open cleat that is inferred to have little or no force of crystallization, and does not displace the coal host.

Anhydrite ($Ca\ SO_4$) to gypsum ($Ca\ SO_4.2H_2O$) transformations involves a volume increase of 61 %. Measured and calculated force of crystallization associated with this transformation ranges from 11Mpa to 15Mpa (Keulen et al., 2001). The 2- 5cm thick horizontal vein systems toward the middle of the seam at Tahmoor comprise of the order of up to 50% of calcite. This calcite is not of replacement origin, it has displaced the coal that it occupies. There is no evidence for a volumetric change in the coal associated with mineralisation. As a result of mineralisation pushing against the host coal via a force of crystallization, and given the relatively high compressibility of coal, and the process occurring at constant volume, it is inferred that any un-mineralised cleat or fractures in close proximity will experience a very high effective stress

The precipitation of minerals into open cleat/fractures can be expected to impart a tortuous route for gas migration. Precipitation of fibrous calcite can be expected to impart the additional outcome of an increase in effective stress acting on un-mineralised cleat and fractures; dense concentration of veins can be expected to have negligible or no permeability as a result of both blockage imposing tortuos pathways exceptional effective stress.

The orientation of mineralized zones and their relationship to major faults at Tahmoor Colliery

The zone of calcite mineralisation in the vicinity of LW19, Tahmoor Colliery appears to have a NW-SE orientation. As development roadways were progressively formed to the SW, the extent and sverityof mineralisation increased. Difficult drainage was encountered for most of 514 panel. A major NW-SE trending fault is present about 400-500m SW of 514 panel. It is inferred that the zone of mineralsation extended to this fault. The known and inferred extent of the zone of mineralisation is illustrated in Figs. 9 and 10.

A 200m wide zone of difficult drainage was encountered in LW's 20 and 21 (611 and 612 panels). The zone of difficult drainage was coincident with the presence of calcite mineralisation. Mapping of 700 panel (mined about 15years ago, and before the advent of routine gas testing), indicated the presence of calcite mineralisation from about 14ct to 6ct. However the shape of the known distribution of calcite mineralisation does not have a linear aspect (Fig 10).

In the southern ends of 513 and 512 panels, a narrow linear zone intersects or extends from the main body of mineralisation in the vicinity of 514 panel. It has a N-S trend. Extrapolation of this feature intersects the zone of mineralisation in 611 and 612 panels (Figs. 9

and 10).   The mineralisation in 611 and 612 panels could be equivocally interpreted as having either a N-S or NW-SE orientation (Fig. 10).

At Westcliff Colliery, several zones of difficult drainage have been encountered and both areas (LW23 and LW 28) and are in close proximity to NW-SE trending faults. It is apparent that zones of difficult drainage at both Tahmoor and Westcliff have close proximity to major NW-SE trending structures.

The origin and timing of mineralisation at Tahmoor Colliery

The precipitation of calcite from solution requires a source of both Ca^{++} and HCO_3^- . The source of HCO_3^- is the dissolution of CO_2 in water. CO_2 can have bacterial, magmatic or thermogenic origins and each has a distinctive carbon isotope fingerprint. $\delta^{13}C$ data   from Tahmoor Colliery (Gould et al 1981) indicate that whilst the CO_2 gas is distinctively magmatic ($\delta^{13}C \approx$ -7), the calcite is not magmatic in origin.   It most likely has a bacterial source ($\delta^{13}C \approx$ +6).   Recent work by CSIRO on Tahmoor samples (M Faiz pers.comm.) is also indicative of bacterial concentration of ^{13}C.   A bacterial origin for CO_2 and calcite could either occur during burial or uplift. The
dominance of fibrous calcite in Tahmoor coals (cf precipitation of calcite in open fractures) and the likelihood of overpressure as a factor in its formation, suggests an early burial rather than a later uplift origin for calcite.

The subjects of both overpressure and/or the presence of fibrous calcite veins have been of interest to the petroleum industry. Abnormally high fluid pressures result when formation pressure rises above hydrostatic pressure to approach lithostatic pressure.   This situation can arise via an increase in vertical compressive stress (during burial compaction of mud-rocks), horizontal tectonic compression, and changes in volume (associated with aquathermal expansion, mineral transformations or hydrocarbon gemeration; Osborne and Swarbrick, 1997). It can lead to the formation of secondary porosity in sandstones that have would otherwise have very low permeability.

Fracturing can also occur in mudstones, some of which have high organic content and are sources of hydrocarbons. A characteristic feature of these mudstones is the presence fibrous calcite (or dolomite or gypsum) in fractures parallel to bedding; some contain bitumens. There is a consensus of opinion that these fibrous minerals grew displacively, with crystals growing perpendicular to the fracture walls and least principal stress (σ_3), and that the fracturing is due to overpressure (Parnell et al., 2000).
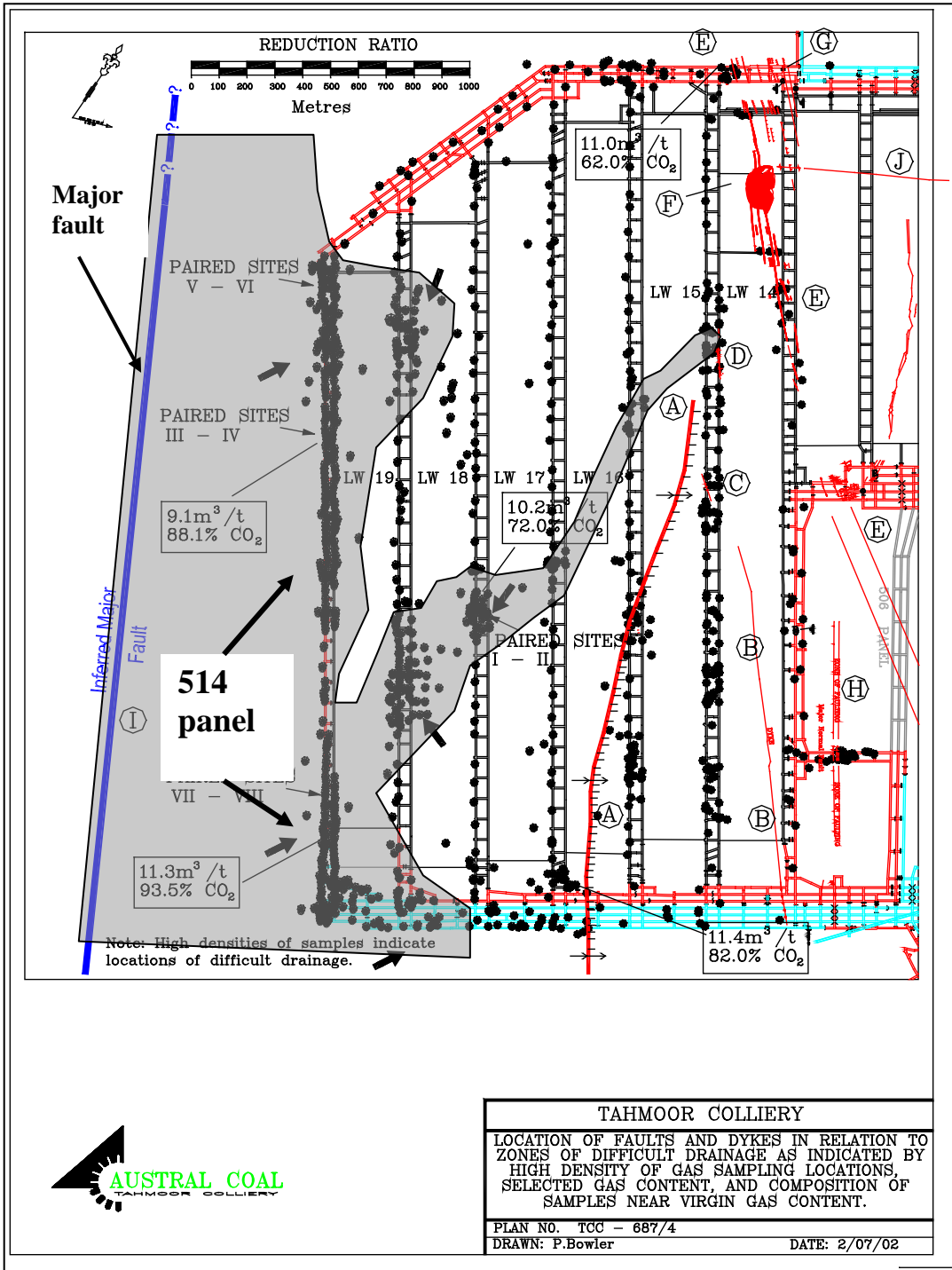
Fig 9.. *Location of zone of difficult drainage in the vicinity of 514 panel, LW19, Tahmoor Colliery (shaded). Note general similarity in orientation to major NW-SE trending fault, SW of 514 panel, LW 19, and presence of N-S trending arm extending across 513 and 512 panels.*
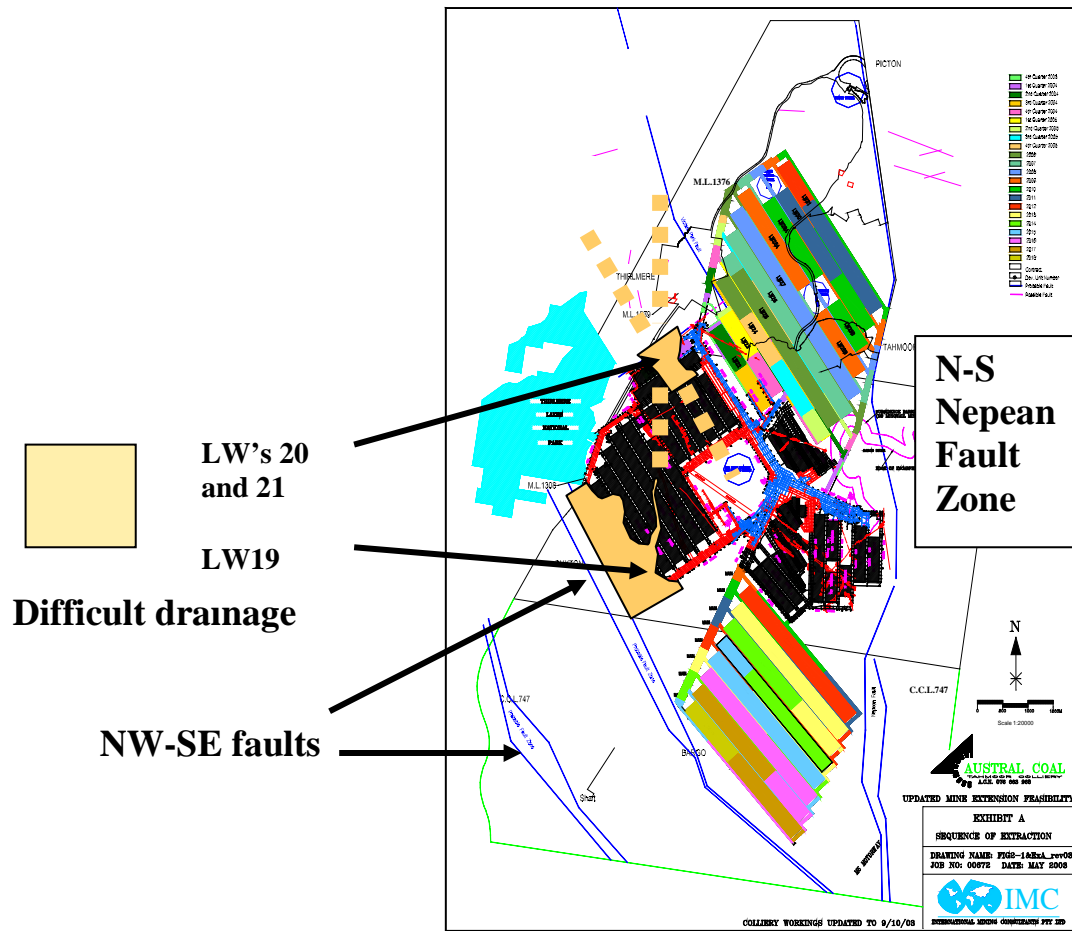
Fig.10. *Location of sites of difficult drainage (LW19 SW)and Lw's20 and 21 (N) in relation to major NW-SE trending structures.*

The author does not know of any examples (in the literature) of fractures and calcite mineralisation in coal, that have been attributed to overpressure.   However there does not seem to be any reason why this should not occur. Moreover, the low tensile strength of coal, would make this material conducive to fracturing via overpressure.   As indicated above, there are many causes of overpressure and it is reasonable to ask which mechanism may have been the causative factor in the formation of calcite veins in Tahmoor. If the cause is tectonic, that may provide significant insights into where to seek out zones of difficult drainage as part of an exploration strategy (below).

Recent work on joints and interpretation of the early geological history of the southern part of the Sydney Basin on the shore platforms at Coalcliff (Mermerian and Fergusson, 2003), provides some indication of how abnormally high fluid pressures may have been attained. The findings of these authors that have relevance to this work are illustrated in Fig. 11.   Mermerian and Fergusson interpreted joints and normal faults oriented at ~ 128º, as the result of NE-SW extension.   They also interpreted joints oriented at 043º as the product of NE-SW compression. In combining their observations of the character of these joints and their inter-relationships, and a consideration of the known tectonic history of the Sydney Basin, they concluded that the joints formed during burial and compaction (cf uplift), and that it was probable that both sets of joints "developed alternately in a complex fashion". In other words the NE-SW component of paleo-stress field fluctuated between extension and compression.

043 joints associated with NE compression.

Normal faults

128 joints associated with normal faults and extension
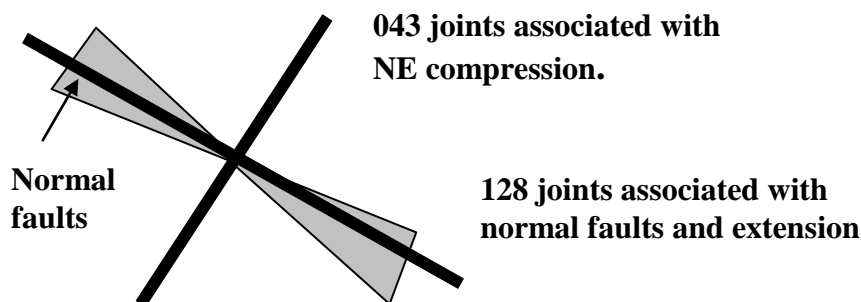
Interpretation/Conclusion (M+F)
- **Joints formed during burial and compaction (cf uplift)**
- **Probable that both sets of joints "developed alternately in a complex fashion" –fluctuating stress field.**

Fig. 11. *Relationship between extensional joints and normal faults, and compressional joints in the Coalcliff area.*

This interpretation, involving episodic tectonic extension followed by compression, has significance in suggesting an overpressure mechanism for at least some Illawarra region coals. Whilst faults are in extension, there is the opportunity for fluid connection between coal and sediments above and below. When faults are in compression, then the fluid connection with overlying strata is closed off, and particularly in those instances where the Bulli Seam is immediately overlain by impermeable mudstone. If burial continues, whilst faults are in compression, then the pressure of fluid in the seam, which cannot escape, increases toward lithostatic pressure, and fracturing (and mineralisation) results. These features are summarized in Fig. 12.

Sibson (1990) has attributed has the build-up and release of fluid pressure to earthquake events. In this model, the earthquake events allow fluid pressure release between periods of build-up. Sibson has cited several examples of quartz vein hosted gold mineralisation due to fault valve behaviour. The model proposed above, and that of Sibson (1990), allow for multiple cycles of fracturing and, as importantly, replenishment of saturated mineralizing fluid.
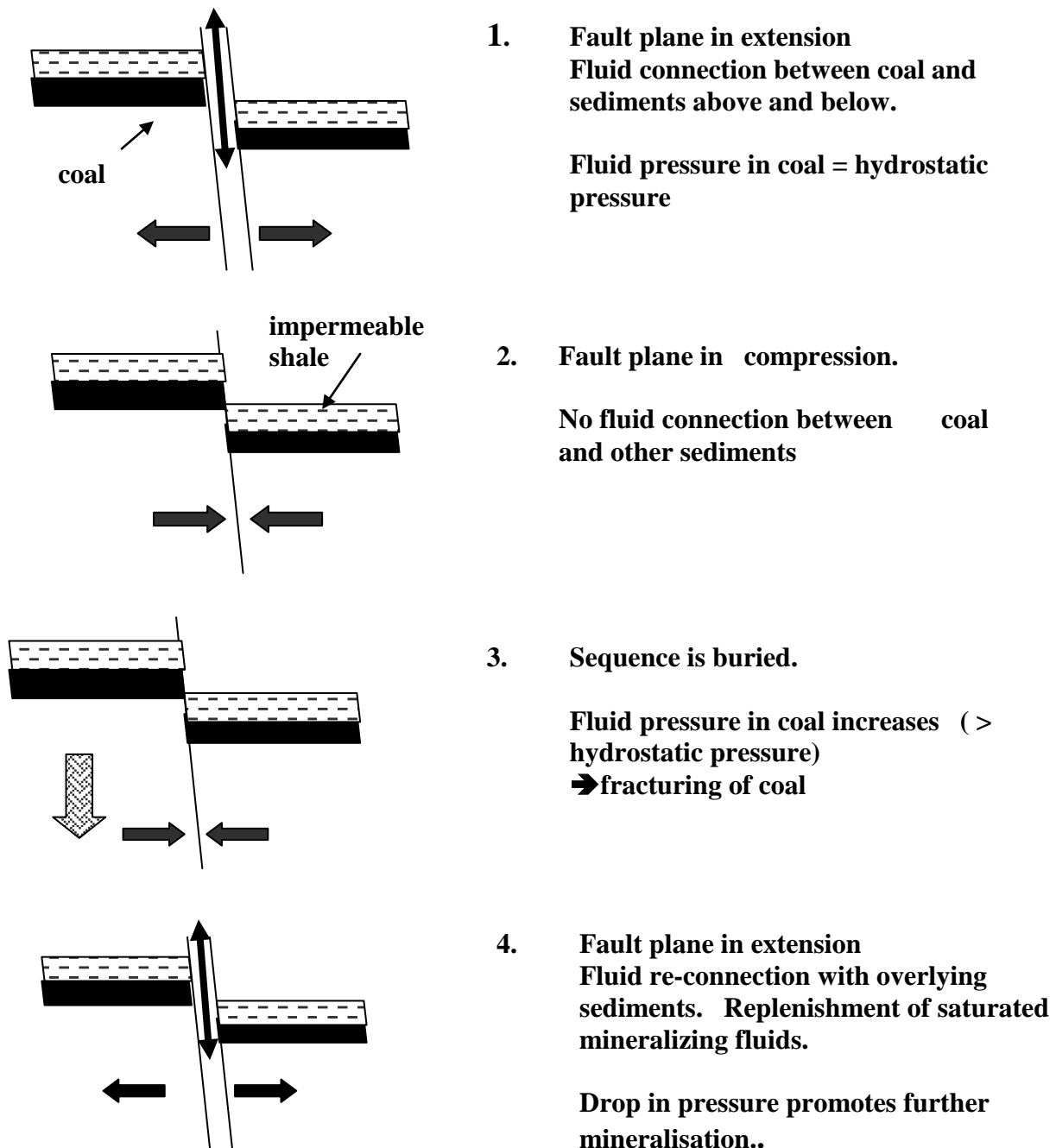
The mineralisation of coal in the SW of Tahmoor Colliery in the vicinity of LW 19 is interpreted as resulting from overpressure and a fault valve effect of the major NW-SE fault. It is possible a similar mechanism may have been present in the northern part of the Westcliff lease. The mineralisation in the vicinity of LW's 20 and 21 is more difficult to interpret as (assuming it is a linear feature), there not sufficient known on its orientation. The origin of the N-S "arm" of mineralisation extending from 514 panel and across 513 and 512 panels is more problematic. It indicates a phase of fracturing (shear ?,) and may record a subtle tectonic event that has no other manifestaion but there are no observations to be certain of this or whether this occurred before or after the main phase of mineralisation.

Tentative fracture/fluid/mineralisation models for Tahmoor and other coals.

The style and context of carbonate mineralisation at Tower Colliery appears to be significantly different to Tahmoor (and perhaps Westcliff).

At Tower Colliery, carbonate mineralisation is related to the presence of a dyke that has intruded a thrust fault. In comparison with Tahmoor Colliery, the extent of mineralisation is relatively localized. Dolomite is present (cf Tahmoor) and appears to replace calcite (Fig. 11 of Gurba et al , 2001). Moreover its presence in the center of the fracture suggests filling from the wall to the center (cf. the dominantly fibrous calcite at Tahmoor). A comparison of photos in Gurba et al., 2001 indicates the cemented breccias of Tahmoor and Tower have a different appearance. Those at Tahmoor are essentially planar and appear to be associated with brecciation of cleat. Those at Tower are less regular and appear to be associated with brecciation of a greater part of the coal mass.

At Tower Colliery, there were essentially two drainage problems.   One was a consequence of carbonate minerlisation, the other due to brecciation of coal that caused bogging of rods.

coal

1.   **Fault plane in extension**
     Fluid connection between coal and sediments above and below.

     Fluid pressure in coal = hydrostatic pressure

impermeable shale

2.   **Fault plane in   compression.**

     No fluid connection between   coal and other sediments

3.   **Sequence is buried.**

     Fluid pressure in coal increases   (> hydrostatic pressure)
     ➜fracturing of coal

4.   **Fault plane in extension**
     Fluid re-connection with overlying sediments.   Replenishment of saturated mineralizing fluids.

     Drop in pressure promotes further mineralisation..

***Fig 12**. Consequences for mineralisation of coals that might arise from tectonic extension followed by compression and burial, in the vicinity of faults.*

In the Tahmoor model, mineralisation appears to be associated with fault activity in the burial phase of the basin's history. However it is possible these or other faults, that may or may not have been sites of mineralisation during burial, were sites of mineralisation during uplift. It is expected that these sites will be characterized by filling of open cleat and/or fractures. To date no examples are known or documented but their occurrence elsewhere in the world indicates they need to considered. Another variant which could affect early and late stage mineralisation but for which no examples are known, is the presence of calcite where the Bulli Seam is overlain by a (permeable) sandstone roof.

The three descriptive models described above are summarized in Fig. 13, and their interpretations compared with a Bowen Basin model Table 2.

The application of calcite (carbonate) mineralisation models to the exploration process.

The reason for distilling a range of calcite mineralisation characteristics into several models is to provide a guide for exploration. The purpose of exploration targeting the location and investigating reservoir propereties of zones of carbonate mineralisation is to enable the best informed decision to be made as to how to manage these zones. The management choices are to either:

- accept the presence of these zones and the delays and inconvenience when it can be demonstrated that the problem is likely to be relatively local, or;

- apply remedial measures if the problem is more extensive (which might involve more intensive drainage or longer times, and moving operations elsewhere temporarily); or

- avoiding the area completely may be the best option.

It is important that the information upon which a decision is to be made is provided well in advance of mining.

The information to date, summarised in the models above, indicates that structures, mostly faults, have a major bearing on the location of zones of carbonate mineralisation and difficult drainage. It is logical to base the search for zones of carbonate mineralisation around exploration activities focused on locating structures (a synthesis of seismic or other geophysical methods, drill-holes – surface, surface to seam, in-seam). An inspection of many surface drill hole records by the author indicates that calcite mineralisation is observable in core. In combination with structural information, this has the potential to be a guide to investigating reservoir properties that would include microscopy and other field and laboratory reservoir testing.

MODEL	Fracture/cement	Fluids - timing/limiting factor	Mineralisation extent, intensity
TAH	Fibrous veins dominant; hybrid of crack and seal and crystallization pressure ?.	High fluid pressures. CO_2 / calcite source-meteoric/bacterial ($\delta^{13}C \sim +6$ to $+15$). Calcite formed during burial. Replenishment of mineralizing fluids by fault valve activity.	Extensive, variable. Wide intensive close to major faults. Peripheral zones with carbonate present but little or no consequence for drainage.
TW	Cementation of pervasive tectonic fractures	CO_2 / calcite source -magmatic fluid - during uplift ??. Single event. Exhaustable supply. Local replacement of calcite by dolomite.	Local. Intensive. Related to intrusion cutting thrust zone
OC	Blocky calcite. Cementation of open cleat/fractures	CO_2 / calcite source- meteoric/bacterial. Calcite formed during uplift.	Restricted to immediate vicinity of fault. Variable intensity.
BB	Illite flakes (several phases on face cleat only) Calcite (butt cleat)	High geothermal gradient. Hot fluids moved basinward from 'highs' due to gravity flow. Thrust propagation caused permeability anisotropy and increase in basinal fluid pressure. This resulted in fluid access to coal via faults, more permeable areas. Formed during burial. Change in direction of tectonic compression. Calcite source fluids – mixed meteoric/bacterial and either marine carbonate or magmatic. Calcite formed after illite during burial.	Extensive mineralisation; increasing near faults (but not as intensive as parts of the Illawarra region). Anistropy of cleat (and mineralsation by illite) is major control on drainage. Severe gas drainage problems rare and very.

the Southern Coalfield, and a comparison with the Bowen Basin (BB). TAH = Tahmoor, TW = Tower (based on Gurba et al., 2002). OC = Open Cleat (based on Fig 11, Laubach et al., 1998 and Pitman et al., 2003).

A.
(TAH)

Mineralisation extensive. Fills existing fractures cleat and creates r fractures

T~

B.
(TW)

Sum mar y of calc **Thrust f**
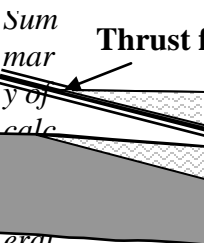
erat isati on mod els that are kno wn (TA H and TW) and anti cipa ted (OC) in

DY

C.
(OC)

Fig. 13.
a

At present, considerable effort and expenditure revolves around locating structures; there is an opportunity to use existing exploration for structures as a springboard for locating zones of difficult drainage years in advance of mining. The alternative is to locate these zones with failed samples tens to several hundreds of metres in front of a continuous miner but at this stage the decision has been made for the mine by the geology, and the "surprise" invariably involves no choice of alternative planning options, as well as substantial cost.

The authors perception of the way calcite mineralisation models might be applied to the exploration and the management of zones of difficult drainage is summarized in Fig. 14.

What data needs to be gathered and synthesized to consolidate or refute the proposed models.

The above is based on little data. There are many facets that require additional data to consolidate the proposed models. In general terms there is a need to:

- characterise the heterogeneity of mineralisation, and other reservoir properties of coals with difficult drainage, and provide a better understanding of the causal role of mineralisation in reducing permeability,

- understand the geological controls on the sites of mineralisation in coal, and

- utilise these findings to develop exploration models for the purpose of locating zones of difficult drainage.

The data needed and the way it can be used is illustrated in Fig.15.

```
┌──────────────┐   ┌──────────┐   ┌──────────────┐          ┌──────────────┐
│ Surface to   │   │ Surface  │   │ Geophysics   │          │ Existing     │
│ seam DH      │   │ DH       │   │              │          │ knowledge/   │
│              │   │          │   │              │          │ data         │
└──────────────┘   └──────────┘   └──────────────┘          └──────────────┘
```

┌──────────────────────┐   ┌──────────────────────┐   ┌──────────────────────┐
│ Locate structures   │   │ Mineralisation   │   │ Calcite   │
│   │   │ visible in core   │   │ mineralisation /   │
│   │   │   │   │ structural model   │
└──────────────────────┘   └──────────────────────┘   └──────────────────────┘

┌──┐
│   Define and focus on targets for   │
│   further investigation of reservoir   │
│   properties etc   │
└──┘

┌──┐
│   Timely location of zones of calcite mineralisation and │
│   assessment of reservoir characteristics   │
└──┘

┌──┐
│   Informed management decision   │
└──┘

┌──────────┐   ┌──────────────────────────────────┐   ┌──────────────┐
│ Accept   │   │ Remedial measures. Go elsewhere │   │ AVOID !   │
│ minor   │   │ temporarily   │   │   │
│ delays   │   │   │   │   │
└──────────┘   └──────────────────────────────────┘   └──────────────┘
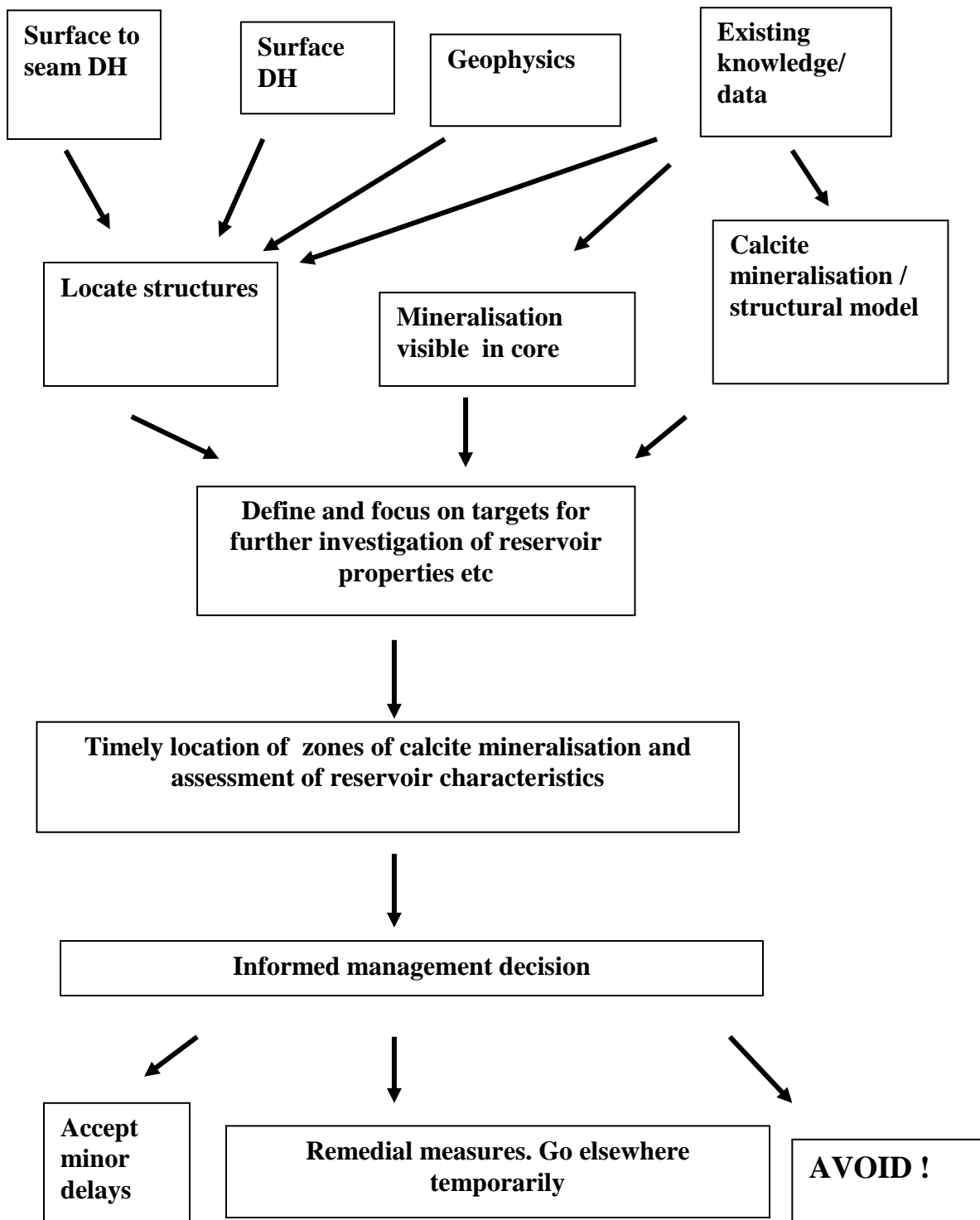
Fig 14. *Application of calcite mineralisation models to the exploration process.*
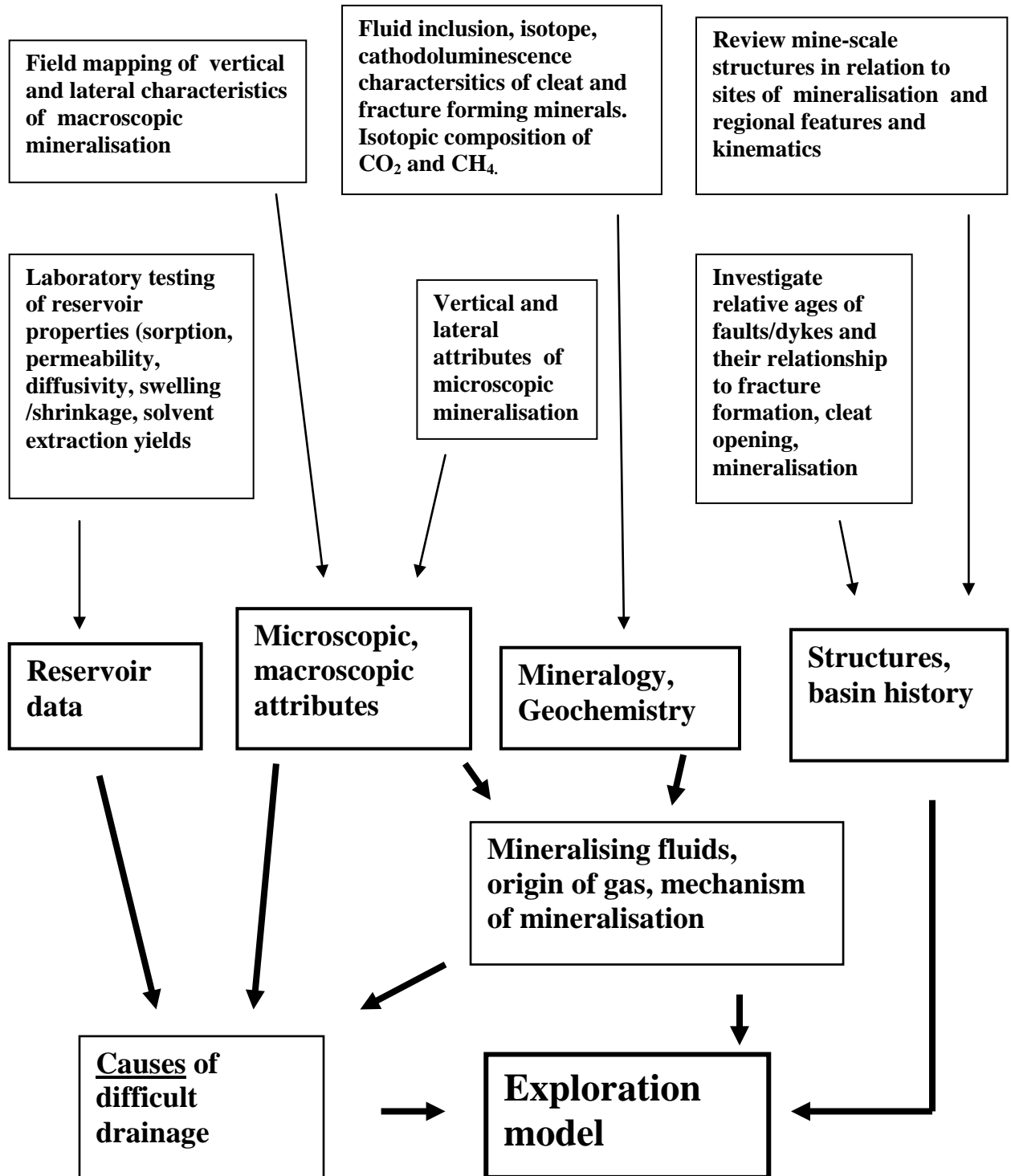
Fig 15. *What data is needed and how it will be used to form an exploration model.*

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