Understanding fracture distribution within intrusive sills the Cordeaux Crinanite a case example from the Illawarra coal measures

Luc Daigle
SCT Operations Pty Ltd, PO Box 824, Wollongong, NSW, Australia

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ABSTRACT

Recent diamond drill hole coring by BHP Billiton Illawarra Coal was used to characterise the distribution of fracturing within the Cordeaux Crinanite intrusive body. Geological data obtained from recent exploration boreholes and surface outcrops provided sufficient information to determine the pattern and history of fracture emplacement within the intrusive body.

The Cordeaux Crinanite is an intrusive sill complex consisting primarily of thick olivine rich dolerite (crinanite) sills and thinner olivine cumulate (picrite) sills. Outcrop exposures of the complex are present along parts of Cordeaux Reservoir and form the bedrock to the Upper Cordeaux Number 1 Dam and Upper Cordeaux Number 2 Dam and much of their catchments.

The intrusive body is roughly circular in plan with a domed top and largely planar base with local bowl shaped features. The intrusive is commonly referred to as a sill but drill intersections show that it gradually cross-cuts stratigraphy. The base ranges from approximately the Balgownie Seam to above the Bulli Seam and into the Coalcliff, the roof may extend up to the Stanwell Park Claystone.

The shape of the body may be best described as a laccolith due to the doming, circular geometry and roughly concordant stratigraphic position, the height to width ratio is more characteristic of a laccolith than a sill. The localised bowl shaped section of the base may form part of the feeder dyke system for the complex. Several, probably associated, feeder dykes have been intersected beneath the crinanite complex in underground workings, these may coalesce to form the basal neck of the complex. The main body of the complex exceeds 100m in thickness, near the margins thickness rapidly decreases and terminates in thin sills which pinch out, the maximum width of the body approaches 3 km.

Layering within the body can be defined by lithology changes and contact chill margins, which form the primary fabric of the complex. Four distinct intrusive phases (units) were identified in the boreholes; their emplacement from top to bottom is as follows:

1. Coarse grained Crinanite (approximately 50m thick).
2. Medium to coarse grained Crinanite (approximately 12m - 25m thick).
3. Picrite (approximately 4m thick)
4. Picritic Crinanite (approximately <1m – 2m thick)

The order of intrusive emplacement was determined from chilled margin relationships and minor cross cutting relationships.

Outcrop exposures of the complex only consist of the coarse grained crinanite which forms the upper stratigraphy of the intrusive (units 1 and 2). At surface crinanite may be covered by a thin (<1 to 3m thick) bright, red-orange soil, in boreholes residual soil is typically 3m to 7m, but oxidation can continue along some joint and fault planes to 35m depth. The crinanite is highly resistant to weathering, mineral filled joints tend to weather out at surface and a thin rind of oxidation forms on outcrops. Even where covered by soil, geomechanical testing shows that the intrusive rocks have a typical UCS of >300MPa, as weathering is shallow, the high strength rock extends to surface exposures. The topography over the exposed crinanite may largely reflect the original intrusive roof geometry due to its high strength and resistance to weathering relative to the surrounding sediments.

Fracturing in the crinanite complex is characteristic of thin bodied intrusives. Two distinct primary fracture sets are discernible; an early-formed set of columnar joints followed by late-formed cooling joint sets and hydrothermal mineralisation (analcime-calcite-zeolite) which fills all the early-formed fractures. Secondary fracture sets created by post emplacement tectonics are present and are represented by regional faulting and jointing, these are not filled with hydrothermal minerals. A final, late-formed fracture set, is present as exfoliation joints, these are present in most outcrops and are typical of intrusive rocks of uniform character. These fractures are sub-parallel to the surface topography and are formed as a result of de-burial de-stressing of the igneous body. These form thin sheet like layers near the surface and quickly diminish in frequency with depth. They cross cut the primary fractures and contain no mineralisation. The cored boreholes show that exfoliation joints become rare below 15m depth.

1 FIELD WORK

Fracture distribution within the intrusive complex was determined from recent exploration borehole cores and from limited outcrop of the Cordeaux Crinanite.

Columnar jointing is recognisable in outcrops as large (>50cm diameter) polygonal blocks. Outcrop is nearly continuous for about a 500m section downstream of the Upper Cordeaux No 2 Dam wall. In this section the columnar joints decrease in diameter towards the crinanite margin. Columnar joint dimensions are influenced by the latent heat and rate of cooling of the intrusive body. Cooling is more rapid near the margins and produces small diameter columns while greater thickness of intrusive results in slower and larger diameter columns.

Low angle, surface parallel exfoliation joints are present in most outcrop exposures (Figure 1). These are seen to cross cut primary fabric and early and late formed joint sets including the columnar joint sets.

Figure 1: Dipping columnar joints are present on the margin of the crinanite complex along Cordeaux No.2 Dam Spillway. Columns in this area are approximately 25cm to 35cm in diameter, these are intersected by various later formed fracture sets.

2 FRACTURE ANALYSIS

Fracturing systems in various igneous bodies are well documented (Waters 1960, Cloos 1922, Price and Cosgrove 1990); fractures encountered in this study have been interpreted from these fracture studies. The relevant emplacement history of planar features including fabric and defect planes can be identified from their cross cutting relationships, orientation, morphology, and mineralisation. The typical division of such features in an intrusive is as follows:

a) **Primary Fabric**: internal flow structures, crystal alignment, lithological variation, emplacement fractures and faulting. Often identified by chill margins and sharp contacts.
b) **Cooling Fractures**: fracture sets which developed as the intrusive cools and shrinks, these include columnar joints in a thin bodied intrusive. Cooling fractures can form as early and late stage events.
c) **Secondary Fractures**: these form after the emplacement and cooling of the intrusive, they are typically related to regional tectonics and can usually be identified by their lack of hydrothermal mineralisation and by cross-cutting earlier formed planar features. Among these are defects that develop due to de-burial unloading and follow the surface exposure of the rock mass. These appear as exfoliation joints which are common features of exposed igneous rocks. As they are load related, they disappear quickly with depth.

Exposures of the Cordeaux Crinanite display the expected defects as described in the following sections.

2.1 Determination of Primary Fabric

Primary fabric is not readily observed in outcrop, however, in core the crinanite is readily divided into a complex of several sub-horizontal sill like bodies of varying thickness. These are distinguished by changes in lithology and by the nature of their contacts. From the study of closely spaced cored holes, Daigle (2006) has defined the following stratigraphy for Cordeaux Crinanite.

Unit 1	Medium to Coarse Grained Crinanite
Unit 2	Fine to Medium Grained Crinanite
Unit 3	Picrite
Unit 4	Picritic Crinanite

(In order of emplacement and position from top to bottom of the intrusive complex).

These individual units distinguished by variation in composition, grain size and chill margins which assist in determining emplacement history.

The contact between Unit 1 and 2 is a thin chill margin indistinct in some holes, or evident only by subtle difference in grain size across the contact zone. Petrographic and geochemical analysis completed indicates that there is little change in the magma composition. Compositional similarity and minor chill margin development suggests rapid intrusion succession.

Unit 3 is a coarse grained picrite (olivine cumulate) its upper and lower contacts are sharp with distinct, thin, chill margins indicating that it intruded the sill complex after substantial chilling of the overlying units. Thin dykes of the picrite intrude the overlying units, supporting the emplacement sequence determined.

Unit 4 is a mixture of coarse grained picrite and crinanite, this thin sill forms the base of the sill complex and varies from having distinct chilled top and bottom contacts to being completely chilled where it is thin.

2.2 Early Formed Cooling Fracture Sets

Tensional forces set up as a magma cools and crystallises can cause jointing. In a homogeneous, thin magma body the joints may develop a characteristic polygonal pattern giving rise to what is termed columnar jointing (Figure 1). Polygonal fracture patterns are identifiable in most outcrops in the study area with smaller columns present towards the complex margins and larger columns predominant towards the centre of the complex.

Size distribution of the columns reflects the thermal dynamics of the body with the margins cooling and crystallising more quickly than the thick central part which cooled slowly and developed much larger diameter columns. Columns formed roughly perpendicular to the contact margins and may plunge back towards the magma source as demonstrated by Waters (1960); this is apparent in outcrop near the Cordeaux Manor. Growth striations are discernible on some columns and represent progressive crack propagation during cooling, these can give an appearance of sub-horizontal layering within individual columns.

The intrusive complex is similar in character to a composite basalt flow, classic subdivision of column architecture into an upper colonnade, entablature and lower colonnade may be possible. The upper colonnade here is represented by the smaller columns (0.25m to 0.5m diameter) on the complex margins and possibly extends as a thin skin over the entire complex, the entablature is represented by the much larger diameter columns (>0.5m diameter) and more massive central core of the complex. The lower colonnade, although not exposed in outcrop, may be represented by the jointing developed in the basal picrite sills and chill margins of the complex. Figure 2 illustrates the conceptual model of columnar architecture.

Nearly all early formed fractures are filled by hydrothermal minerals. Even on the tight columnar joints a thin film of analcime +/- calcite +/- zeolite is present.

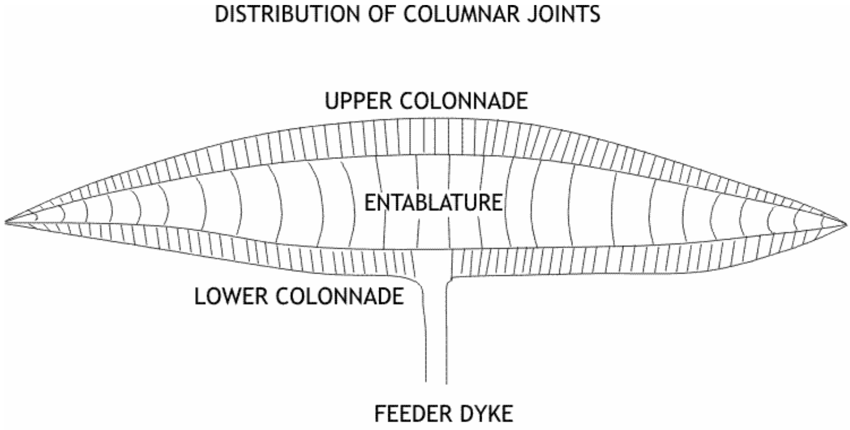
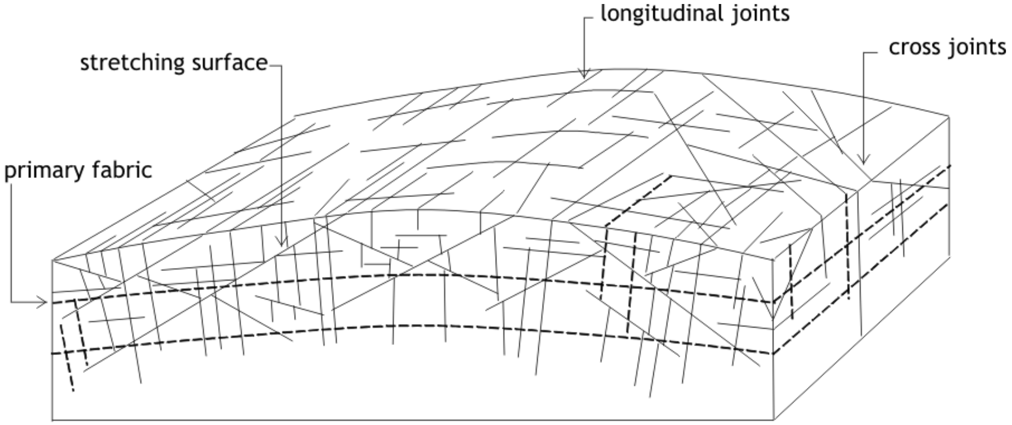


Figure 2: Columnar jointing conceptual model of columnar architecture.

2.3 Late Formed Cooling Fracture Sets

Progressive cooling and resultant shrinking of the Cordeaux Crinanite has resulted in the formation of additional fracturing. These fractures propagate through the entire body and their orientation is influenced by the geometry of the sill complex. Cloos (1922) described the idealised pattern of defects that may develop within an igneous body (Figure 3), ranging from low-moderate dip conjugate sets through to high angle fractures perpendicular to the cooling surface and running longitudinal to the body. These fractures are most commonly filled with hydrothermal minerals (analcime +/- calcite +/- zeolite) deposited as latent heat from the body inducing hydrothermal circulation systems. These fractures cross cut the primary fabrics (sill contacts) and early formed cooling joints (columnar set).

Numerous fractures observed in the core and outcrop are readily identifiable as late cooling fractures. These are particularly notable in outcrop where their cross cutting nature is evident.



IDEALISED FRACTURE DISTRIBUTION IN AN IGNEOUS BODY MODIFIED FROM CLOOS (1922)

Late stage Fracturing:
Related to the thermal dynamics of the intrusion, Hans Cloos (1922) recognised the following fundamental types of primary fracturing:
Cross fracturing, longitudinal fractures, stretching fractures, marginal fissures, and marginal thrusts

Figure 3: Igneous body conceptual model of late stage cooling fractures.

2.4 Regional Tectonic Fracturing

Regional tectonic deformations are well documented in the area, faulting and jointing are the best examples. Within the Cordeaux Crinanite, these defect planes should be present. However, they were not readily determined in the core or in outcrop. These late features are post igneous emplacement and also post date the hydrothermal event associated with the cooling of the sill complex. Thus regional tectonic fabrics should be notable by the absence of hydrothermal mineralisation. The scarcity of observed post emplacement tectonic fractures may be a function of the local structural domain being largely unaffected by regional deformation and insufficient outcrop and boreholes to intersect the features present.

2.5 De-burial Stress Relief Fracturing

Exfoliation jointing is a common feature of outcropping igneous bodies. De-burial due to surface weathering and erosion unload the rock and stress relief manifests as surface parallel joints which form thin layered sheets. These fractures rapidly decrease in frequency with depth, in the cored holes they occur to approximately 15m depth. Price and Cosgrove (1990) provide a good description of exfoliation fracturing. The extent of these joints is limited by the degree of surface erosion (depth of overburden) and topography. Exfoliation joints are observed to cross cut primary and early formed fabrics such as columnar joints and mineral filled fractures. This relationship is illustrated in Figure 1.

3 SUMMARY AND CONCLUSIONS

Fracturing of the intrusive complex is strongly influenced by the shape and dimensions of the body, the relative sill-like layering and moderate thickness of the body has permitted the development of columnar jointing to form as an early cooling feature of the complex. Continued cooling has produced late stage cooling fractures characteristic of most intrusive bodies and associated development of hydrothermal circulation with vein mineralisation. Post emplacement of the complex continued deformation by regional tectonics, has locally produced fault and joint sets in the surrounding country rock and should affect the intrusive by cross cutting the emplacement fabrics, but are these fabrics are less conspicuous due to limited outcrop exposure. Exfoliation joints form the final fractures resulting from erosion and related de-stressing of the rock.

Compilation of the core log data and review of outcrop exposures combined with petrologic relationships permitted the identification of five fracture types within the Cordeaux Crinanite and their emplacement history, these are listed in their order of formation and summarised in Table 1.

Table 1: Fracture Types and Emplacement History within the Cordeaux Crinanite

Primary Fracturing	
1.	**Emplacement Foliation** Fracturing and foliation related to emplacement of the intrusive body. These may include joints and faults in the enclosing strata. Individual sill boundaries defined by chill margins, thin dykes, changed grain size and lithology.
2.	**Early Cooling (Columnar Jointing)** Begin to form as the melts congeal and cool, their size distribution and orientation are affected by proximity to intrusive body margins and geometry.
3.	**Late Cooling Fracturing** Influence of regional stresses, intrusive body geometry and thermal dynamics result in fracturing characterised by hydrothermal veining. Major fracture sets include cross fracturing, longitudinal fractures, stretching fractures, marginal fissures and marginal thrusts.
Secondary Fracturing	
4.	**Regional Stresses (Tectonic)** Regional jointing and faulting related to post emplacement tectonics.
5.	**De-burial Stress Relief (Exfoliation)** Surface parallel fracturing related to de-burial, cross cuts primary fracture sets and forms thin sheets. These fractures are restricted to near surface of the outcrop and frequency decreases with depth.

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