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Recracking of jointed rock masses in the Sydney Basin, New South Wales, Australia

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Abstract

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Keywords

Joint, faulted joint, recracking, secondary joint, Sydney Basin

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Recracking of jointed rock masses in the Sydney Basin, New South Wales, Australia

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ABSTRACT: Fracture mapping of Late Permian – Early Triassic flat-lying sedimentary rocks in the Sydney Basin, New South Wales, Australia, shows that joints developed originally in extension were faulted in subsequent events. Joints with a regional distribution fall into two, early and late formed groups. Group I joints propagated horizontally and never interfered with each other. These joints were subsequently reworked or recracked. Recracking commenced with jointing and continued with lateral slip. Faulted joints grew horizontally by linking of recracked segments. En echelon arrays are the result of vertical propagation of faulted joints into intact rock. Recracking of rock also resulted in the formation of sets of secondary joints (Group II). The sense of movement on conjugate faulted joints and orientation of sets of secondary joints, are related to three compressional stress fields. The intensity of recracking and the amount of lateral slip is mostly related to the strength of infilling materials, the length and continuity of parent joint, the angle between the existing fractures and the maximum compression direction, and the number of compressional events imposed on the fracture.

Key words: Joint, faulted joint, recracking, secondary joint, Sydney Basin.

1. INTRODUCTION

In recent years many advances have been made in the understanding of the origin and development of fracture patterns in weakly deformed strata [1, 2, 3, 4]. Furthermore, the principles of linear elastic fracture mechanics have provided a new understanding of fracture propagation and interaction [2, 5, 6]. These studies have shown how joints mainly form from mode I failure with effective tensile stress occurring at the tip of the joint and that once a joint set is formed it may subsequently interact with a new set of joints [7, 8, 9, 10,11]. Recracking (reactivation or reopening) of pre-existing fractures can occur when a second rupture follows a pre-existing fracture, either by propagating through the cement or by following the cement - intact rock boundary (also called intermittent growth [12]). Slip on pre-existing fractures has been reported from various geological settings [13, 14, 15, 16].

The area studied consists of coastal rock platforms and adjoining cliffs, located between Wollongong and Coalcliff, on the south coast of New South Wales, Australia (Fig. 1). These flat lying strata form part of the Late

Permian Illawarra Coal Measures and the overlying Early Triassic Narrabeen Group. They are shallow-marine to fluvial rocks consisting of mainly of sandstone, mudstone, coal and conglomerate. Joints, faulted joints, widely-spaced dykes, normal faults and monoclines are the main structures in these rocks. Fractures were studied by detailed mapping of 30 outcrops, and 5160 m of scanline surveys.

Three sets of early formed, vertical joints, striking 010°, 043° and 128° (Group I), developed in the study area. Plumose surface markings indicate that these joint sets formed as pure opening mode fractures or joints. Sets of laterally-slipped fractures and secondary joints (Group II) were mapped throughout the study area. We argue that interactions between sets of the early formed joints of Group I were minimal and that several late-stage recracking events are responsible for the reactivation of these joints and formation of relatively shorter secondary joints. We review this model in the light of joint interactions recognised in other regions such as Arches National Park in Utah [6, 11, 15, 16, 17] and the Appalachian Plateau [9, 10, 16, 17]. This paper is concerned with the nature of reactivated joints and episodes of reactivation as well as the stress fields responsible for reactivation.

2. FRACTURE PATTERN

A detailed analysis of joints in a wave cut platform at Coalcliff (platform 2) was carried out. The outcrop consists of homogeneous medium-coarse lithic sandstone with pebbly bands and minor mudstone as well as ironstone bands (Fig. 2). Regional fractures are vertical and are usually straight. They form two sets: (a) NNE joints striking 005°-015° with a mean direction of 013°, and (b) NE joints striking between 035° and 050°, with a mean direction of 046° (Fig. 2). The apertures of individual fractures range from 2 to 20 mm, and fracture lengths range from 1 m to approximately 100 m. Each fracture is composed of segments 1-20 m long. Segments are parallel with the overall trend of the fractures and are mostly planar. The average spacing, in 1-3 m thick sandstone beds, is about 2-8 m. Spacing changes are locally due to differences in rock type and bed thickness. In some thin ironstone bands the spacing is 20 mm or less. The vertical dimension of fractures is much less than their horizontal extent.

At platform 1, some lateral movement can be mapped along the NNE and NE fractures. Lateral movement is dextral for NNE and sinistral for NE striking fractures. In this outcrop, NNE and NE striking joints, with a dihedral angle of 33°, are not conjugate shear fractures, as they show no sign of original shear traction and displacement. Surface markings characterized by simple, elliptical plumose structure on their surfaces support an origin by Mode I failure. In this outcrop, joints were recracked and slipped laterally in subsequent events to produce faulted joints. Original joints are dilated and filled with undeformed calcite. Recracking is more frequent in the NE set. Lateral movements along faulted joints are small and generally have accommodated less than a few millimetres of slip. No vertical slip occurs on these joints. The typical aperture of a faulted joint is less than 10 mm. These fractures have grown by the amalgamation of recracked segments. No slickenlines were observed on fracture walls. This is mainly because of the small displacements, and partly due to subsequent weathering and erosion. Erosion has exploited joints that were recracked and increased the widths of the faulted joints to more than 300 mm.

Strike-slip movements along the faulted joints at platform 2, were measured where they displace markers, such as older joints. Short disconnected segments, a few meters long, have small displacements, as small as 1 mm as determined by field inspection with a hand lens. Longer faulted joints, a few tens of meters, have displacements in the range 20-30 mm. Thus the amount of displacement is proportional to the length and continuity of a faulted joint. Similar lateral displacements occur along joints, normal faults and dykes, throughout the study area (see below).

3. RECRACKING OF PRE-EXISTING JOINTS

A set or sets of suitably oriented fractures represent a significant anisotropy that can potentially control nucleation and growth of faults [13]. In flat lying sedimentary sequences, the recracking propagation can be both horizontal and vertical.

Horizontal recracking

Recracking normally took place along pre-existing mineralized and closed joints (Fig. 2). In the study area, recracked fractures have lengthened horizontally by connecting segments of the parent joints. The lengthening process occurred when; disconnected short segments linked and formed long, continuous, open fractures. This process has increased the horizontal extent of the parent joint (Fig. 2). Where two joint sets previously intersected each other, the horizontally propagating recracking front along one joint set may have deflected at an intersection and followed the other joint set.

When the recracking front reached the end of the pre-existing joint it either terminated or continued to grow in-plane or out-of-plane of the parent joint. In many cases the fracture has either tilted or twisted from the parent joint orientation to a new direction that is parallel to σ_1 [e.g. see 18, 19]. Further horizontal or vertical propagation of a fracture into the intact rock developed the wide range of secondary joints seen on the rock platforms (see below).

Vertical recracking

Fractures that originally propagated in sandstone terminated when they encountered mudstone or claystone beds. During reactivation, when the fracture front in a sandstone bed reached a contact with a much thinner interbed of mudstone, it often penetrated the mudstone bed, and continued into the overlying or underlying sandstones. In the vertical direction and at the edge of a pre-existing joint, the propagating front may have done one of the following: (1) terminated, (2) proceeded as a planar fracture through intact rock, and (3) formed an array of short (few cm) en echelon joints (see below).

The major parameters that control joint propagation across interfaces are strength of the interface, geometric and material properties of the layers on the either side of the interface and loading [20]. A strong contact between two similar layers will not fail, and the recracking front will continue across the contact without any change in direction. A weaker contact will fail and the propagating front has either terminated or stepped.

4. FORMATION OF SECONDARY JOINTS

Shear along existing joints resulted in a new group of fractures, that developed at the tip, along the sides, or in between pre-existing joints. These dilatant fractures (mode I) are called secondary fractures [13], splay cracks [14], and pinnate or feather joints [21], and formed as a result of small slips along faulted joints. In plan view, the traces of these fractures are straight or curved, and compared to the parent joints; they are short (50 mm to 2 m). They are subvertical, and strike 020°-030° at platform 2 (Fig. 2).

Several types of secondary joints have been recognised in association with recracking, among them are those that form at the termination points or along the sides of the pre-existing fractures. Secondary joints develop either by horizontal or vertical growth of the parent joint and normally indicate the direction of maximum horizontal compression (Fig. 3).

Horizontally grown secondary cracks

One of the most common types of secondary joints are those that form at the termination points of faulted joints in response to shearing along them. These fractures are either straight, and bend abruptly from the termination point, or are curved and sometimes branched and resemble the hairs in a horse-tail (e.g. Figs 3, 4). Horse-tail fractures always grow out of the plane of the host fracture. Their clockwise or counter-clockwise bending indicates the sense of shearing and the direction of maximum tension [11, 13]. Horse-tail fractures represent the location where the slip terminates along the host fracture and the direction of minimum compression [22].

Short fractures can occur anywhere along the length of a faulted joint (Fig. 4). These fractures occur on either side of the parent joint, but normally do not cross it. Some of the secondary joints are wedged open due to slip on the host faulted joint, with the width of opening decreasing away from the parent faulted joints. Secondary joints are more frequent near the end of each sheared segment, or near the termination points of a faulted joint (Fig. 4). Where the spacing between two parent fractures is relatively small, the secondary joints, which have initiated from one fracture, terminate against the second one and form an en echelon pattern. These short secondary joints are more frequent at the area of two overlapping segments of a faulted joint (Fig. 4). The presence of pinnate joints branching from both unfaulted and faulted parts of host fracture suggests that some pinnate joints develop prior to fault slip rather than as a direct consequence of fault slip. The cause of this pre-slip development could be pre-fault stress accumulation in the wall rock, thus suggesting that pinnate joints may also serve as precursors to slip [11].

In a horizontally propagating front, the fracture tip tilts uniformly about an axis in the fracture plane but normal to the direction of propagation [18]. All horizontally propagating secondary cracks occur in the extensional quadrants of a faulted segment (Fig. 4). These two quadrants undergo net dilation during slip on small faults [13]. Repeated movements at different locking points lead to the formation of secondary cracks on both sides of the faulted joint [21]. This also happens when compressional events of different orientations developed differently oriented sets of secondary joints (see below).

Vertically grown secondary cracks

Some of the reactivated joints show an array of small en echelon cracks at their termination points. These cracks also form along the length or beside other fractures. En echelon cracks are different from horse-tail fractures in that they are not connected with the host fracture in plan view (e.g. Fig. 3). Instead, these en echelon fractures form above the upper edge of a parent fracture that has terminated at a layer interface. These features likely formed when an existing joint was reactivated under a combination of mode I and mode III deformation. Instead of twisting as a unit, it subdivided into en echelon secondary joints by rotating about vertical axes in the fracture plane [1, 6, 18, 23].

Interactive secondary crack

There are other secondary joints that abut against a nearby fracture with a 90° angle (e.g. Fig. 3b). The recracking front propagated out-of-plane of the parent joint when it reached the proximity of a nearby open fracture, and abutted against it at a normal angle. The curving perpendicular geometry is the result of the interaction of the recracking front with a nearby through-going free surface [6, 24]. When a recracking front grows towards an already opened fracture, the stress field systematically rotates and changes due to the presence of the open joint [25]. At the free surface, one of the principal stresses is perpendicular to the fracture face and its magnitude is zero. As these sigmoidal patterns developed due to the rotation of σ_1 near a free surface of any orientation, they are not indicators of far-field stress, nor can they be used to infer the sense of displacement along a faulted joint.

5. EPISODES OF RECRACKING

Following lithification of the sediments of the Illawarra Coal Measures and the Narrabeen Group, several sets of extension joints (Group I) were formed and sealed with minerals [26]. Later in the history of the basin, the development of new stress field enabled resolved shear stresses on properly oriented pre-existing joints to result in recracking and lateral slip. Mode I secondary joints (Group II) were formed during this time and initiated at roughness elements and irregularities along a faulted joint [see 6, 22]. Both faulted joints and secondary joints may have been sealed with calcite, but only faulted joints show more than one episode of infilling. From the orientation of 430 secondary fractures measured in different rock units of the study area three main sets are recognised, and each represents a distinct episode of compressional deformation (Fig. 5).

NNE-SSW compressional event

At platform 2, the compression that acted from the NNE was responsible for the formation of secondary joints that have a mean orientation of 027° (Fig. 2). Evidence for this compressional event has been recognised throughout the study area, although its orientation changes slightly due to local changes in rock type. Pre-existing N-NNE and NE fractures have been reactivated by this compressional event. Dextral movements along N-NNE joints, earlier formed normal faults and dykes and sinistral slip along NE fractures are all related to this event. SE joints, dykes and normal faults are least affected by this deformation as they occur approximately at right angles to the compression direction. The mean orientation of NNE secondary cracks measured between platform 2 and platform 22, is 024° (Fig. 5) and is regarded as the mean orientation of σ_1 for this event.

E-W compressional event

A well defined set of 85-105° striking secondary joints (mean 097°) is developed in most parts of the study area

(Fig. 5). E-W compression caused sinistral shear on SE fractures as well as dextral shear on NE oriented fractures. This compression had almost no effect on N-NNE oriented fractures because the compression direction was almost at right angles to these fractures. At platform 2, recracking is more frequent along NE fractures (Fig. 2) and probably resulted from the effect of major NNE-SSW as well as E-W compression, while this is not the case for NNE joints, which were sub-normal to the E-W compression and only affected by NNE compression.

SSE-NNW compressional event

The third set of secondary joints has a mean orientation of 163° (Fig. 5). These fractures are the least important, both in size and number. The compressional event responsible for the formation of these fractures caused sinistral shear along N-NNE and NE fractures as well as a dextral shear along SE fractures.

6. RELATIVE AGE OF COMPRESIONAL EVENTS

The principal criteria for determining the sequence of fracturing are abutting and overprinting relationships and the offset of one structure by another [21]. Recracking of, and slippage along, Group I regional joints, dykes and normal faults indicates that these compressional events were the youngest group of deformational events in this part of the Sydney Basin [26]. Overprinting relations (see below) suggest that the NNE-SSW compression predated the E-W compression, but the relative age of the SSE-NNW compressional event to these is unknown.

At Wombarra (Fig. 6a) the 095°-100° secondary joints developed along the sides and in between NE fractures. The NE fractures show sinistral displacement with the NNE secondary joints developed at the ends of and in between them. This pattern suggests that the 040° joints had already opened, and slipped due to the NNE compressional event, and therefore predated the E-W compression that formed the 095°-100° secondary joints.

In another example (Fig. 7a), 090° secondary cracks cut 040° joints without any lateral displacement, but sinistral displacement along the same 040° joint has displaced a Group I fracture striking 115°. Sinistral slip of the 040° fracture is related to the NNE compression. This configuration suggests that at this locality the NNE compression, which was responsible for the sinistral slip along the 040° fracture, was active earlier than the E-W compression, which formed the 090° secondary cracks. Elsewhere (Fig. 7b), sinistral slip of a 140° fracture has displaced two parallel 015° secondary joints. E-W compression is responsible for this sinistral movement, while the 015° cracks are the product of NNE compression. Similar overprinting relations have been found at Austinmer and it is concluded that the NNE compression was older than the E-W one.

Throughout the study area, the 090°-100° secondary joints are most frequently developed along the NE fractures and less frequently along the SE fractures. The dihedral angle between the E-W compression direction and the SE joints is about 30°, which is less than the 45° dihedral angle it makes with the NE joints. From Mohr-Coulomb fracture criterion [11], it is anticipated that fracturing is more likely to occur on the SE joint set rather than as observed on the NE joint set. Our explanation for this, is that the NE fracture set was recracked during the earlier NNE compression event resulting in the development of open and weaker NE fractures that were therefore more susceptible to additional recracking and secondary joint development during the E-W compression. Whereas the SE joints were not affected by the earlier NNE compression and were therefore still intact and stronger when affected by the later E-W compression event and therefore show less evidence of recracking and secondary joint development despite the more favourable dihedral angle between the joint set and the E-W compression direction.

In most cases, the sense of displacement inferred from the orientation of secondary joints is confirmed by the slip measured along fractures. Contradictions occur locally, where one member of a fracture set shows sinistral movement and another dextral slip (e.g. Fig. 8). In other examples, the sense of displacement along fractures is the opposite to that inferred from the orientation of secondary joints. Frequently, more than one set of secondary cracks occur along the sides of a parent fracture and sometimes form a feather-shaped pattern at ends of faulted joints (see examples in Fig. 6 b, c, d).

In all of these examples, a single event cannot explain the formation of two differently oriented sets of secondary cracks. Opposite senses of strike-slip displacement along faulted joints of the same set have also been reported from the Garden Area of Arches National Park, Utah where this configuration is related to inhomogeneous deformation [6].

7. JOINTING AND RECRACKING PROCESSES

Joint propagation and interaction with pre-existing fractures has been well illustrated in Arches National Park of Utah ([5, 6] and in the Appalachian Plateau [9]. These studies have shown that a regional set of long joints is frequently reworked during the formation of a younger set of regional joints under a new or rotating stress field. A requirement for this process is that joints remain as open fractures and would therefore control the near-field principal stress directions. Younger joints change direction as they approach an open joint so that they veer into parallelism with the older joint surface or hook so that they intersect the older joint at right angles. In the southeastern Sydney Basin, in contrast to these regions, joint reworking during the progressive development of early formed Group I joints has not been recognised and it was quite late in the history of the region where compressional events initiated a wide variety of interactions (see below).

Mode of fracturing

At platform 2 (Fig. 2), two sets of 010° and 045° joints were formed separately with no original interaction. These joints were reactivated in shear during the subsequent compressive event. The sense of slip along these fractures and the direction of secondary cracks indicate that the direction of regional compression was contained within the dihedral angle during this second event. Pre-existing fractures formed planes of weaknesses in the rock mass. The fracture toughness is considered less than the tensile strength of intact rock, because rather than forming a new set of joints in intact rock, the later episode of deformation has almost universally resulted in slip along pre-existing fractures.

Comparison between the directions of the compressional events and the strike of recracked sets showed that pre-existing joints at 10°-30° angles to the compression direction have been most frequently recracked. Where the angle between two sets of fractures was between 60° and 90°, each set was recracked by a separate compressional event with σ_1 at a 10°-30° angle to the recracked set (e.g. Fig. 9). It should be noted that an already recracked set could be reactivated by a subsequent compression even if the acute angle between the contemporary compression and the pre-existing faulted joint was more than the 30° limit for closed fractures.

Sequence of deformation

Different parts of a faulted joint were not fractured simultaneously, nor were different fractures of a set or members of interfering systems formed at the same time (e.g. Fig. 10). Secondary joints propagate from or abut against pre-existing fractures. In some places, a group of secondary fractures have been mapped which cut through neighbouring fractures without any interaction (Fig. 11). Through-going secondary cracks have only formed when the pre-existing fractures were closed.

Traces of faulted joints are segmented and segments are fractured sequentially. Segments form with an alternate sequence of fracturing of different segments in the same group of closely spaced joints. Segments of one fracture, or two fracture sets, interfered with each other when a recracking joint approached an already opened fracture. As a result of recracking, a network of connected open segments developed in rock which accommodates lateral slip along faulted joints [2, 4, 10, 11]. These observations on faulted joints are almost identical with those that have been reported for strike-slip faults developed in sandstone [15] and strike-slip faults formed during the laboratory tests on clay models [27].

Recracking and stress field

Each joint set developed in rock, represents a unique stress field [18, 25]. In some outcrops the fracture pattern consists of two or more regional joint sets. Consequently, it is expected that each new, differently oriented, stress field may cause shear stresses on pre-existing fractures. Two extension joint sets mapped at platform 2 (Fig. 2), or similar sets mapped in the other parts of the study area, have not interfered with each other.

Group I regional joint sets of the study area are mineralised so that the fractures have been healed and no longer act as major planes of weakness controlling near field principal stress orientations. On the other hand, where the effective normal stress on an existing joint is sufficiently compressive, a propagating joint will cross through the earlier formed joint as if the rock was intact [2, 9, 28]. Such cross cutting of the later set takes place at a depth where there is a significant traction across the surfaces of the earlier systematic joints.

Joints can form under a relatively small differential stress [18, 29] and thus during the formation of a new set of Group I regional joints, differential stress was too low to overcome the strength of infillings of existing joints. In the late compressional events, responsible for the reactivation of the Group I joints, the stress difference was high enough to overcome the strength of fracture infillings. It can be argued that the fracture toughness was less than the tensile strength of the intact rock, and so the pre-existing fractures were capable of recracking and nucleating faults. Finally, the role of pore water pressure, which was significant during the burial and formation of Group I regional joints, was probably less important during the more recent compressional events.

Change of the stress field can occur by two processes. First, the regional stress fields can change orientation over time, as was the case for Alleghanian Plateau tectonics [9], and southeastern Sydney Basin [26]. Second, jointed beds can rotate within a regional stress field that remains fixed in orientation [11]. Regional change in horizontal stress orientation, was clockwise during the Alleghanian Orogeny [9], but has not been identified for the southeastern part of the Sydney Basin, due to the lack of regional studies.

Repeated recracking of Group I joints produced faulted joints as well as secondary joints (Group II joints). Secondary joints have been found to be systematic across a geological province, such as the Appalachian Plateau detachment sheet, to the extent that they are found to be useful as a tool for unravelling the tectonic history of the region [9]. Group II joints of the study area serve as effective kinematic indicators. The observed less than 18° angle between secondary (pinnate) joints and host NNE or NE oriented faulted fractures is considerably less than the conventional 30°-35° angle between σ_1 and isolated primary fault planes predicted by Coulomb fracture criterion [11].

8. ORIGIN OF COMPRESSIONAL STRESS

Because systematic joints align parallel to the trend of the maximum horizontal stress (σ_1), late-formed joints are reported to be aligned with the regional trend of the contemporary tectonic stress (modern-day S_H), and are thus used for mapping the orientation of neotectonic stress field [4, 13, 17, 29].

Group I joints as well as faults and their associated joints have been affected by the recracking episodes [26]. This evidence suggests that these episodes occurred quite late in the geological history, possibly as young as post-early Tertiary time [26]. We previously indicated that the NNE-SSW and E-W compressional recracking events may have reflected variation of *in situ* stress orientation [26] as determined from overcoring, hydraulic fracturing and earthquakes [31]. More recent analyses of *in situ* stress in Australia have found that the Sydney Basin, in contrast to other parts of eastern Australia, has a complicated pattern of stress with local sources considered necessary to explain the variation in stress [32, 33, 34].

In northeastern Australia, the principal compressional stress direction is NNE and thought to reflect plate-boundary forces associated with subduction along the Solomons and New Hebrides subduction zone [34]. In southeastern Australia, especially along the southern margin, the principal compressional direction is NW-SE and has been related to plate-boundary forces associated with oblique convergence in the South Island of New Zealand and more orthogonal convergence along the subduction zone south of New Zealand [34, 35]. An east-west orientation of principal compressional stress has been recognised in central Australia and has been considered the orientation of the main stress trajectories for the Sydney Basin region and related to the plate-boundary forces associated with the Tonga-Kermedec subduction zone to the east of Australia and north of New Zealand [34, 35].

Although the late Tertiary to Recent age of the recracking episodes in the southeastern Sydney Basin cannot, as yet, be conclusively demonstrated from radiometric dating of igneous rocks affected by the recracking episodes, our preference has been that these events are late [26] and are possibly neotectonic. It has been increasingly recognised that the relatively high levels of intraplate seismicity in southeastern Australia and associated widespread evidence for tectonic deformation in some regions, such as the Mt Lofty and Flinders Ranges of South Australia and the southern margin and eastern highlands of Victoria, are indicative of high rates of compressional deformation anomalous for the intraplate setting of southeastern Australia [35].

We consider that the E-W and NNE-SSW compressional episodes of the southeastern Sydney Basin, if they are related to the modern stress field, may also be related to plate-boundary forces with the former associated with the Tonga-Kermedec subduction zone to the east and the latter reflecting the Solomons and New Hebrides subduction zone to the northeast. In this case the local variation of *in situ* stress in the Sydney Basin is considered a reflection of interacting far-field plate-boundary forces rather than local controls, such as local escarpments [e.g. 32], on *in situ* stress directions [cf. 34, 35].

9. CONCLUSIONS

In the Late Permian - Early Triassic strata of the southeastern Sydney Basin, joints formed by mode I failure and faulted joints are parallel with each other. Early formed Group I joints do not interfere with each other. These joints are dilated and filled with undeformed calcite, by comparison the subsequently formed faulted joints are mostly opened, with evidence of lateral slip. Secondary joints developed primarily as a result of shearing along recracked joints. These fractures are systematic and form sets of relatively short dilatant joints. Secondary joints form at the end, along the sides and in between faulted joints or cut through closed joints. They normally show no sign of subsequent shearing. The faulted joints grew horizontally by the connection of recracked segments with secondary cracks.

The recracking and lateral displacements across the study area are related to three separate deformation events with σ_1 oriented 024°, 097° and 163° respectively. Each of these events was responsible for recracking and lateral slip along suitably oriented pre-existing fractures and for the formation of one set of secondary joints parallel to the prevailing σ_1 direction. The consistent direction of secondary joints indicates that the far-field stress field was roughly uniform for each episode of compression in this part of the basin.

The intensity of recracking and the amount of lateral slip is believed to be related to the strength of infilling materials, the length and continuity of parent joint, the angle between the existing fractures and the maximum compression direction, and the number of compressional events imposed on the fracture.

During each event, the pre-existing sealed fractures that formed 10°-30° angles with prevailing σ_1, have been recracked with lateral slip along their strike. An already recracked joint has commonly been subsequently reactivated by a different σ_1 in a different orientation. The result of the alternating reactivation of interfering set(s) is a network of connected recracked segments that have accommodated shear displacement caused by changes in the orientation of σ_1.

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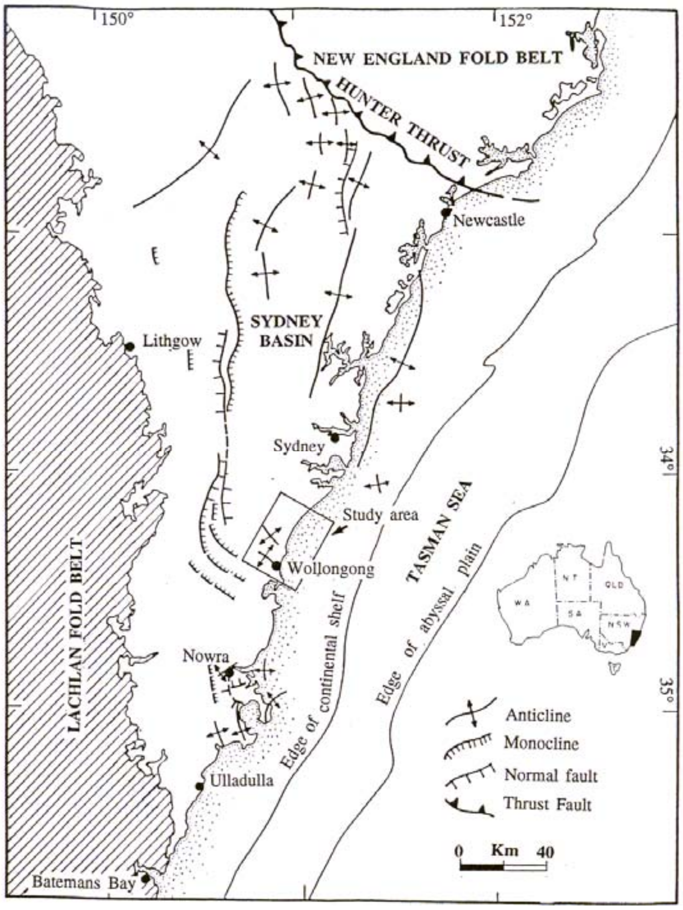

150°
152°
NEW ENGLAND FOLD BELT
HUNTER THRUST
Newcastle
SYDNEY BASIN
Lithgow
Sydney
34°
Study area
Wollongong
TASMAN SEA
LACHLAN FOLD BELT
Edge of continental shelf
Edge of abyssal plain
Nowra
35°
Ulladulla
Batemans Bay
WA
NT
QLD
SA
NSW
Anticline
Monocline
Normal fault
Thrust Fault
0 Km 40

Fig. 1 (a)

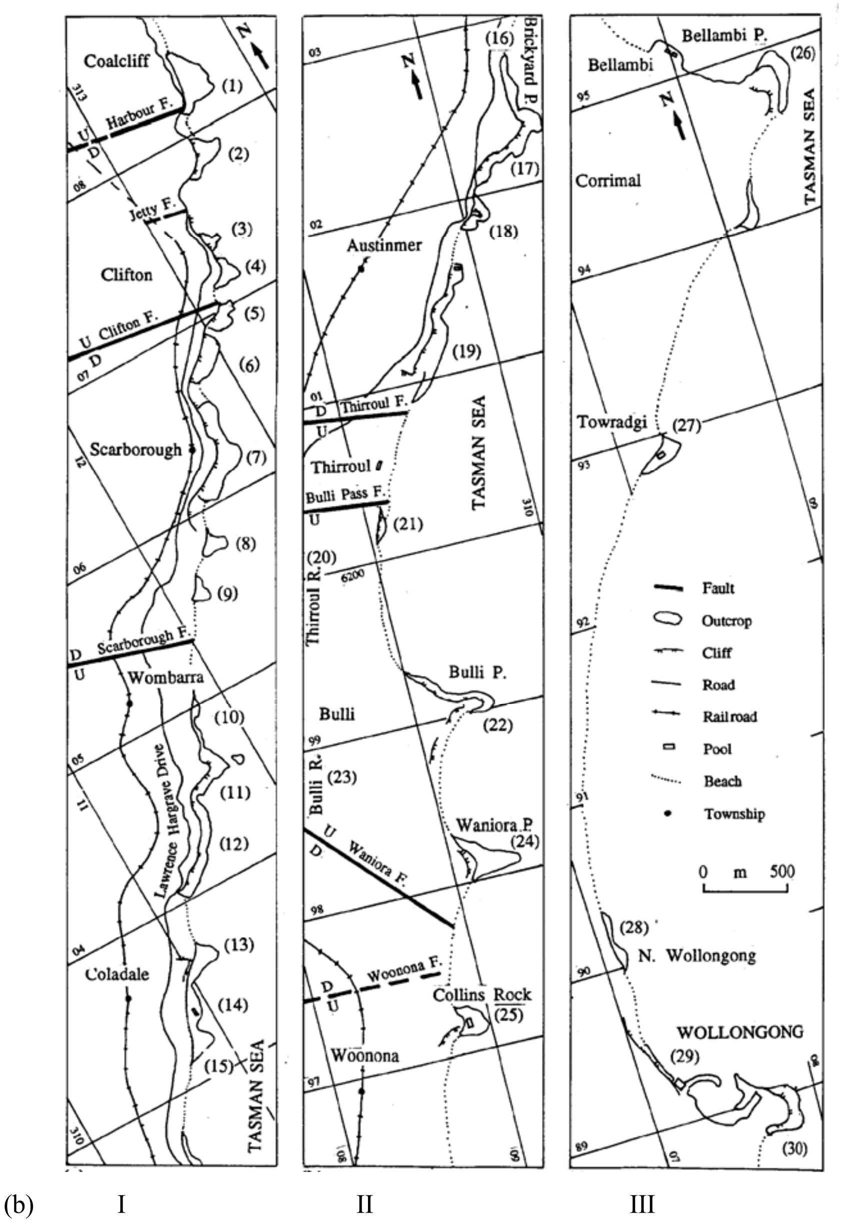


Fig. 1. (a) Location of the study area in the Sydney Basin, Australia [from 26]. (b) Location map of the studied outcrops. Northern (I), central (II) and southern (III).

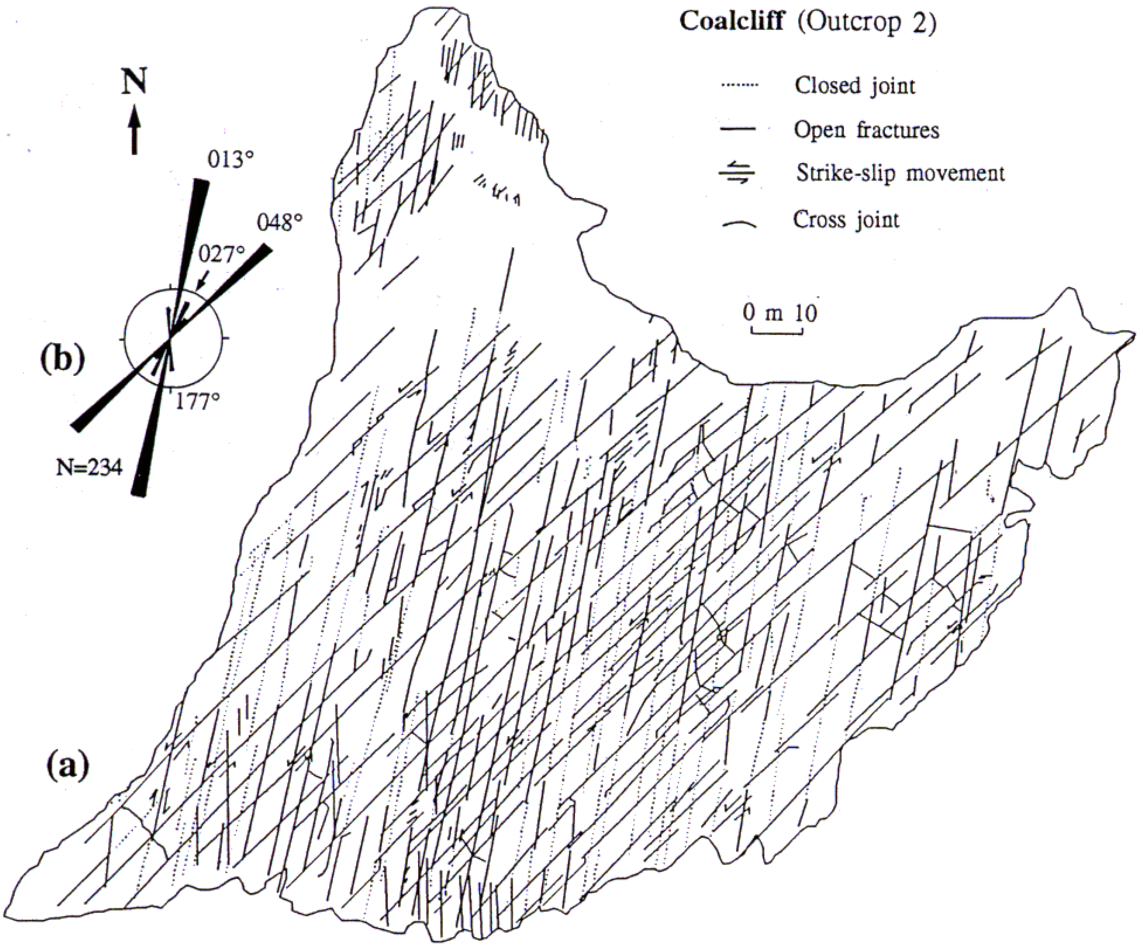


Fig. 2. (a) Fracture pattern of Coal Cliff Sandstone at platform 2, NSW. (b) Rose diagram of 234 fractures in this platform. [From 26.]

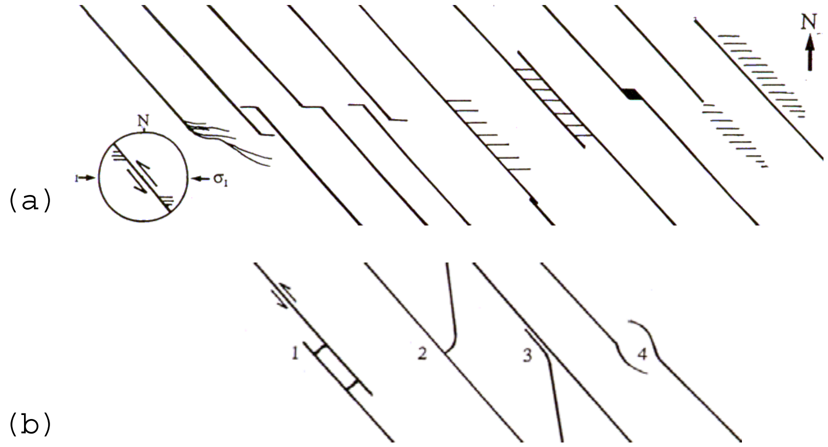


Fig. 3. Classification of secondary cracks in the study area. (a) Secondary cracks which indicate the orientation of far-field stress and the sense of slip along the faulted joints. Circular inset indicates the E-W direction of far-field compressive stress, responsible for the sinistral shearing and formation of secondary cracks. (b) Secondary fractures which form due to the local reorientation of stress field: bridge fractures (cross joints, 1), curving perpendicular (2) and curving parallel (3) fractures, and interaction between two segments of a same fracture propagating towards each other (veers in the sense of Cruikshank *et al.,* 1991) (4). [From 26.]

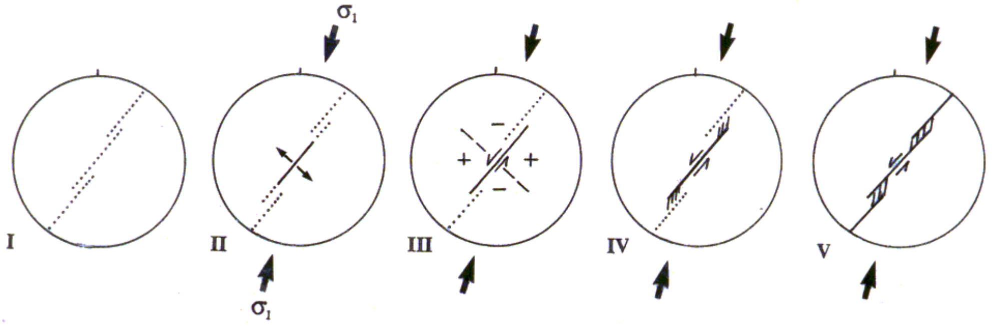
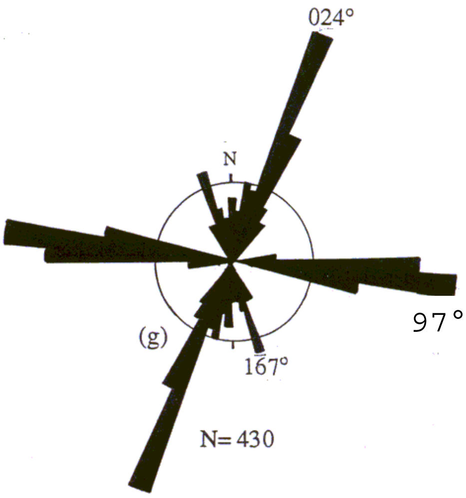


Fig. 4. Recracking and horizontal enlargement of a segmented NE joint (I). Due to a NNE horizontal compression one segment started to recrack (II), and slipped (III). Secondary cracks developed at the dialational quadrants of the faulted segment (III) and (IV). The next segments recracked and linked by secondary cracks and bridge fractures (V).

Fig. 5. Rose diagram (5° intervals) with the orientation of 430 secondary cracks in the Illawarra Coal Measures and lower Narrabeen Group, between Platform 1 and 22. [From 26.]



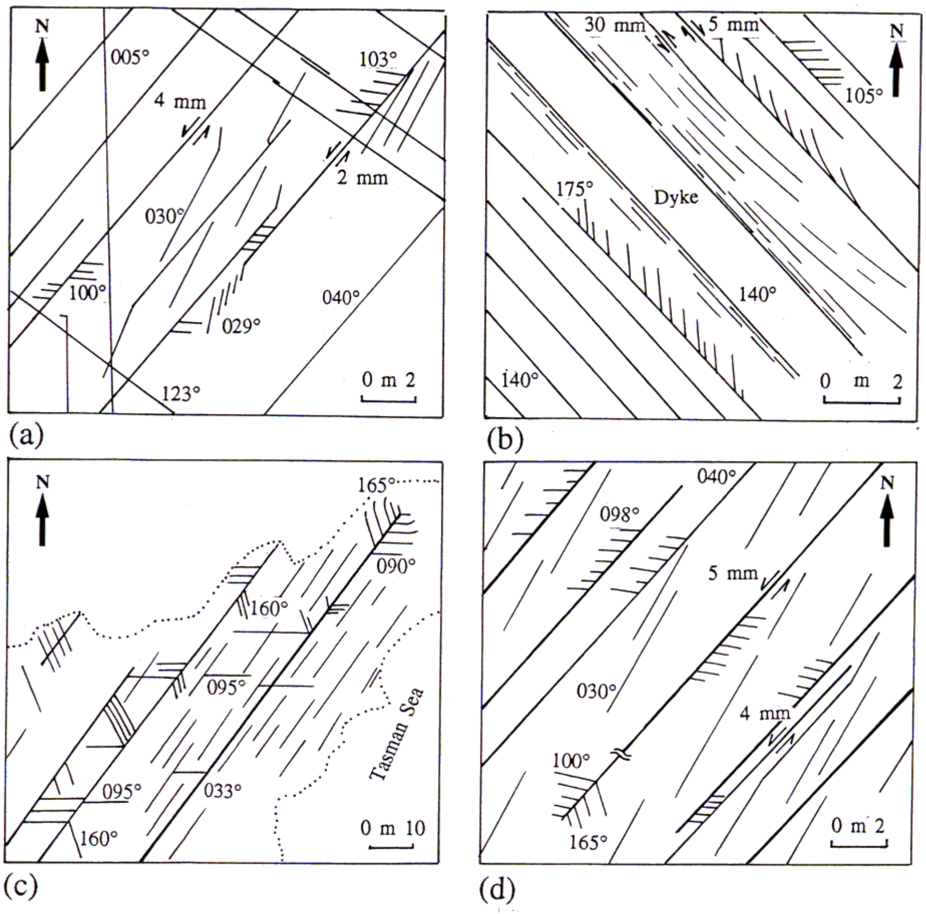


Fig. 6. Development of multiple sets of secondary cracks along faulted joints. (a) NNE and E-W oriented secondary cracks formed along a set of NE faulted joint (Wombarra). [From 26.] (b) 160-180° as well as 090° secondary fractures formed along adjacent joints of a 140° striking dyke at Austinmer, and NE oriented joints at Scarborough (c), and Wombarra (d). Feather patterns formed by two sets of 090° and 160° secondary cracks near the termination points of some faulted joints (c, d).

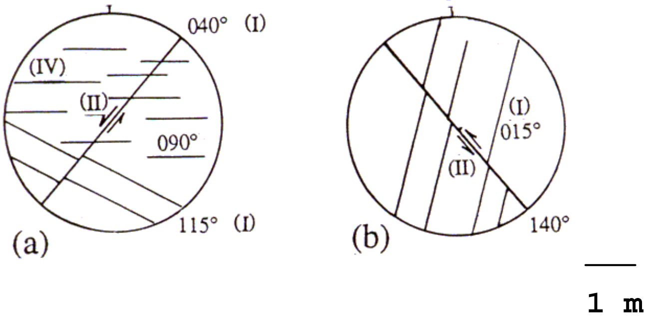


Fig. 7. Sequence of deformation events at Wombarra. (a) Formation of 040° and 115° fractures (I), sinistral displacement of 040° fracture due to the NNE-SSW compression (II), healing of the NE fracture (III), formation of through-going 090° secondary cracks due to the E-W compression (IV). (b) Formation of 015° secondary fractures due to NNE-SSW compression (I), sinistral displacement of 140° fracture due to E-W compression (II).

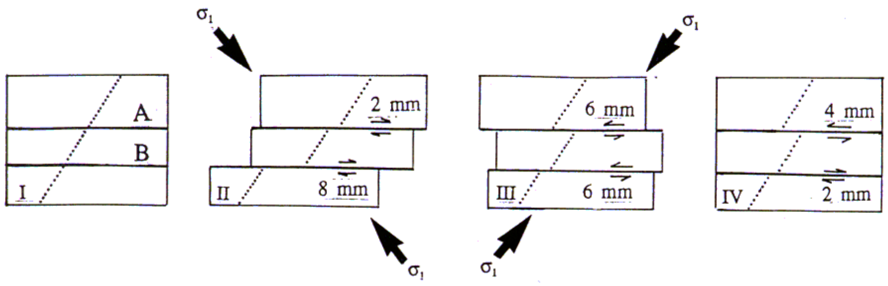


Fig. 8. Model for development of opposite senses of lateral slip in two neighbouring, NNE striking, faulted joints at Coledale. In the first deformation, dextral slip along two fractures, A and B (I), has been for 2 and 8 mm respectively (II). The difference in lateral slip is mostly due to the different lengths of faulted segments and the variation in strength of infilling materials. In a subsequent event, both fractures have been slipped sinistrally along their strike for 6 mm (III). The outcome has caused an overall different sense of displacement for A and B, which is therefore attributed to 2 deformations (IV).

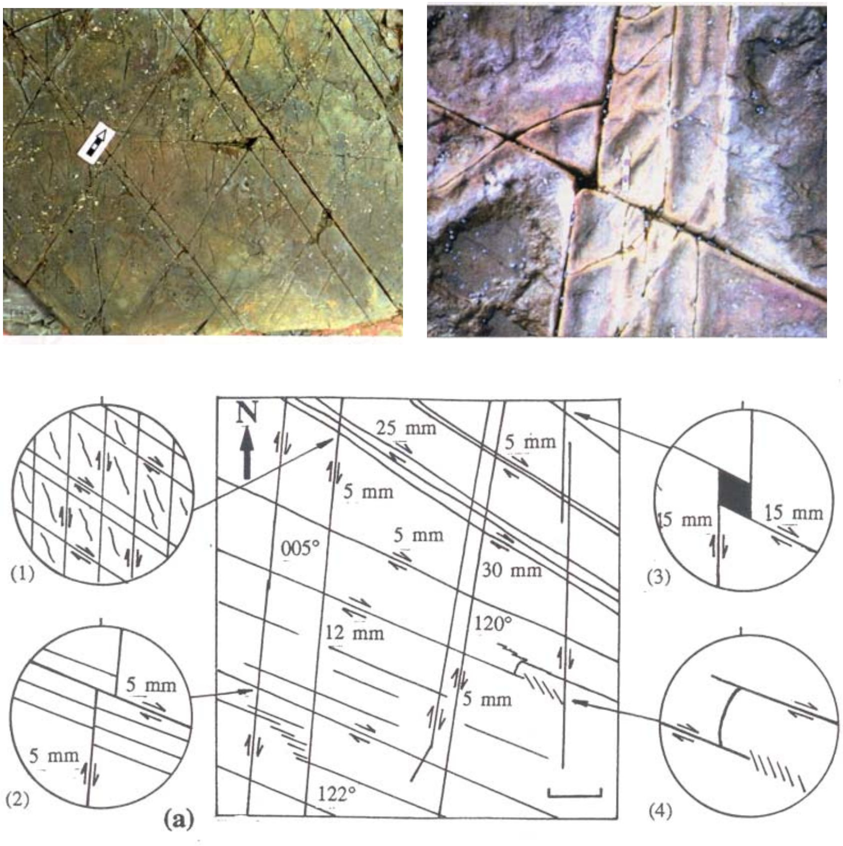


Fig. 9. Fracture map demonstrating the relation between secondary cracks and lateral displacement in laminated siltstone and fine-grained sandstone of the Wilton Formation at Austinmer. Short, slightly curved, 160° striking secondary cracks (insets 1 and 4) represent the direction of SSE compression which was responsible for the dextral slip along the 120° joints at this locality. At Austinmer dextral slip on 000-005° fractures is due to the NNE compression. The amount of lateral slips ranges between 0 and 30 mm. Small rhombohedric cavities are the results of dextral slip on both sets (inset 3). Inset 2 suggests that the slip along the NNE joints was prior to slip along SE fractures.

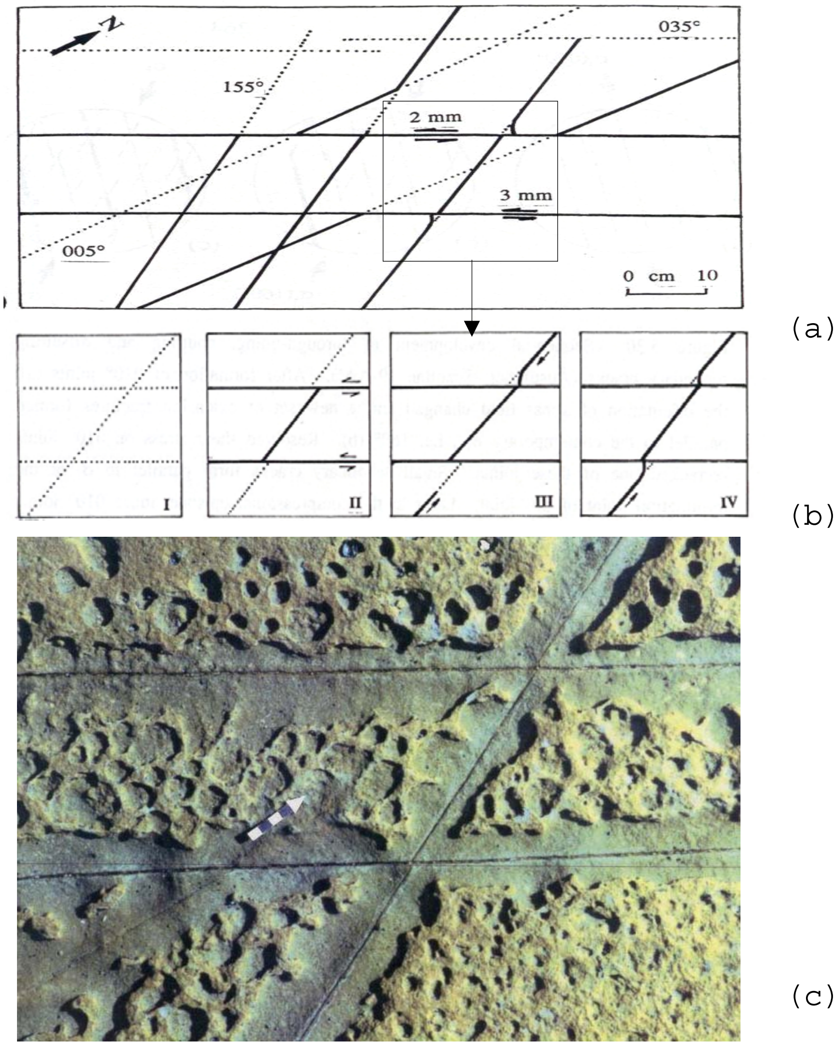


Fig. 10. (a) Alternative recracking of three sets of vertical joints striking 005, 035, and 155° in a 5 cm thick, medium-grained sandstone bed at Platform 1. Each fracture consist of both open and closed segments. (b) Stages of recracking in the central part of (a). Recracking was sequential and for a single joint, the propagation was from either side toward the free surfaces (b). (c) Photograph of (b). North arrow is 5 cm.

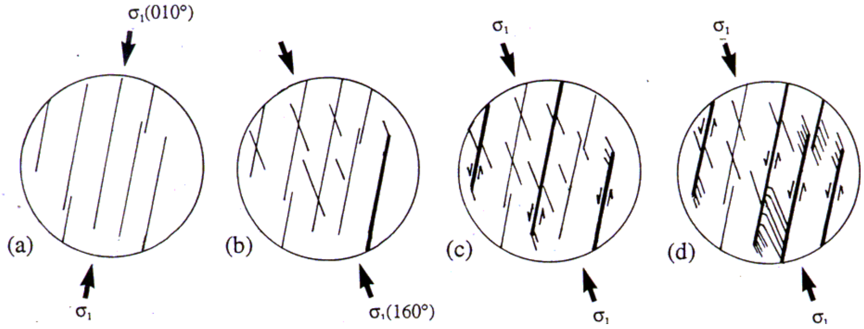


Fig. 11. Sequential development of through-going, abutting and offsetting secondary cracks (Austinmer). After formation of 010° joints (a), the orientation of stress field changed and a new set of joints formed parallel to the contemporary σ_1, i.e. 160° (b). Resolved shear stress on 010° joints recracked one of these joints. Small secondary cracks form parallel to σ_1 at the termination point of this joint. Later in the same compressional episode, more 010° joints recracked and sinistral slips along them displaced the already existing 160° joints (c). Finally, more secondary cracks formed where the faulted segments were under tension.

Recracking of jointed rock masses in the Sydney Basin, New South Wales, Australia

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بازشکست توده های سنگی درزدار، در حوضه رسوبي سيدني، استراليا

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چکیده: بررسی انجام شده در لایه های رسوبی افقی زغالدار ، نشان داد که درز ها در ابتدا به صورت اکستنشن ایجاد شده و سپس گسلیده اند. تداخل موجود در بین دسته درز ها، ناشی از عملکرد دو رخداد مجزای درزدار شدن است. درزهایی که به طور ناحیه ای گسترش یافته اند، در دو گروه اولیه و ثانویه قرار می گیرند. دسته درزهای گروه اول عمدتا به طور افقی رشد کرده و هرگز در یکدیگر تداخل نکرده اند. این درزها بعد ها بازشکسته شده اند. باز شکستگی با درزیدن آغاز شده و با لغزش جانبی (گسلش) ادامه یافته است. رشد افقی درزهای گسلیده با اتصال قطعات بازشکسته، انجام می شود. رشته درزهای ان اشلان نیز حاصل رشد قایم درزهای گسلیده به داخل سنگ بکر اند. فرایند بازشکستگی سنگ سیستمی از درزهای ثانوی (گروه 2) را به وجود آورده است. لغزش در دسته درزهای باز شکسته گروه اول و جهتیابی دسته درزهای گروه دوم، حاصل سه میدان تنش فشاری نسبتا جدید است. شدت باز شکستگی و مقدار لغزش جانبی وابسته به مقاومت مواد پر کننده، طول و تداوم درزها، زاویه بین درز قبلی و جهت فشارش ثانوی و تعداد رخدادهای فشارشی است که بر روی یک شکستگی عملکرده، است.

کلیدواژه ها: درز، درز گسلیده، باز شکستگی، درز ثانوی، حوضه سیدنی، استرالیا