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Application of younging tables to the construction of relative deformation histories—1: Fracture systems

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Abstract

For a collection of age relationships there are several possible histories. Younging tables provide a simple and direct method with which all valid deformation histories can be identified. The application of this technique to fracture systems is illustrated using two case studies. These examples demonstrate how unobserved relationships, synchronous structures, and fractures that appear in more than one stage of a deformation history can be dealt with using younging tables. Suggestions are made for the presentation of relative deformation histories that highlight ambiguities and convey a visual impression of the confidence that may be placed on a particular history. Application of the approach to the analysis of grain fragmentation has identified a range of multi-stage deformation histories. All of these histories involve, to a greater or lesser extent, the operation of extension fractures, shear fractures, linked shear fractures and extension fractures, and several sets of synchronous extension fractures. Analysis of an exposed fracture system using younging tables has raised the possibility of the simultaneous growth of two sets of orthogonal extension fractures with the implication that the scale of stress homogeneity may be only a few metres.

1. Introduction

Establishing the sequence of events within complex fracture systems is an essential step in the analysis of fracture mechanisms and the creation of palaeostress histories. At the grain- and outcrop scales detailed studies have used complex overprinting relationships to constrain the temporal development of fracture systems (e.g. Dunne and North, 1990; Lloyd and Knipe, 1992). Such studies provide valuable insights into fracture processes and they emphasise that, the successful analysis of brittle deformations is critically linked to the construction of accurate relative deformation histories.

Construction of a relative deformation history requires the collection of age relationships and the ordering of this data into a temporal sequence. Structural histories are commonly assumed to follow a deformation sequence in which each recognisable event overprints earlier ones to form a linear history. However, this assumption is flawed because it does not recognise that all structural data sets have intrinsic ambiguities that do not allow single deformation histories to be constructed (Potts and Reddy, 1999). This is the case even when all age relationships are observed. Simple linear histories also fail to account for the additional and inherent complexities of real deformations that arise from unobserved relationships, the potential for structures to appear more than once in any particular deformation history and the possibility of both cyclic and non-cyclic deformation paths (Potts and Reddy, 1999).

To develop our understanding of fracture systems a rigorous and systematic approach to relative deformation histories is required. Foreman and Dunne (1991) recorded and presented relative age data from a

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collection of fractures in a table (their table 1) but they did not describe how the contents of the table should be processed. The table of Foreman and Dunne (1991) is identical in structure to a chronological matrix (sensu Angelier, 1991, 1994) which allows manipulation of age data to produce the best possible deformation history (Angelier, 1991, 1994). Unfortunately, searching for and reporting the most probable history (cf. Potts and Reddy, 1999) ignores other histories, which are equally valid (Potts and Reddy, 1999). The 'younging table' method, recently outlined by Potts and Reddy (1999) allows relative age information to be manipulated in a rapid and repeatable way and enables the validity and ambiguities associated with *all* possible deformation histories to be assessed. In this paper we present two case studies that illustrate the practical application of younging tables to the analysis of fracture systems. We highlight a significant advance in data processing and show how this approach can be used as part of a systematic investigative programme to handle and manipulate large data sets. Our approach also addresses the problems associated with unobserved relationships and, importantly, provides new insights into fracture processes at both the grain- and outcrop scales. The procedures described in this paper are applicable to any collection of discrete structures such as fractures, faults, joints, veins, intrusive sheets and stylolites, making it a widely applicable and therefore useful technique.

The first case study describes the role of grain-scale fracture processes in the fragmentation of a matrix-supported grain of feldspar during mylonitisation. Despite the fact that our sample is from a different locality, in a different part of the Moine thrust belt of Northwest Scotland, the fracturing of the feldspar displays some similarities to the behaviour of grains within the microbreccia zone examined by Lloyd and Knipe (1992). Both systems involve the sequential development of fractures in different orientations and their subsequent reworking. However, important differences become apparent when younging tables are applied to our data. In this case study, we emphasise the range of different valid deformation histories that can be constructed from a single data set. The range of possible histories is established by considering all of the various sequences of structures that form linear or serial non-cyclic deformation histories in which each fracture appears only once. This study also illustrates how younging tables that include synchronous structures may be manipulated. It further serves to illustrate how deformation histories may be presented in order to provide an indication of the evidence that has been used to constrain them, whilst highlighting any ambiguities that arise from unobserved relationships.

In the second example, we use younging tables to assess the palaeostress history associated with the formation of an outcrop-scale fracture system. Previous work in this area has interpreted steeply dipping, orthogonal vein sets to be the products of four discrete phases of deformation. Where, during each phase, the fractures grew in only one of the two orthogonal orientations (Dunne and North, 1990). This fracture history was interpreted to be a direct response to the repeated switching of the intermediate and minimum principal stresses within a horizontal plane (Dunne and North, 1990). Significantly, this conclusion was taken to indicate that stresses were homogeneous on a scale very much greater than an individual exposure. Our analysis of Dunne and North's data using younging tables shows that individual fractures must appear in more than one stage of all possible deformation histories. This feature of the deformation histories was not apparent in the original data due to the 'absence' of key relationships. This important result introduces the possibility of deformation histories in which members of the two fracture sets may have grown simultaneously. Our reassessment of the fracture data illustrates that younging tables represent an important advance in the analysis of fracture systems, the construction of palaeostress histories and the understanding of brittle deformation processes.

2. Case study 1: Grain-scale fracturing of potassium feldspar

The role of tension cracks in the development of macroscopic shear fractures (Atkinson, 1987) has been highlighted in a detailed microstructural investigation of deformation mechanisms in quartzite (Lloyd and Knipe, 1992). Lloyd and Knipe (1992) proposed a model (their fig. 10) in which an individual grain is gradually assimilated into a microbreccia zone. In this model, the fracture history consists of three distinct phases. (1) Formation of extension fractures that open normal to the microbreccia zone. (2) Formation of extension fractures that open parallel to the shear direction of the zone, which are bound by adjacent, pre-existing extension fractures that developed during phase 1. (3) Contemporaneous shear displacement on the fractures formed in phase 1 and extensional opening of the fractures that formed during phase 2. On the scale of a grain, these processes act simultaneously and their effects spread progressively across a grain as the microbreccia zone widens. The operation of these processes, in the order described, results in two sets of fractures characterised by a collection of age relationships. A different local sequence to that proposed by Lloyd and Knipe (1992) will give a different history and a different collection of relative ages. Thus, the construction of a deformation history is an essential step in understanding fracture processes. In this study we present the results of an investigation of the fracturing of an isolated feldspar grain during mylonitisation. The grain contains multiple sets of shear and extension fractures similar to those described by Lloyd and Knipe (1992).

Arkoses of the late Mesoproterozoic Sleat Group (Torridonian) exposed on the Isle of Skye, Scotland, UK were deformed as part of the Moine thrust belt during the Caledonian Orogeny (Barton, 1978; Potts, 1982; Coward, 1988). On Skye, in the footwall of the Moine thrust, there is a strong bedding-parallel fabric (Potts, 1982). The grain of K-feldspar forms part of a sample of deformed arkose which contains the bedding-parallel fabric (grid reference NG 77852375, Lat. 57° 15′ 02″ N Long. 05° 40′ 59″ W). The orientations, geometries and opening directions of the fractures in this and other grains indicate that the fractures formed during the growth of the bedding-parallel fabric. The grain of feldspar is a different grain to that used by Reddy et al. (1999) to investigate relationships between intra-grain microstructures and $^{40}Ar/^{39}Ar$ ages but it is from the same sample and its Ar isotope characteristics are discussed in detail elsewhere (Reddy et al., 2000, grain 2).

The sample was serially sectioned and the central slice of the grain was used in this fracture study. The grain was examined using standard petrological optical microscopy and both backscattered and forescattered scanning electron microscopy. These data were combined into a single diagram (Fig. 1) and used to determine relationships between fractures within the feldspar grain. The fractures were classified as either shear or extension fractures (Hancock, 1985). The shear fractures are thin closed fractures that displace pre-existing microstructures and display no evidence of dilatational opening except at irregularities in the fracture trace (e.g. Hancock, 1985). The extension fractures are thick, filled fractures. The fill consists of newly precipitated quartz, feldspar and mica, or matrix. The fractures display evidence of dilatational opening and some have irregular walls that match. Crosscutting relationships were used to indicate which of a pair of fractures is the youngest (Hancock, 1985; Dunne and Hancock, 1994). Extension fractures of different orientation were considered to be of the same age if there was continuity of microstructure in the fill of contiguous fractures (Dunne and Hancock, 1994). L- and T-shaped combinations of shear and extension fractures in which the shear on one fracture is matched by dilatational opening on the other (in the style of a dilatational jog) were taken to indicate synchronous operation (Hancock, 1985; Dunne and Hancock, 1994).

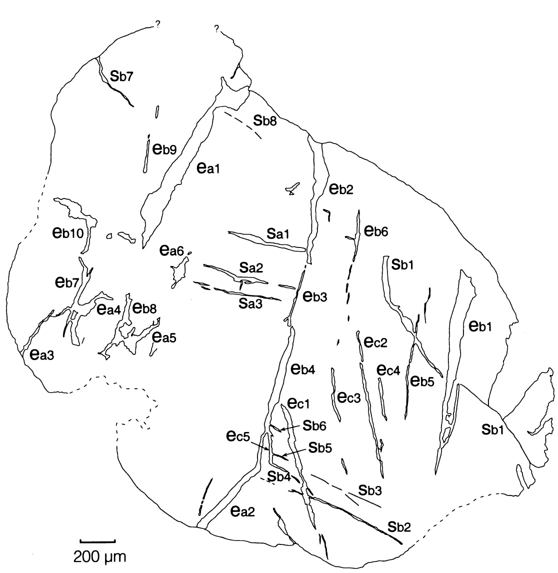

Fig. 1. Line tracing of an atomic number contrast image (not shown) of a fractured grain of potassium feldspar (sample 1680A2-XZ-4a). The fractures (shown in outline) are labelled 'e' for extension and 's' for shear. The extension fractures display three orientations labelled a–c and the shear fractures display two orientations labelled a and b. Fractures of a given type and orientation are labelled 1–*n* as necessary.

A total of 32 fractures were observed. Each fracture was given a unique label (see Fig. 1 for details). Note that, to constrain fully a linear non-cyclic deformation history containing 32 fractures in which each structure appears only once, 496 relationships must be observed (Potts and Reddy, 1999). If any of the fractures appear in more than one stage of the deformation history then more than 496 relationships must be sought up to a maximum of 992 for a cyclic deformation history (Potts and Reddy, 1999). Inspection of the 32 fractures indicates that only 14 relationships were observed between various combinations of 18 fractures. The discrepancy between the observed and the required number of relationships indicates that the data cannot be used to unambiguously define a single deformation history and several valid deformation histories must be constructed.

2.1. Construction and manipulation of younging tables

To investigate the range of possible deformation histories, the relationships between the different fractures within the feldspar grain were recorded in a younging table (Potts and Reddy, 1999). To facilitate a clear understanding of our analytical approach, the procedures for manipulation of the relative age data are outlined below as a series of steps.

Step 1. The age relationships of the 32 fractures were recorded in a younging table (Fig. 2). We have used different symbols to draw a distinction between the two types of null relationship: those where no relationship can ever be observed (×) and those in which a relationship probably exists but has not been observed (?). Cases of the former type include those where the fractures are parallel (e.g. sa2 and sa3, Fig. 1) or they are located in very different parts of the fracture system (e.g. sb7 and ec4, Fig. 1) or both (e.g. eb9 and eb1, Fig. 1). Cases in which a relationship probably exists but cannot be observed include, for example, ec1 and eb4 (Fig. 1). Each pair of fractures displays only one mutual relationship and so all of the observations were plotted in one half of the table (Fig. 2).

Step 2. No age relationships were observed for 14 of the fractures and these were removed from the younging table (Fig. 3a). Recognition of these fractures is easily achieved by either referring to the original data (Fig. 1) or examining the younging table (Fig. 2). In a younging table, the row *and* column associated with a structure for which no relationships have been observed will contain only crosses (e.g. ea3) or only question marks (no examples) or a mixture of both (no examples). Fractures removed at this stage must be reintroduced once the possible deformation histories for the interacting fractures have been determined.

Step 3. We split the table into groups and constructed a younging table for each group. A group contains fractures that display some form of interaction with other members of the group. Groups may comprise two or more fractures. Groups that contain only one pair of fractures can be easily recognised

	ea1	ea2	ea3	ea4	ea5	ea6	eb1	eb2	eb3	eb4	eb5	eb6	eb7	eb8	eb9	eb10	ec1	ec2	ec3	ec4	ec5	Sa1	Sa2	Sa3	Sb1	Sb2	Sb3	Sb4	Sb5	Sb6	Sb7	Sb8
ea1	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	□
ea2	×	○	×	×	×	×	×	×	×	□	×	×	×	×	×	×	?	×	×	×	?	×	×	×	×	?	?	?	?	?	×	×
ea3	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ea4	×	×	×	○	×	×	×	×	×	×	×	×	□	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ea5	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ea6	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
eb1	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	□	×	×	×	×	×	×	×
eb2	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	□	×	×	×	×	×	×	×	×	×	×
eb3	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
eb4	×	=	×	×	×	×	×	×	×	○	×	×	×	×	×	×	?	×	×	×	□	×	×	×	×	?	?	?	?	?	×	×
eb5	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	□	×	×	×	×	×	×	×
eb6	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
eb7	×	×	×	⅄	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
eb8	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
eb9	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
eb10	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ec1	×	?	×	×	×	×	×	×	×	?	×	×	×	×	×	×	○	×	×	×	?	×	×	×	×	□	□	□	×	□	×	×
ec2	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×	×
ec3	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×	×
ec4	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×	×	×
ec5	×	?	×	×	×	×	×	×	×	=	×	×	×	×	×	×	?	×	×	×	○	×	×	×	×	?	?	□	□	□	×	×
Sa1	×	×	×	×	×	×	×	⅄	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×	×
Sa2	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×	×
Sa3	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×	×
Sb1	×	×	×	×	×	×	⅄	×	×	×	⅄	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×	×	×	×	×	×	×
Sb2	×	?	×	×	×	×	×	×	×	?	×	×	×	×	×	×	Y	×	×	×	?	×	×	×	×	○	?	?	?	?	×	×
Sb3	×	?	×	×	×	×	×	×	×	?	×	×	×	×	×	×	⅄	×	×	×	?	×	×	×	×	?	○	?	?	?	×	×
Sb4	×	?	×	×	×	×	×	×	×	?	×	×	×	×	×	×	Y	×	×	×	=	×	×	×	×	?	?	○	?	?	×	×
Sb5	×	?	×	×	×	×	×	×	×	?	×	×	×	×	×	×	×	×	×	×	=	×	×	×	×	?	?	?	○	?	×	×
Sb6	×	?	×	×	×	×	×	×	×	?	×	×	×	×	×	×	Y	×	×	×	=	×	×	×	×	?	?	?	?	○	×	×
Sb7	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○	×
Sb8	⅄	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	○

Fig. 2. Younging table containing the observed relationships between pairs of fractures found in the K-feldspar shown in Fig. 1. The key to the symbols is shown in Fig. 3. The positions of the fractures in the table are arbitrary (based on the alphabetical and numerical order of the labels).

because the rows and columns associated with both of the fractures contain only one common age relationship (e.g. ea4 and eb7, Fig. 3a). Groups that contain three or more structures were recognised in a similar straightforward and systematic manner. A fracture that did not form part of a pair was chosen as a starting point (e.g. eb1, Fig. 3a). The rows and columns associated with this fracture were examined for interactions with other fractures (e.g. eb1, Fig. 3a) and a list was compiled of those fractures with which a relationship had been observed (e.g. sb1, Fig. 3a). The rows and columns associated with these fractures (e.g. sb1) were examined for other relationships (e.g. eb5, Fig. 3a) and all additional fractures were added to the list. This process was repeated until no more interactions were encountered. The list of fractures defines a group. Several fractures remained unassigned, and one of these was used as a new starting point and the grouping process was repeated. The grouping process was repeated until all of the fractures had been assigned to groups. Our feldspar data (Fig. 3a) contains five groups (Fig. 3b–f).

Step 4. The younging table in Fig. 3(b) was condensed by placing all synchronous structures under a single arbitrarily named header (e.g. G = ea2, eb4, ec5, sb4, sb5 and sb6, Fig. 3g). In other examples there may be more than one set of synchronous structures. Each sub-group of contemporaneous fractures should be given a separate header. Synchronous structures form an essential part of deformation histories in which structures can appear in more than one stage of the history (e.g. fig. 5 of Potts and Reddy, 1999). Since

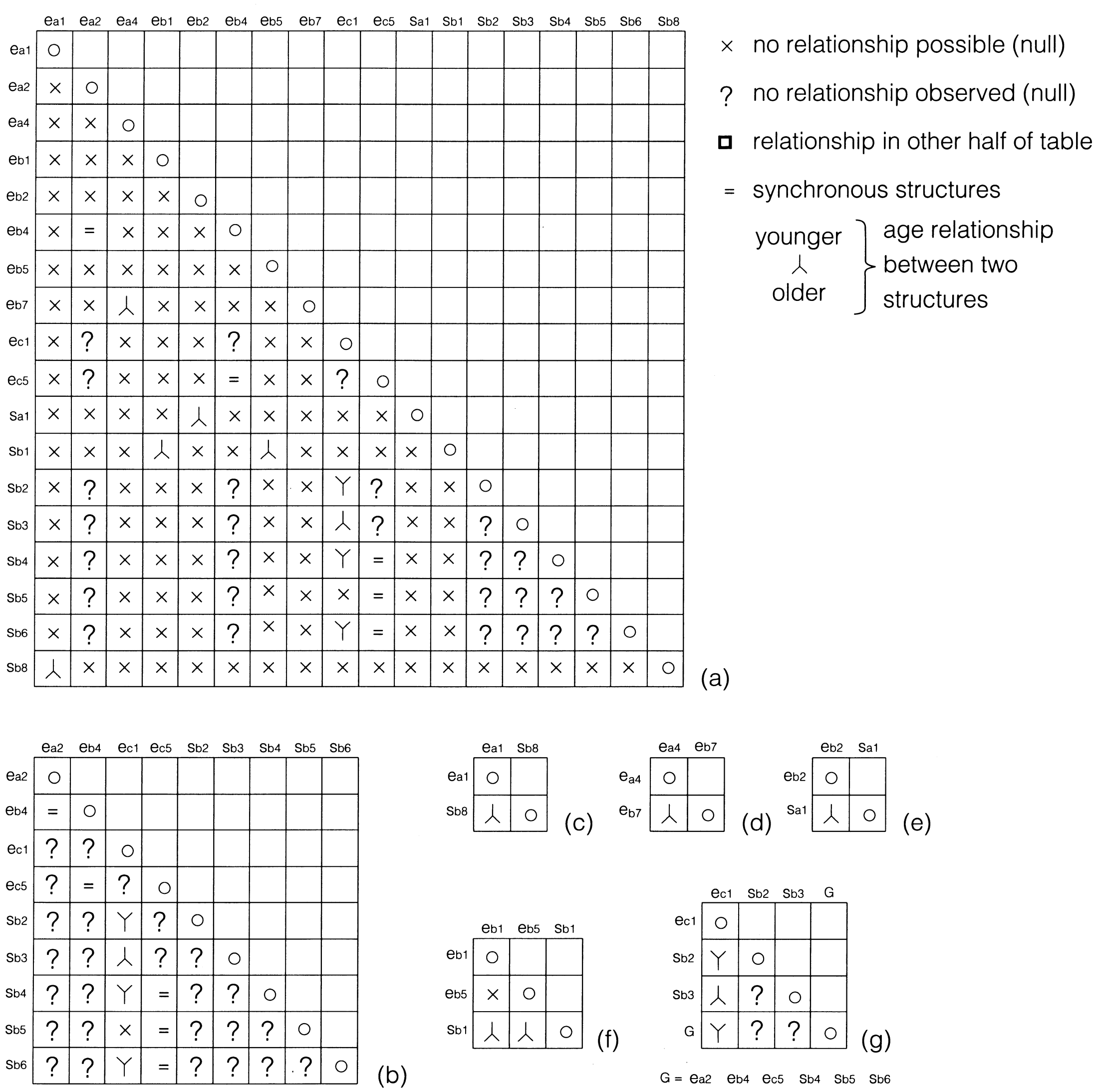

Fig. 3. Various stages in the manipulation of the younging table displayed in Fig. 2. (a) Younging table that displays only those fractures for which relationships have been observed. (b)–(f) Younging tables derived from the table displayed in (a). The members of each table (group) only display relationships with other members of the group. (g) Younging table derived from (b) by placing synchronous structures (ea2, eb4, ec5, sb4, sb5 and sb6) under the same arbitrarily named header (G). For clarity, the upper right halves of the younging tables have been left blank.

the relationships between many members of this subgroup are not known then other, more complex histories are possible. These missing histories can be analysed using younging tables but, for brevity and clarity, this analysis has not been included in the paper.

Step 5a (for younging tables with no null relationships). Since the initial positions of the fractures within a younging table are assigned arbitrarily, some tables will contain younging symbols that point in both directions. When all of the symbols point in the same direction, a possible deformation history can be read directly from the table (Potts and Reddy, 1999). If the younging symbols point upwards the oldest fracture lies in the bottom row and the history is read upwards. If the younging symbols point downwards then the oldest structure lies in the top row and the deformation history is read downwards. Those tables that contain symbols that point in both directions can be manipulated using the procedure described in Potts and Reddy (1999). This involves moving upwards the headers of any rows that contain symbols that point

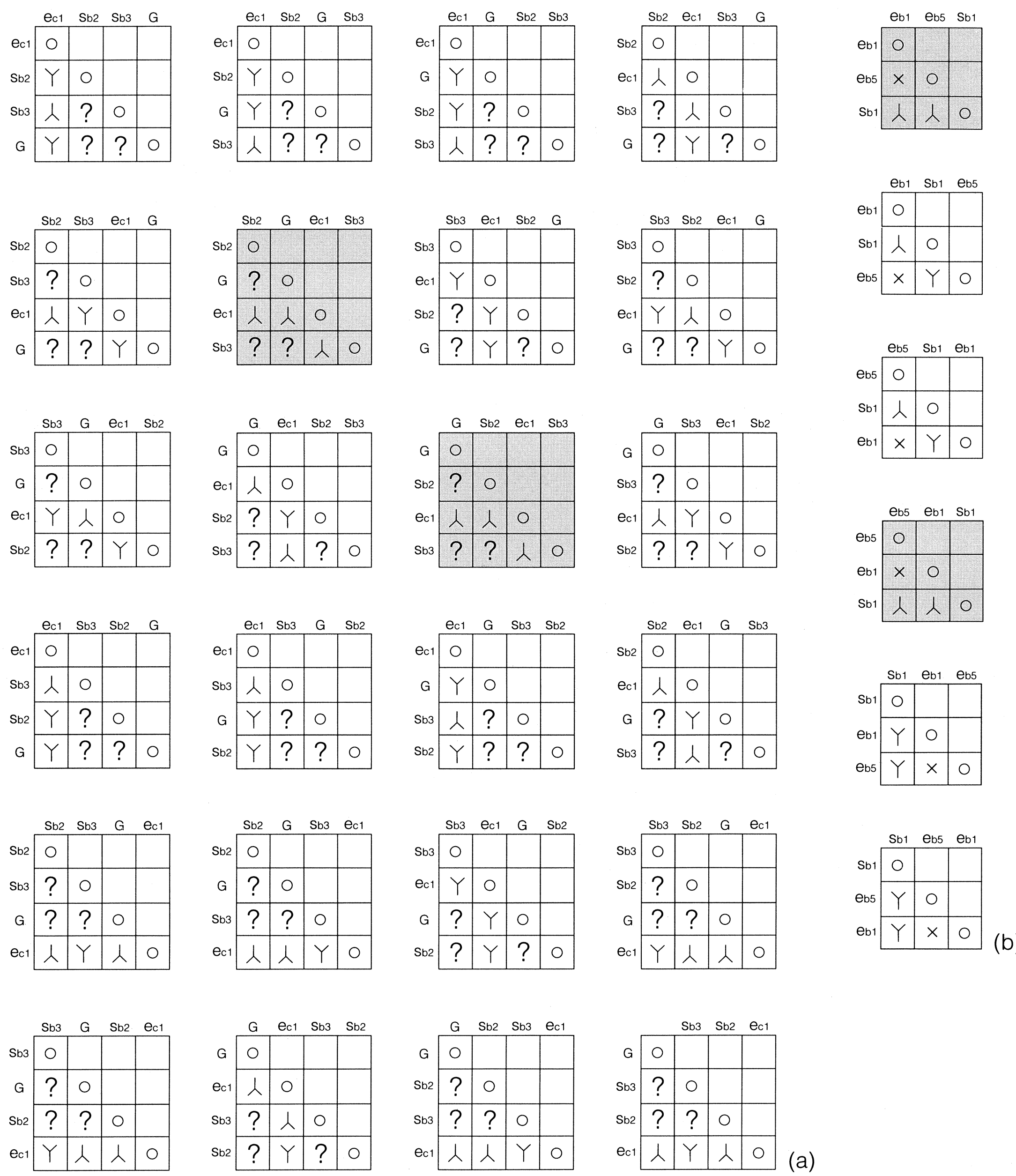

Fig. 4. Two sets of younging tables displaying all possible permutations of the data displayed in Fig. 3(f) and (g). (a) Younging tables derived from Fig. 3(g). (b) Younging tables derived from Fig. 3(f). Tables that show possible deformation histories are shaded. For clarity, the upper right halves of the younging tables have been left blank.

downwards by exchanging them with the row above. In addition, the headers of the columns must be reordered so that they display the same sequence when read from right to left as the rows when they are read from bottom to top. The table should be revised so those younging symbols associated with the new sequence are consistent with the observed age relationships. This procedure is repeated until all of the younging symbols point upwards. When this is achieved, the oldest structure lies in the bottom row and the deformation history is read upwards. Note that in this context, a collection of synchronous fractures constitutes a single structure.

Step 5b (for younging tables with null relationships). In general, the presence of one or more null relationships in a younging table (Fig. 3f and g, respectively) ensures that more than one deformation history will be consistent with the data. Even if all of the symbols for which data is available all point in the same direction (Fig. 3f), more than one valid history may be constructed. It must be emphasised at the outset that possible histories can be found using the procedure described above (Step 5a) combined with trial and error, intuition or experience. However, for small numbers of structures (five or fewer) there is an alternative approach that involves constructing a younging table for each of the possible non-cyclic deformation histories in which each of the structures appears only once. We have utilised this approach to recognise the possible deformation histories associated with the groups shown in Fig. 3(f) and (g). For three and four structures there are, respectively, six (Fig. 4b) and 24 (Fig. 4a) non-cyclic deformation histories in which each fracture appears only once. Note again that we consider a collection of synchronous fractures as a single structure. Each younging table (Fig. 4) represents one of the $n!$ permutations of n structures. Based on the observed structural relationships, tables in which the younging symbols point in a consistent direction contain valid deformation histories. For each of the groups in this example there are two possible deformation histories (Fig. 4) and, given the unobserved relationships, both of the deformation histories for each group are equally valid. This procedure neglects many different types of possible deformation histories (see Potts and Reddy, 1999). However, as we show below, other more complex histories that involve synchronous relationships can be calculated from these linear non-cyclic histories.

2.2. Interpretation of younging tables

Manipulation of the age data obtained from the grain of K-feldspar has produced a series of younging tables (Figs. 3(c–e) and 4) that summarise in a systematic way the relative ages of the fractures. In this section we describe how these younging tables can be used to constrain the number of possible deformation histories that are consistent with the original observations. We also suggest a way in which this information may be displayed.

The interpretation of younging tables that contain no null relationships is described in Potts and Reddy (1999) and Step 5a above. For the group of fractures comprising ea2, eb4, ec1, ec5, sb2, sb3, sb4, sb5 and sb6 the valid younging tables (Fig. 4a) indicate that ec1 must be younger than sb3 and sub-group G (ea2, eb4, ec5, sb4, sb5 and sb6) must be younger than ec1 (Fig. 4a). Thus, the sequence of these structures is fixed. However, the tables also show that sb2 may be younger or older than the sub-group G (Fig. 4a). A result of this type, where one structure (e.g. sb2) may be older or younger than another (e.g. sub-group G), is consistent with a third possibility, that the two structures are synchronous, such that sb2 could be the same age as the sub-group G. In other examples, where no synchronous structures have been observed this possibility may be rejected but this decision is subjective. Similarly for the group of three fractures sb1, eb1 and eb5, the valid younging tables (Fig. 4b) indicate that sb1 must be the oldest structure but either eb1 or eb5 may be the youngest fracture. The data are also consistent with eb1 and eb5 being synchronous, so again there are three possible deformation histories.

To report succinctly the complexities introduced by the ambiguities established above, we suggest that deformation histories should be presented in a diagrammatic form similar to the 'geological event network' proposed by Lisle (1981). In such a diagram (Fig. 5), a box represents each structure or collection of synchronous structures. All relevant information such as the orientation and style of the structure can be placed in the box. The boxes can be arranged in their correct relative positions to display the relative ages of the different structures. To reinforce this age structure, we have placed tie lines between the boxes (Fig. 5). We have used a horizontal line to indicate that two structures are synchronous and a vertical line with an arrowhead to show the relative ages of two structures. It is important that these lines should only be used when evidence of the relationship exists. Therefore, a vertical line joins sb3 and ec1 (Fig. 5a) because a relationship between these two fractures has been observed. No relationship has been observed between sb3 and sb2 (Fig. 5a) hence no line is displayed. This diagrammatic display of deformation histories is strongly recommended because the history and the presence (or absence) of supporting evidence can be indicated in the same diagram.

The size and shape of each box has no significance, although such a feature could be used to extend the system. In our example (Fig. 5), the size of the box is varied to accommodate the topology of the diagram and produce simpler tie lines (cf. fig. 5 of Lisle, 1981). We have chosen to draw the box containing sb3 longer than that of ec1 (Fig. 5a). We have done this so that if relationships between sb3 and either sb2 or any of the fractures ea2, eb4, ec5, sb4, sb5, and sb6 are established at a later date, for example in an adjacent serial section, then this data can be easily included in the diagram. In contrast, Lisle (1981) chose to place structures of similar type into columns. This action allows the timing of similar and dissimilar structures to be highlighted but leads to complex tie line geometries. The two approaches illustrate identical features but emphasise different aspects of the same set of age relationships.

To convey some visual impression of the confidence that may be placed on different parts of a possible deformation history, lines of different type can be used to enclose the boxes (e.g. Fig. 5a and b). We have used solid lines to indicate when structures are in their correct relative positions (e.g. Fig. 5a, c, d and e). Dotted lines indicate that a structure may appear in any one of several positions in the diagram (e.g. sb2 in Fig. 5a). Where the relative ages of structures are poorly constrained (e.g. eb1 might be older or younger than eb5 or they may be of the same age), the greater degree of uncertainty can be conveyed using a third type of line, in this case dash–dot (Fig. 5b).

The independent groups and uncertainties illustrated in Fig. 5 constitute the most accurate deformation history for the data. Attempts to relate the two or more independent groups of a deformation history (such as the five shown in Fig. 5a–e) must use either arbitrary criteria or assumptions that cannot be validated. For example, one might choose to make the total history as short as possible. This could be achieved by assuming that sb2 is of the same age as sub-group G so that the segment of the history displayed in Fig. 5(a) consists of three stages. The various two- or three-stage histories displayed by the rest of the data (Fig. 5b, c, d, and e) can be positioned so that individual fractures are synchronous with those in Fig. 5(a) such that the total number of stages is restricted to three. Alternatively, one can choose to make the history as long as possible. In this case a 13-stage history can be proposed. This is achieved by taking each group (Fig. 5a–e) to be of a different age and making those groups displayed in Fig. 5(a and b) consist of four and three stages, respectively. Deformation histories with all possible lengths between three and 13 can be proposed, and for all possible lengths there are many possible histories. Clearly, the whole process of relating groups

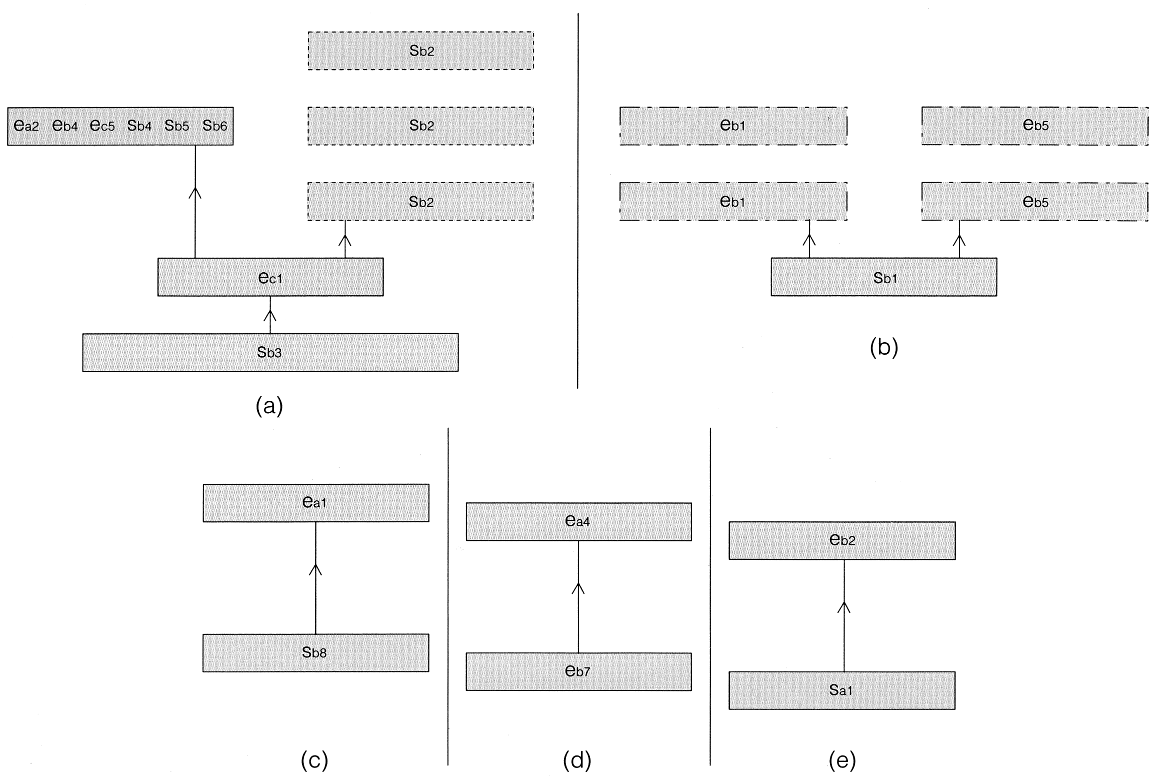

Fig. 5. The five independent parts of the deformation history obtained from the manipulation of the younging tables. (a) Derived from Fig. 4(a). (b) Derived from Fig. 4(b). (c)–(e) Derived from Fig. 3(c–e). Note that, for a complete analysis, the 14 fractures removed in Step 2 (case study 1) should be included as independent parts.

of data is completely arbitrary and the minimum number of histories does not provide any information concerning the likelihood of any particular history (Potts and Reddy, 1999). It is also worth noting that a complete deformation history for this feldspar grain must contain the 14 fractures that were removed during Step 2 of our analysis. Without further constraints these 14 fractures would each form separate areas in Fig. 5 and therefore, lead to a significant increase in the number of possible deformation histories.

When several viable deformation histories can be identified from a set of observations, sequences derived from geological models may be used to favour one of the deformation histories. For example, the presence of the synchronous relationships ensures that all possible histories must contain at least one period during which shear and extension fractures operated together (Fig. 5a). This could be used as evidence that shear and extension fractures operated together during every stage of the deformation history. One of the many possible histories of this type is a three stage history in which sb3, sb8, eb7 and sb1 are synchronous and older than ec1, sa1, ea1, ea4 and eb5 which are also synchronous and older than ea2, eb4, ec5, sb2, sb4, sb6, eb2 and eb1. Other histories can be written using different criteria. For example, a three-stage history can be written where stage 1 is dominated by shear fractures (comprising sb3, sa1, sb8 and sb1). Stage 2 consists of extension fractures (ec1, eb2, ea1, eb7 and eb5) and stage 3 consists of both shear and extension (ea2, eb4, ec5, sb2, sb4, sb5, sb6, ea4 and eb1). Where geological models are used to select a preferred deformation history considerable care must be taken to avoid circular arguments. By choosing to favour a history based on a kinematic model, the deformation history cannot be used to support that kinematic model.

The examples above illustrate the complexities associated with the construction of relative deformation histories. We have shown that a large number of histories are consistent with the data and it may seem that we can say nothing useful about fracture processes. However, this is not the case and despite the large number of possible deformation histories we have gained some insights into the fracture processes that have affected the feldspar grain.

The deformation history has a minimum of three and a maximum of 27 stages. All of these histories include at least one stage during which shear and extension fractures operated together. In addition, a large proportion of the extension fractures does not interact with other structures. In these respects the system is similar to fragmentation model of Lloyd and Knipe (1992), with the extension fractures equivalent to the isolated extension fractures that form during the early stages of their model.

There are several differences between the fracture processes described by Lloyd and Knipe (1992) and those that we infer from our detailed analysis of this grain. Firstly, all of the valid deformation histories for the feldspar grain include stages in which shear fractures cut extension fractures and extension fractures cut shear fractures. This is not a feature of the model of Lloyd and Knipe (1992) and it may indicate that, if the formation of extension fractures always precedes the combined operation of shear and extension fractures then, our isolated grain must have undergone more than one period of fracture nucleation. Multiple periods of nucleation may be a direct consequence of the grain's isolation within a deforming matrix where, it remains subject to deformation imposed by the matrix. Whereas, in the microbreccia zone, weakly deformed portions of the original grain may be retained as relatively intact parts of the wall rock where they remain as the deformation becomes concentrated within the zone (Lloyd and Knipe, 1992). Secondly, the members of one set of shear fractures (those labelled set a) do not display any synchronous relationships with any other fractures including extension fractures. This suggests that they may have operated without the assistance of extension fractures. Constraints imposed by the boundaries of the microbreccia zone may have placed restrictions upon the range of viable shear fracture orientations, which the matrix of the isolated grain of feldspar did not. To develop a more complete model of feldspar fragmentation in mylonites of which the features described above will form a part, more data is required. For individual grains this data must be more detailed and consider the interactions between large numbers of fractures as we have done here. Also, further progress requires comparisons to be made between several grains in several samples from many localities. In the past, the processing and analysis of such large amounts of information would have rendered further more detailed work impractical. As we have shown younging tables provide a practical method by which this information can be used to develop more sophisticated models of fracture processes.

3. Case study 2: Exposure-scale fracture sets

The use of fracture orientations to determine palaeostresses is a well-established approach (e.g. Angelier, 1994; Dunne and Hancock, 1994) and while several sets of synchronous shear fractures can develop during a single phase of deformation, extension fractures can only form in one orientation (Hancock, 1985). Thus, multiple sets of extension fractures are interpreted in terms of multi-stage deformation histories (e.g. Dunne and Hancock, 1994). Orthogonal extension fractures that indicate two or more phases of fracturing raise the possibility of principal stresses that switch or exchange orientation (e.g. Dunne and North, 1990) and they emphasise that knowledge of the deformation history is a key step in the analysis of these fractures. In a detailed study of orthogonal extension fractures Dunne and North (1990) proposed a four-stage deformation history, which involved principal stresses that switched orientation in a horizontal plane. Younging tables (Potts and Reddy, 1999) provide a method by which the range of valid deformation histories can be identified and we have applied the approach to the data of Dunne and North (1990) to assess whether their deformation history is unique. Other deformation histories may indicate that other palaeostress histories are consistent with the observed overprinting relationships.

The fractures are exposed in sandstones of Carboniferous age near Amroth, Wales, UK (grid reference SN17560722, Lat. 51° 44′ 00″ N Long. 04° 38′ 31″ W). They formed during the latest stages of the Variscan Orogeny (Hancock et al., 1983) and they have been studied in detail by Dunne and North (1990) (station 8). The fractures comprise two sub-vertical orthogonal sets that strike toward either 200° or 290°

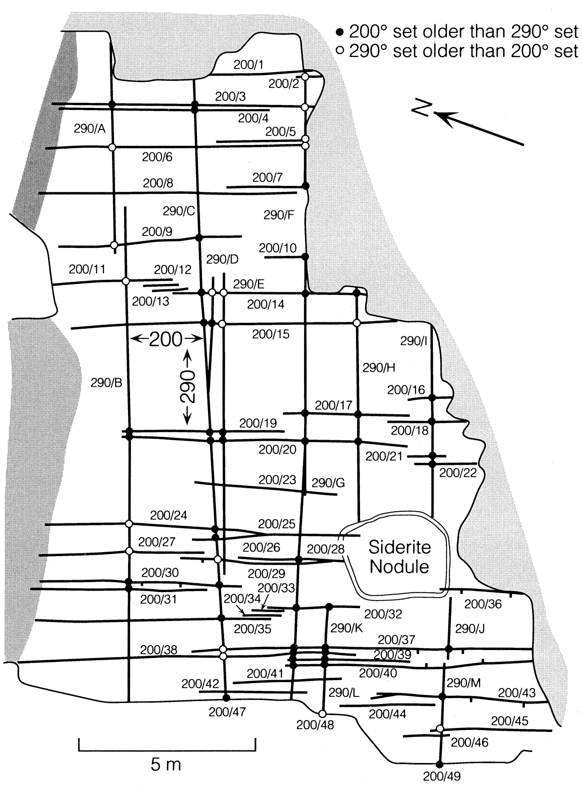

Fig. 6. Detailed map of a fractured bedding surface exposed near Amroth, Wales, UK (station 8) after Dunne and North (1990). The labels were added for the purposes of this study. Individual fractures in the set that strikes 200° are labelled 1–49 (working down the diagram), e.g. 200/1. Individual fractures in the set that strike 290° are labelled A–M (working from top left to bottom right), e.g. 290/A.

(Fig. 6). The published data of Dunne and North (1990) were sufficiently detailed to enable us to complete the younging table analysis from their paper. During a recent visit to the site all of their observations were confirmed and no new relationships were observed. When exposed, the veins display simple crosscutting relationships (Hancock, 1985; Dunne and Hancock, 1994) that enable the relative ages of pairs of fractures to be established unambiguously. No evidence of synchronous fracturing was observed (Dunne and North, 1990).

The data set comprises 62 fractures, each of which has been labelled (see Fig. 6 for details). The fractures show a total of 65 relationships between various combinations of 49 fractures. Note that, to fully constrain a linear non-cyclic deformation history containing 62 fractures in which each structure appears only once, 1891 relationships must be observed (Potts and Reddy, 1999). If any of the fractures appear in more than one stage of the deformation history then more than 1891 relationships must be sought up to a maximum of 3782 for a cyclic history (Potts and Reddy, 1999). Since the total number of observed relationships is only 65 then a number of deformation histories will be valid.

3.1. Construction and manipulation of younging tables

Manipulation of the younging tables broadly follows that described above for the fractured K-feldspar grain and so we only briefly outline the early steps. However, the later stages of the analysis require a different approach that reflects the presence of fractures that must appear more than once in each of the possible deformation histories. Therefore, this part of the analysis is described in more detail.

Step 1. All of the age relationships were recorded in a younging table (Fig. 7).

Step 2. The 13 fractures for which no relationships have been observed were removed (Fig. 8). As before, fractures removed from the analysis at this stage must be reintroduced once the possible deformation histories derived from the interacting fractures have been identified.

Step 3. The 49 interacting fractures (Fig. 8) were divided into groups and younging tables were constructed for each of the groups (Fig. 9). These data form two groups: one group contains 44 fractures (Fig. 9a) and the other contains five (Fig. 9b). No synchronous fractures were observed. Hence, the step that involves placing sub-groups of contemporaneous structures under common headers (Step 4 above) has been omitted.

Step 4a (for younging tables with no null relationships). Younging tables with no null relationships can be manipulated using the approach outlined in Step 5a above.

Step 4b (for younging tables with null relationships). The younging tables displayed in Fig. 9 contain null relationships. The table that contains five fractures (Fig. 9b) was processed using the procedure outlined in Step 5b above. The ambiguities introduced by the lack of relationships between fractures 200/43, 200/45, 200/46 and 200/49 lead to six valid deformation histories (not shown).

Because the number of possibilities is prohibitively large, we did not process the group of fractures displayed in Fig. 9(a) using the approach described in Step 5b above. Instead, we used an alternative approach, which is similar to that described in Step 5a above. Note that, all of the younging tables displayed in Fig. 10 display only 27 fractures whereas the table in Fig. 9(a) contains 44. This reduction is used to make the diagrams physically smaller because of space limitations associated with publication. Unlike other reductions described in this paper, it has no scientific basis and we must emphasise that we do *not* recommend its use. The 27 fractures that were removed were chosen because they can occupy a wide range of positions within the table without contributing directly to its structure. They are analogous to fracture sb2 in case study one (Fig. 5). Consequently our manipu-

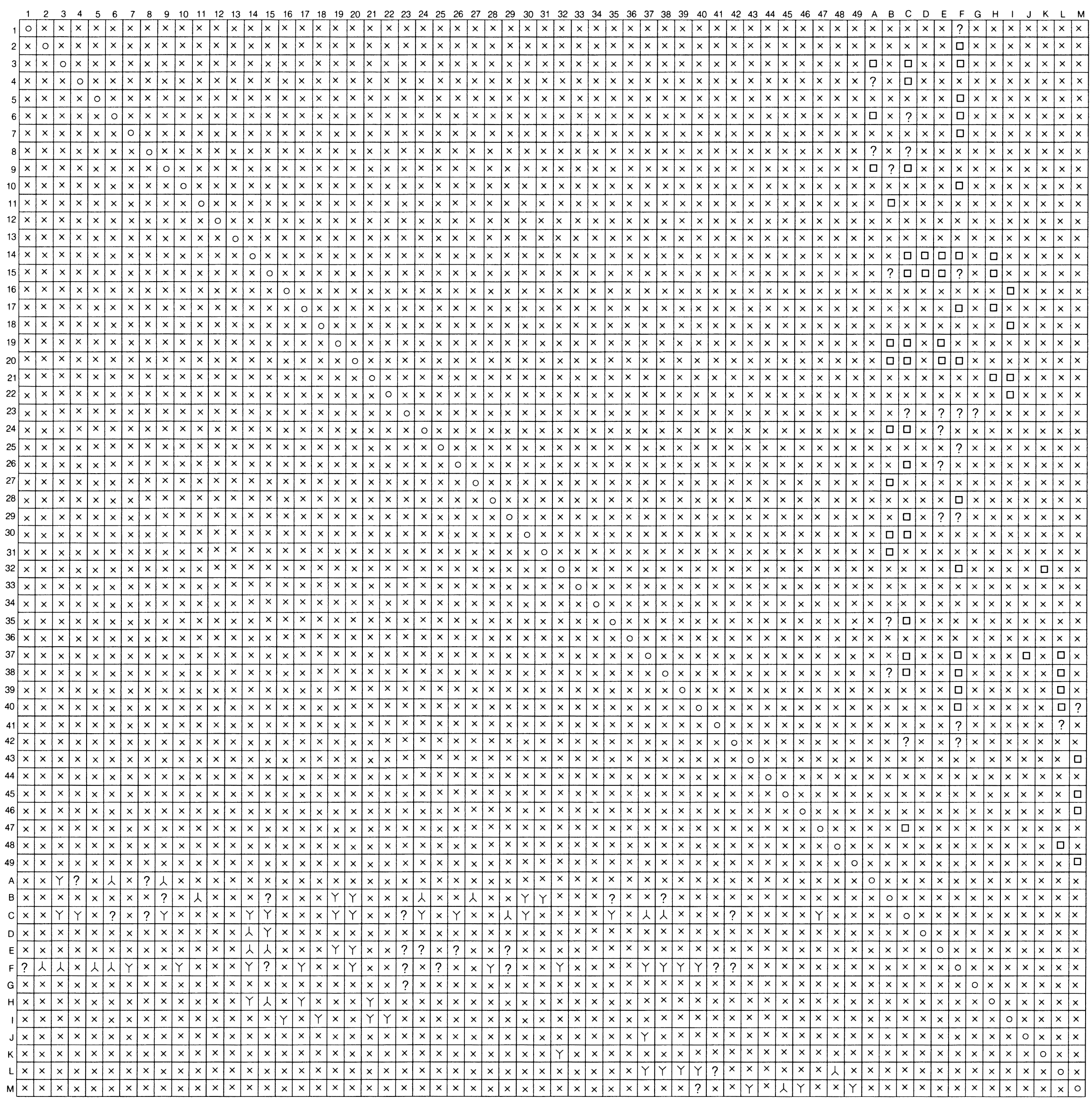

Fig. 7. Younging table displaying the relative ages of pairs of fractures observed in Fig. 6. The key to the symbols is shown in Fig. 3. The positions of the fractures in the table are arbitrary (based on the numerical and alphabetical order of the labels).

lation and subsequent interpretation of the relative age data outlined below are not affected by this reduction.

As before, fractures in the wrong relative position can be recognised by younging symbols that point downwards in the younging table. The correct relative position of a fracture can be obtained by moving the header of a particular row upwards and, simultaneously, moving the header of the equivalent column to the left. After each move the table is revised. This process is repeated in a stepwise manner until a position is reached where the younging symbols switch orientation and point upwards (Potts and Reddy, 1999). We have found that considerable efficiency can be achieved by using the following guidelines. (1) When a fracture is in the wrong position and *some* but not all of the younging symbols in the row point downwards (e.g. 290/E, Fig. 10a) the fracture can be moved through several positions in a single step. The fracture should be moved to a position *above* those fractures for which the younging symbols point downwards (e.g. for 290/E above 200/19 and 200/20) but *below* those for which the younging symbols point upwards (e.g. for 290/E below 200/14 and 200/15). (2) If all of the younging symbols in a row point downwards (e.g. 290/L, Fig. 10a) then the fracture should be moved to a position *above* the highest fracture with which it displays a mutual relationship (e.g. 200/37). (3) If, for a particular fracture, all of the symbols in a row point upwards then its position need not change. (4) Sub-groups of fractures that occupy adjacent positions and (locally) form a correct sequence can be moved as a single unit (e.g. 200/37, 200/38, 290/L and 290/J, Fig. 10b and c).

The rules described above can be applied repeatedly and in any order until all of the symbols point upwards. Arbitrary movements of data will not lead to

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Fig. 8. Younging table after the removal of fractures for which no relationships are available. For clarity, the upper right half of the table has been left blank.

erroneous deformation histories but, in general, they require more actions in order to reach a solution. Most problems can be resolved by the repeated application of the guidelines outlined above, (compare Fig. 10b and c and Fig. 10c and d) such that all of the symbols point upwards. When null relationships are present other possible deformation histories must be sought. These are found by searching for other configurations in which all of the symbols point upwards.

Step 5. Ordinarily, relationships such as those between 200/15 and 290/H, 200/37 and 290/C, and 200/38 and 290/C (Fig. 10d) would have been resolved by this stage but these data and their manipulation illustrate another important aspect of younging tables. When the table is rearranged so that the symbol for 200/15 and 290/H points upwards (Fig. 10e), the symbol for 200/15 and 290/D is reversed (Fig. 10e) and vice versa (Fig. 10d). Indeed, using only the lower left half of the table no deformation history can be constructed for which the symbols for both 200/15 and 290/H, and 200/15 and 290/D point in the same direction (Fig. 10d and e). Only when one of the symbols for one of these relationships is placed in its correct position in the *upper right half* of the table (Fig. 10f) do both symbols point upwards. The conflicting relationships 200/15 and 290/D, and 200/15 and 290/H can only be resolved by placing the symbol for *either* 200/15 and 290/D *or* 200/15 and 290/ H in the upper right half of the table (Fig. 10f and g, respectively). Note that, both histories (Fig. 10f and g) are equally valid.

A similar feature arises from the relationships between the fractures 290/C, 200/3, 200/9, 200/37 and 200/38. If only one half of the table is used no deformation history can be found for which the symbols for these relationships point simultaneously

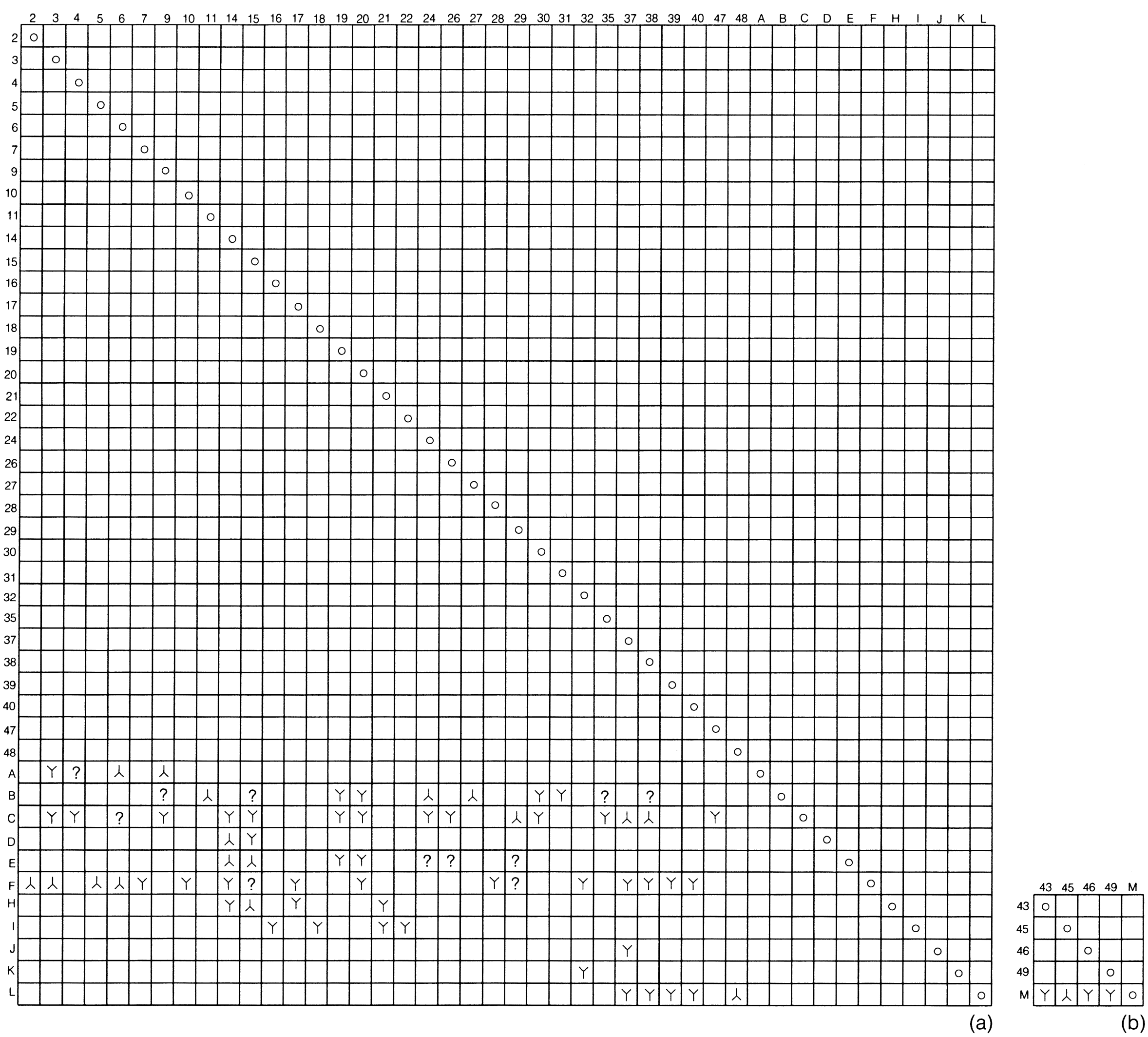

Fig. 9. Younging tables formed by splitting the table displayed in Fig. 8 into two groups. For clarity, the upper right halves of the younging tables have been left blank. For further clarity, the symbols for null relationships where no relationships are possible (crosses) have been omitted.

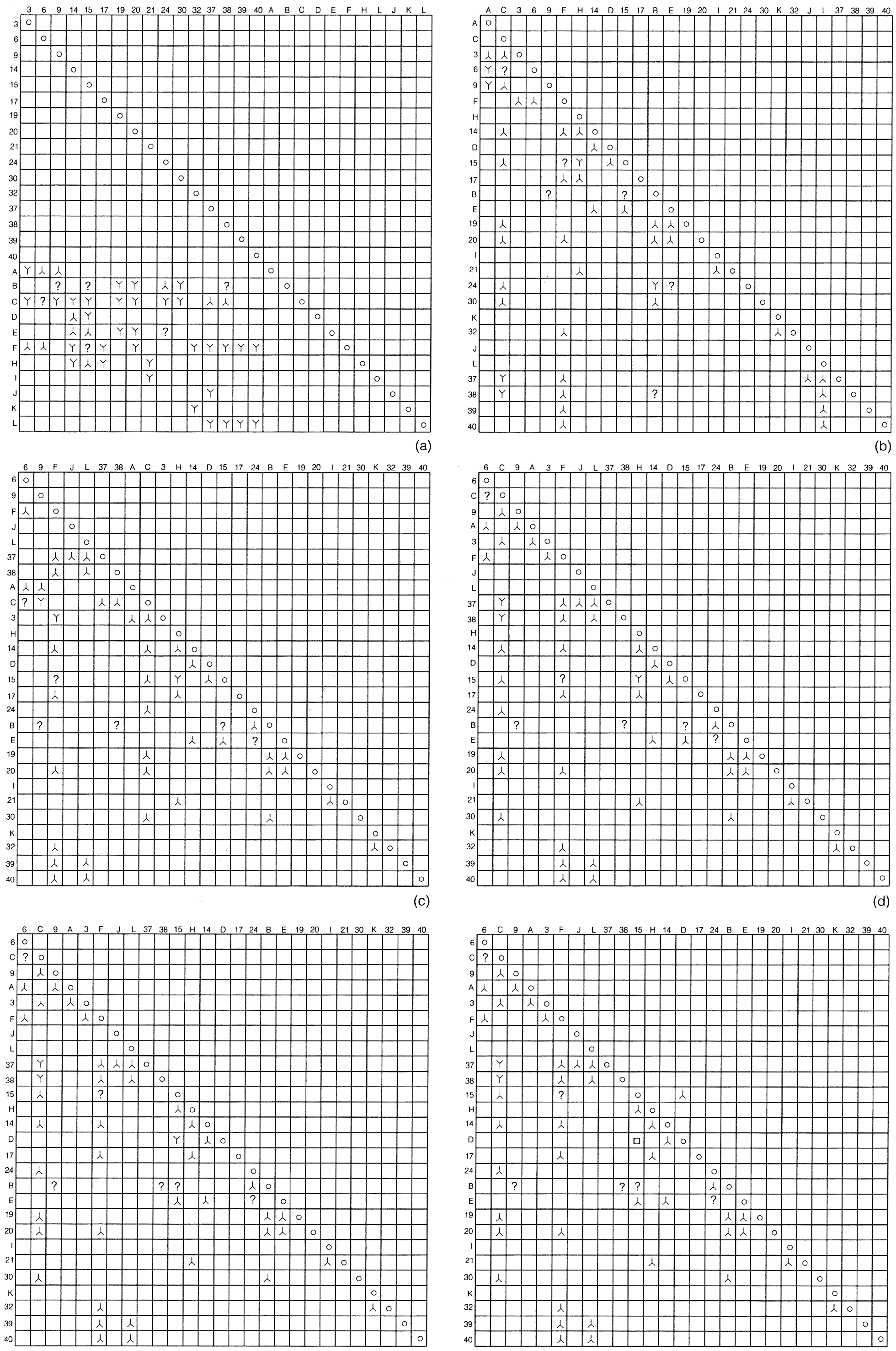

Fig. 10. Various stages in the manipulation of the younging table displayed in Fig. 9 after the removal of 27 fractures (see explanation in text for this non-standard procedure). For clarity, the upper right halves of the younging tables have been left blank. For further clarity, the symbols for null relationships where no relationships are possible (crosses) have been omitted.

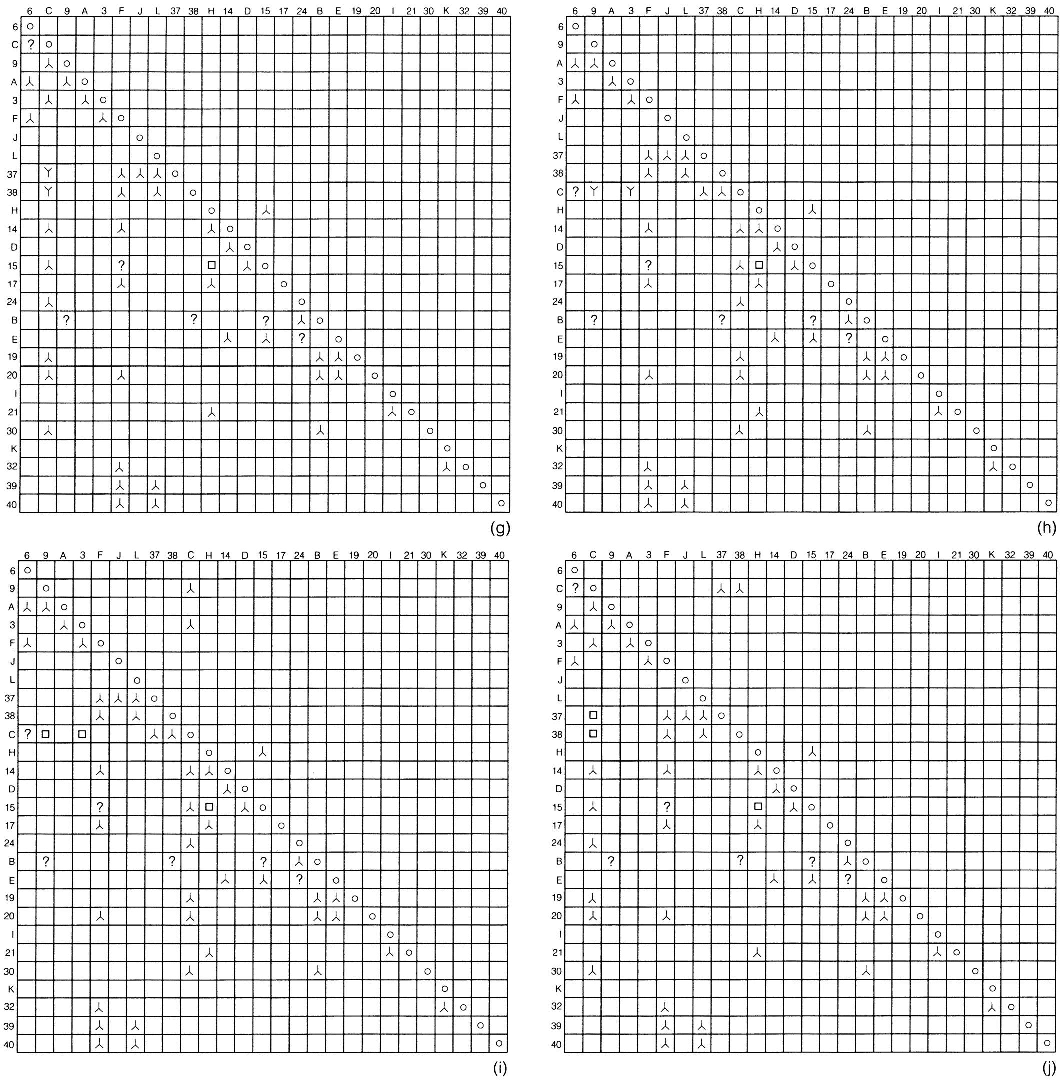

Fig. 10 (*continued*)

in the same direction (compare Fig. 10g and h). However, if the symbols for these fracture relationships are placed in the upper right half of the table (e.g. Fig. 10i and j) then all of the data can be reconciled. Again both of these histories are equally valid.

The fractures associated with a relationship that plots in the upper right half of a younging table (e.g. 290/D and 200/15, Fig. 10f) define a sub-group (e.g. 290/D, 200/14, 290/H and 200/15, Fig. 10f). The oldest (e.g. 290/D) and youngest (e.g. 200/15) members of the sub-group form the lower and upper bounds to the sub-group (Fig. 10f). Providing that the sequence displayed in Fig. 10f (i.e. 290/D, 200/14, 290/H and 200/15) is preserved then, the history of the sub-group may start with any one of the four fractures (e.g. 290/D, 200/14, 290/H and 200/15). In each case the relationship associated with the oldest and youngest fractures (e.g. 200/15 and 290/H, Fig. 10g) plots in the upper right half of the younging table. Two other histories are compatible with the data, 290/H, 200/15, 290/D and 200/14 (where the relationship between 290/H and 200/14 plots in the upper right half of the table) and 200/14, 290/H, 200/15 and 290/D (where the relationship between 200/14 and 290/D plots in the upper right half of the table). Note that, the sequence 290/D, 200/14, 290/H and 200/15 which honours the data, is preserved in all of these histories.

The situations displayed in Fig. 10(i) and (j) are very similar but slightly more complex. The sub-group is defined in Fig. 10(i) by 290/C and 200/9. Although the fractures 290/J and 290/L lie within the bounds of the sub-group (Fig. 10i) they do not contribute directly to its structure and, for the moment, they can be ignored.

The fractures 200/37 and 200/38 differ only in their relationships to 290/J, which does not contribute to the structure of the sub-group. Thus, with respect to the rest of the sub-group (i.e. 290/C, 290/F, 200/3, 290/A and 200/9), 200/37 and 200/38 behave in an identical manner and they can be treated as one structure. Six histories can be written that preserve the sequence 290/C, 200/37 and 200/38, 290/F, 200/3, 290/A and 200/9. Each history starts with, in turn, one of the fractures 290/C (Fig. 10i), 200/37 and 200/38 (Fig. 10j), 290/F, 200/3, 290/A and 200/9. For each of these starting points a different pair of relationships will plot in the upper right half of the table. Note that, fractures 290/J and 290/L must always lie above 200/37 and 200/38 and they cannot form starting points.

The first sub-group has four members and four possible deformation histories. The second sub-group has six members that could form starting points (i.e. treating 200/37 and 200/38 as one structure and excluding 290/J and 290/L) and six possible deformation histories. Therefore, it would appear that the number of possible histories is equal to the number of valid starting points. The two sub-groups are independent consequently there are 24 sets of deformation histories. Each set corresponds to one of the 24 combinations of relationships that must plot in the upper right halves of the younging tables. Two of the cases are shown in Fig. 10(i) and (j). Since the data set is incomplete (there are some null relationships) each of the 24 cases described above must be examined for other possible deformation histories (see case study 1: Step 5b). Before considering all of the possible histories the 27 fractures that were removed for brevity (during Step 4b) and the 13 removed in Step 2 should be restored. It is unfortunate that there are insufficient data to reduce significantly the number of possible histories but the purpose of this example was to demonstrate that the existence and form of more complex histories could be recognised using younging tables.

3.2. Interpretation of younging tables

Most parts of the younging tables displayed in Fig. 10 can be interpreted in similar ways to those described in case study one. However, the relationships that plot in the upper right half of each younging table must be interpreted in a slightly different manner. The younging table displayed in Fig. 10(g) indicates that 290/D cuts 200/15, 200/14 cuts 290/D, 290/H cuts 200/14 and 200/15 cuts 290/H. Thus, 200/15 is both older (implicitly) and younger than 290/H and it appears in more than one stage of the deformation history. For a pair of fractures, the presence of younging symbols in both halves of a table suggests that the deformation history contains at least one structure that appears in more than one stage of the history. Inspection of Fig. 6 indicates that no relationships appear to have been missed. Indeed, it is hard to see how two orthogonal fractures could display two relationships! However, a younging table checks for internal consistency. In this example of crosscutting fractures individual relationships are tested against those from all or a significant part of the fracture system. Thus, for each symbol that plots in the upper right half of a table there must be an implicit or latent relationship that would plot in the lower left half of the table. This pattern of relationships can be achieved in many ways. For example, while fracture 200/15 propagated from where it is cut by 290/D to where it cuts 290/H (Fig. 6), fracture 200/14 cut 290/D, 290/H cut 200/14 and 290/H grew to a position where it could be cut by 200/15. This history suggests that, within a region of approximately 6 m^2 both fracture orientations (200° and 290°) may have grown simultaneously. Similar reconstructions can be produced from all of the deformation histories generated by the two sub-groups (Fig. 10) and each history can be interpreted in terms of simultaneous propagation. However, these same histories can be interpreted in terms of episodic growth (Dunne and North, 1990) but each history will have more than four stages. The deformation history proposed by Dunne and North (1990) for the same area is valid and there is, given the present data set, no objective way of discriminating between it and those proposed by us. Whilst neither model can be chosen in preference to the other, our analysis does raise the possibility of simultaneous growth.

The original study of Dunne and North (1990) was undertaken to determine the stress history and the scales of stress homogeneity associated with outcrop-scale fracturing. Their deformation history consists of a minimum of four stages and in each stage only one set of veins grew. Because the fractures are orthogonal extension fractures, this history was used to argue that the horizontal principal stresses must have repeatedly switched orientation. If, as suggested by our analysis, fractures of both sets grew at the same time within a few metres of each other then, the scale of stress homogeneity may be smaller than an individual exposure and the principal stresses need not switch orientation. This result has important implications for palaeostress analysis. The scales of stress homogeneity define the size of a station, which affects both data collection and subsequent interpretation and the simultaneous growth of extension fractures in more than one orientation places severe constraints on the range of possible stress states. In this case the possibility of other more complex deformation histories was established through the application of younging tables. New insights into fracturing may arise simply as a result of considering alternative histories or, they may develop from testing these histories.

4. Discussion

The crosscutting relationships between multiple fractures are generally complex and their analysis requires the manipulation of large amounts of data. Often the amount of data can be overwhelming and key aspects of the deformation history may not be recognised. Younging tables provide a powerful way of displaying such data that allows manipulation in a systematic way.

In the absence of younging tables repeated observations such as those in case study one (shear fractures cut extension fractures and extension fractures cut shear fractures) would frequently be interpreted as evidence that the fractures were approximately synchronous in age. If each fracture is treated as an individual, longer and more complicated histories must be considered (e.g. Dunne and North, 1990) but these histories provide more information about brittle processes and stress regimes. However, the complexities introduced by large numbers of fractures makes analysis time consuming and laborious such that the presence and form of alternative solutions are often obscured. The systematic approach provided by younging tables allows all possible histories to be recognised.

Younging tables permit the recognition of groups of interacting fractures. Analysis of each of these groups allows the relative deformation history of the structures within the group to be established. Often a unique deformation history for a particular group of data cannot be derived. However, the approach enables the different possible deformation histories for each group to be determined. Although the deformation history of each group cannot be correlated directly with those derived from other sub-populations, the younging tables provide sufficient information to ensure that all possible histories can be established.

The fracture system examined in case study 1 is relatively simple and the short segments of the deformation history displayed in Fig. 5 can be investigated with ease. There is no doubt that all of the analysis could have been completed without the aid of younging tables but the time taken would have been much greater and the likelihood of recognising all possible histories would have been reduced. It is less clear whether or not the analysis in case study 2 could have been completed without younging tables. In particular, the recognition of other more complex histories in which a fracture appears in more than one stage of a deformation history.

The rapid identification of the full range of possible histories allows other hypotheses to be developed and this should enable new directions in fracture research to be pursued. Many of the histories are so different it should be a relatively simple task to test their validity and these tests may provide new insights into brittle processes. In the second, exposure-scale study reconstructions based on the more complex histories derived from the younging tables suggest local propagation directions for the fractures. These predictions can be compared with microstructures in the fracture fill or surface features of the fractures that may be used to determine propagation directions (e.g. Hancock, 1985). Not only will this provide a test of a particular history but also a successful outcome will allow fracture processes to be investigated in greater detail. There is a considerable amount of information contained in the age relationships of a fracture system. Younging tables provide a means by which this information can be utilised in order to obtain a greater understanding of brittle deformations.

5. Conclusions

Younging tables are an efficient way to handle large data sets such as those associated with fracture systems.

Unobserved structural relationships introduce ambiguities into the analysis of deformation histories. In general, the presence of one or more null relationships ensures that more than one deformation history will be consistent with the data. Possible deformation histories can be identified through the manipulation of younging tables.

Younging tables were designed to investigate simple deformation histories with little or no expectation that they could be applied to more complex situations (Potts and Reddy, 1999). However, the use of younging tables is not restricted to serial non-cyclic deformation histories in which a fracture appears only once. Synchronous structures can be handled with ease and the presence of fractures that must appear in more than one stage of a deformation history can be recognised.

Younging tables check for internal consistency; individual relationships are tested against those from all or a significant part of the fracture system under investigation. Thus, the presence of more complex histories can be found without any assumptions or prior knowledge and this represents an important advance in the analysis of fracture systems.

The complexities and ambiguities associated with a set of possible deformation histories can be expressed succinctly when presented in diagrammatic form (e.g. as a deformation event network Lisle, 1981). In addition, the amount of supporting evidence can be indicated.

A greater understanding of fracture systems can be gained from knowledge of the possible deformation histories when more than one history is compatible with the data and younging tables provide the means by which these histories can be identified.

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