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GEOMETRY AND DEVELOPMENT OF VEIN SYSTEMS IN THE PLYMOUTH LIMESTONE

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INTRODUCTION

Calcite veins (Figure 1) in the paving slabs outside Plymouth City Museum (Drake Circus, Plymouth) are analysed and stages in their development are inferred. The slabs are smoothly polished, are easily accessible, and have several generations of veins which act as displacement markers. The veins appear to be at high angles to the surfaces analysed. They therefore provide an ideal opportunity to examine vein development. The Middle Devonian Plymouth Limestone (Hobson, 1978) has been used extensively as a building stone and for paving slabs in Plymouth. The limestone characteristically contains solution seams, veins and deformed fossils, particularly corals and stromatolites. Extensive deformation affected the Plymouth Limestone during the Variscan Orogeny, at the end of the Carboniferous.

Individual vein systems initiate as en echelon veins, with some ductile strain being indicated by distortion of earlier veins. As displacement and vein widths increase, the bridges between the veins rotate and deform, and eventually break. Rhomb-shaped pull-aparts can be formed from previously separate vein segments which are linked by fractures. As shear and displacement increase further, a through-going fault often develops, and the veins and bridges become brecciated.

THE GEOMETRIES OF VEINS IN THE PLYMOUTH LIMESTONE

The veins examined form zones, in which the en echelon vein segments are usually at about 45° to the zone boundaries (Figure 1), implying that the zones have undergone approximately simple shear (McCoss, 1986). The zones show a range of geometries, with different amounts of linkage between the vein segments. Some zones have little or no linkage, with only limited shear and dilation (Figures la and lb). Olson and Pollard (1991) show that the sigmoidal nature of the vein segments may be caused by vein interaction and by bending of the bridges between the vein segments, so need not be caused by ductile shear of the vein system. The deflection of earlier veins, however, indicate some ductile shear (Figure 1) (see Ramsay, 1967, Fig. 3-25E). Some zones show greater shear and further rotation of the bridges, with increased linkage between segments and the development of pull-aparts (Figures lc to le) (Gamond, 1983, 1987; Peacock and Sanderson, 1995). The bridges rotate anticlockwise in a sinistral vein system. Other zones show extensive brecciation, with the development of a through-going fault (Figure 1f).

THE DEVELOPMENT OF VEINS IN THE PLYMOUTH LIMESTONE

The series of vein geometries illustrated in Figure 1 can be used to infer the development of vein systems in the Plymouth Limestone (Figure 2). Similarly, the geometries of normal fault and of veins have been used to make inferences about fracture development by Peacock and Sanderson (1994, 1995). A series of en echelon veins (Figure 2a) interact, with the bridges deforming and rotating (Figure 2b). As vein dilation increases, so does the folding and rotation of the bridges, which start to break (Figure 2c) (Nicholson and Pollard, 1985, Figs. 1 and 2). Veins in the Jurassic limestones of Somerset (Peacock and Sanderson, 1995) are often connected by solution seams. Some pressure solution seams occur in the bridges of the veins described here, at high angles to the long axes of the veins, but they are not strongly developed. The bridges are eventually completely broken by fractures (Figure 2d), and the bridges may become brecciated as displacement continues (Figure 2e). A through-going fault has then developed. The blocks of brecciated wall-rock often show rotations of tens of degrees, which is indicated by the reorientation of earlier veins. A similar sequence of development can also occur spatially, with changes in geometries within a vein system, as shown by Nicholson and Ejiofor (1987). The sequence of development suggested in Figure 2 supports experimental results (e.g. Brace and Bombolakis, 1963; Horii and Nemat-Nasser, 1985; Petit and Barquins, 1988) and other field studies (e.g. Martel *et al*., 1988; Peacock and Sanderson, 1995) that faults often develop from sets of extension fractures.

CONCLUSIONS

This analysis of calcite veins in the paving slabs outside Plymouth City Museum provides an insight into the development of vein arrays:

1) The systems initiate as sets of en echelon veins, with a component of ductile strain being indicated by distortion of earlier veins (Figure 2a).

2) As displacement and vein widths increase, the bridges between the veins rotate and deform (Figure 2b), and eventually break (Figures 2c and 2d). Rhomb-shaped pull-aparts can form from formerly separated vein segments which are linked by connecting fractures (Figure 2e).

3) As shear and displacement increase further, a through-going fault forms, with the veins and bridges becoming brecciated (Figure 2e).

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(See over for figures)

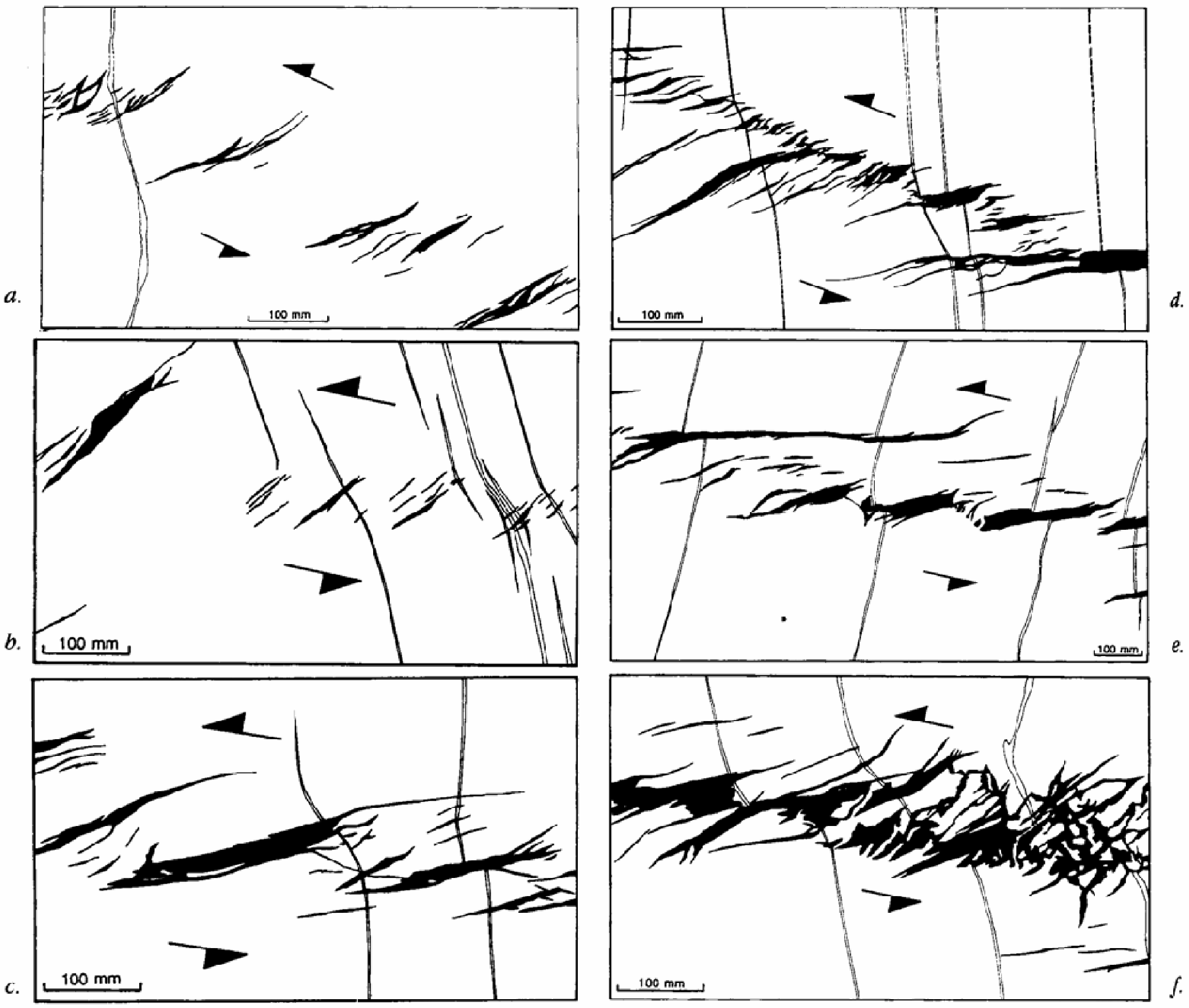

Figure 1. Line drawings of zones of calcite veins (black) in paving slabs of Plymouth Limestone outside Plymouth City Museum. The zones are drawn as being sinistral, although (a), (e) and (f) as now viewed are dextral, i.e. they are drawn in mirror-image. Displacements can be measured using earlier veins (white). Other veins occur in the slabs, but they are not shown if they do not act as displacement markers. a) A zone in which only limited linkage occurs between overstepping veins, with some veins having a separation which is large relative to their lengths and widths. Ductile deformation is indicated by deflection of the earlier vein. b) Example in which limited linkage occurs. c) Some linkage occurs, with pull-aparts developing (Gamond, 1983, 1987; Peacock and Sanderson, 1995). Shear on the vein segments is indicated by the displacement of the earlier veins. d) The veins form a distinct zone in which the bridges between the veins have rotated and are often broken. e) The bridges have started to break with pull-aparts being well-developed. f) A zone in which the veins have linked to form a through-going fault. Extension and shear have caused extensive breakage of the bridges, with brecciation occurring.

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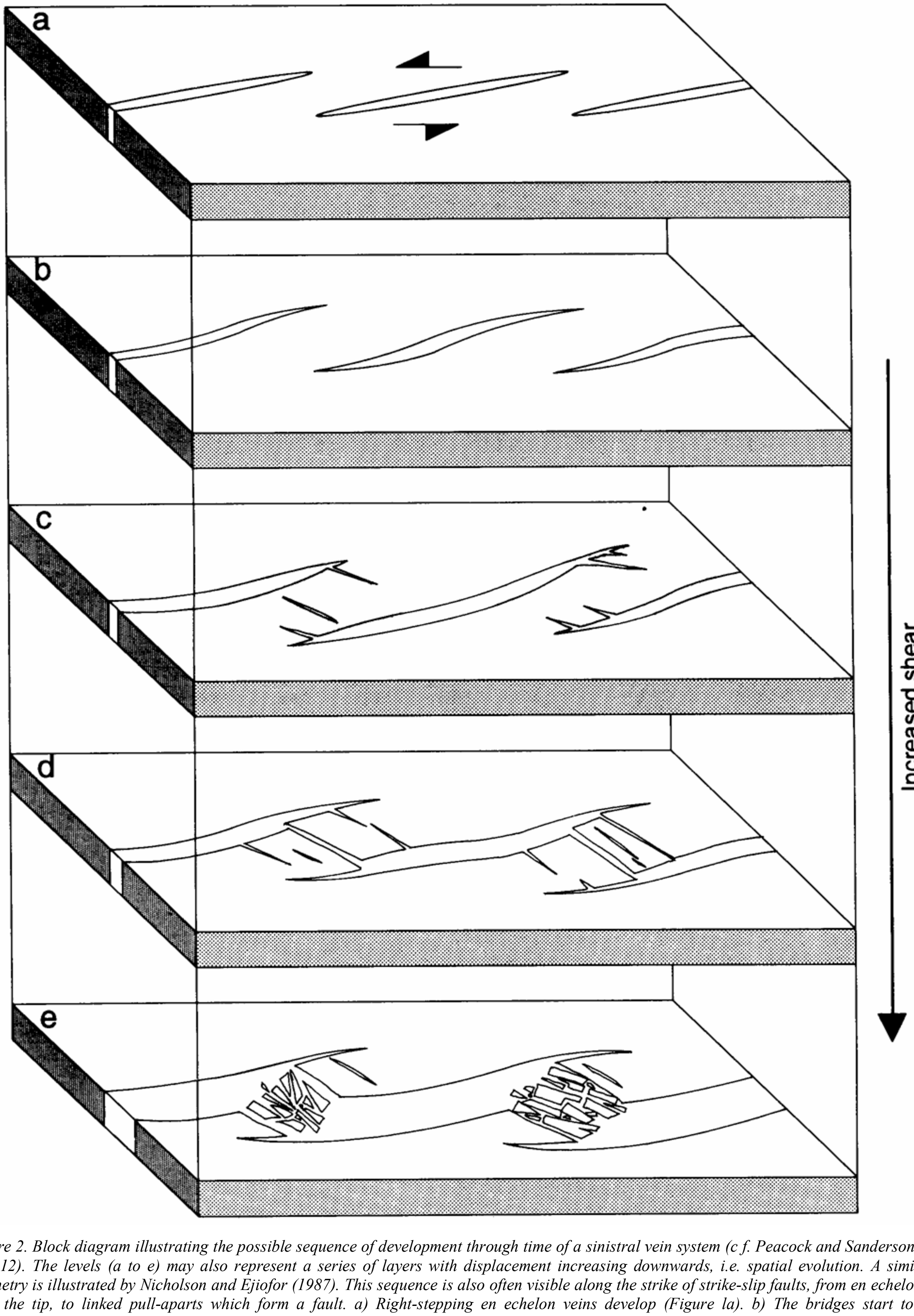

Figure 2. Block diagram illustrating the possible sequence of development through time of a sinistral vein system (c f. Peacock and Sanderson, 1995, Fig. 12). The levels (a to e) may also represent a series of layers with displacement increasing downwards, i.e. spatial evolution. A similar 3D geometry is illustrated by Nicholson and Ejiofor (1987). This sequence is also often visible along the strike of strike-slip faults, from en echelon veins near the tip, to linked pull-aparts which form a fault. a) Right-stepping en echelon veins develop (Figure la). b) The bridges start to rotate (anticlockwise in sinistral shear) as the veins grow (Olson and Pollard, 1991) (Figure lb). c) The bridges start to break (Figure 1c). Veins are shown here to break the bridges, although solution seams can link the overstepping veins. d) The veins are linked by through-going fractures (Figures 1d and 1e). e) A through-going fault is developed, with the bridges often being brecciated as displacement continues. As shown in Figure 1(f), the brecciation is often more complex and extensive than illustrated in Figure 2(e), which shows a simplified version of the geometry.