THE HETEROGENEOUS STRUCTURE OF FAULT ZONES WITHIN CARBONATE ROCKS: EVIDENCE FROM OUTCROP STUDIES AND IMPLICATIONS FOR FLUID FLOW

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(1) Introduction

Fractures, and in particular faults, are commonly responsible for enhancing porosity and permeability within tight carbonate successions and are one of the principal controls on fluid flow in the sub-surface. Knowledge of the heterogeneity in fault zone structure is a pre-requisite for the construction of models of fault zone evolution and also for assessments of the fluid capacity and flow behaviour within faulted carbonate sequences. This paper presents field evidence of the structural heterogeneity of fault zones in carbonate successions, and describes the processes responsible for causing such fault zone heterogeneities. The implications for fluid flow within heterogeneous fault systems are considered, drawing on examples from mineralised fault systems in limestone successions.

(2) Fault zone structure and heterogeneity in carbonate rocks

In their simplest form, faults in carbonate rocks comprise a single fault trace. However, in practice, faults often comprise a pair of slip surfaces or multiple slip surfaces, that bound lens-shaped zones of complex deformation. Therefore, faults are rarely simple structures with a continuous homogeneous content. Commonly, fault zone structure is highly heterogeneous, with marked lateral and vertical variations in the fault zone width, content and internal structure occurring over short distances (Figure 1). Fault zone heterogeneities (*i.e.* deviations from a single planar fault surface) occur on all scales and can have a variety of forms, such as fault bends, relay zones and branch lines. Heterogeneity is associated with various structures within the fault system, which are described further below.

(3) Structures responsible for fault zone heterogeneity

(i) Fault bends

Fault bends are local deviations in the dip and/or strike of a fault surface and may occur over a wide range of scales (cm-km). In profile, bends may be the result of fault plane refraction during the propagation of the fault through a succession of rheologically contrasting rock layers. Alternatively, bends may result from the linkage of non-coplanar segments of an originally segmented fault trace, either in the vertical or horizontal section.

Fault zones are often wider and more complex at fault bends than elsewhere on the fault. Here, the fault zone may contain lenses of more or less deformed wall rock (Figure 2). Subsidiary deformation outside the fault zone is also strongly associated with these changes in the fault geometry. Dense fracture arrays (so-called damage zones) comprising joints, calcite veins and minor faults also tend to be localised around these fault bends. Thus, layer-controlled bends may give rise to layer-parallel, linear zones of accentuated fracture permeability, whereas bends with a steep plunge may give rise to sub-vertical permeable corridors.

(ii) Relay Zones

Between overlapping fault segments, displacement is transferred between the faults by deformation of the intervening host rocks. These domains are referred to as relay zones. Displacement transfer achieved by rotation of the layering (beds) gives rise to a relay ramp. However, relays cannot sustain infinitely high displacement gradients; they are breached by the propagation of one, or less often two, of the relaying fault segments. With progressive displacement, the breached relays become increasingly deformed (Figure 3). Deformation within breached relays in massive carbonate rocks tends to be more complex than in relay zones in well-bedded successions, due to the difficulty in accommodating bed rotations within the relays. Within relatively massive carbonate successions, antithetic faults, synthetic faults and relay ramp bedding plane slip surfaces interact to systematically accommodate ramp deformation (Figure 3). Fault densities within breached relay zones are one to orders of magnitude greater than regional or outcrop fault densities. These fracture densities provide highly permeable conduits in fractured reservoirs.

(iii) Branch-lines

Where two fault segments link, the linear zone of intersection between the faults is known as a branch-line, the plunge of which depends upon the relative orientations of the intersecting faults. The presence of a branch-line on a fault gives rise to an angular fault bend on the footwall fault which may determine the local slip direction on the fault, causing an obstacle to stable pure dip-slip displacement. Therefore obliquely-plunging branch-lines are likely to be modified by abrasion of the footwall fault, ideally into that of a cylindrically curved fault surface. For this reason, branch-lines are characterised by anomalously thick fault breccias (Figure 4) and, as they have a significant vertical extent, they are likely to be important permeable conduits in normal faults.

(4) Processes controlling fault zone development and growth

Tip-line bifurcation is a principal process by which fault heterogeneities form. As a fault propagates, retardation of the tip-line, at a point or a layer, can cause two overlapping fault lobes to develop (Figure 5). This process is responsible for the formation of segmented fault traces and therefore relay zones. The nature of the fault segmentation (*i.e.* vertical or lateral) depends upon the direction of tip-line propagation through the plane of observation. A related phenomenon is the generation of fault segments within certain layers prior to the development of a through-going fault.

Asperity bifurcation refers to the process by which heterogeneities are removed from the fault surface and are incorporated into the fault zone. As displacement increases, fault plane irregularities, such as fault bends, are removed by the formation of a secondary short-cutting fault surface (Figure 6). The asperity is therefore incorporated as a fault-bound lens into the fault zone.

Both bifurcation processes give rise to paired slip surfaces bounding fault zones and occur at all scales. Significantly though, the kinematic interpretation attached to the timing of fault activity of the paired slip surfaces is opposite. In tip-line bifurcation, at least two slip surfaces are active at the same time at some stage during the fault zone development, whereas, in asperity bifurcation, the original slip surface is superceded by a fault that bypasses the asperity.

(5) Fluid flow in faulted carbonate rocks

What observational evidence supports the notion that fault zone heterogeneity controls heterogeneity of sub-surface flow? Base-metal ore deposits in the Dinantian of Britain and Ireland provide finite records of the flow of ore genetic fluids associated with normal faults in limestone. The occurrence of ore within the fault systems is particularly localised around fault irregularities, such as fault dip changes associated with rheological boundaries, breached relay zones and branch-lines. The strongly heterogeneous structure of the fault zones demands that fluid flow within such systems is equally heterogeneous, or more likely, that the fault system heterogeneity is compounded by the cubic flow law, so that fluid flow is extremely heterogeneous. Thus fluids are concentrated within the domains close to fault irregularities.

These findings are consistent with the fact that flow within fractured reservoirs is notoriously difficult to predict. The heterogeneous nature of fault zones combined with the cubic flow law, would suggest that the flow response at wells could, in the limit, appear practically bimodal, with very poorly performing wells or large portions of wells dominating contrasting with those wells, or more likely portions of wells, that perform very well. Therefore methods which increase the likelihood of defining fault surface irregularities are crucial to optimising the flow from individual wells. Drilling the precise location of the highly fractured or brecciated components of such systems is often beyond the resolution limits of most datasets, though the identification of relays or branch-lines which are at or above the limit of seismic resolution may sometimes be possible.

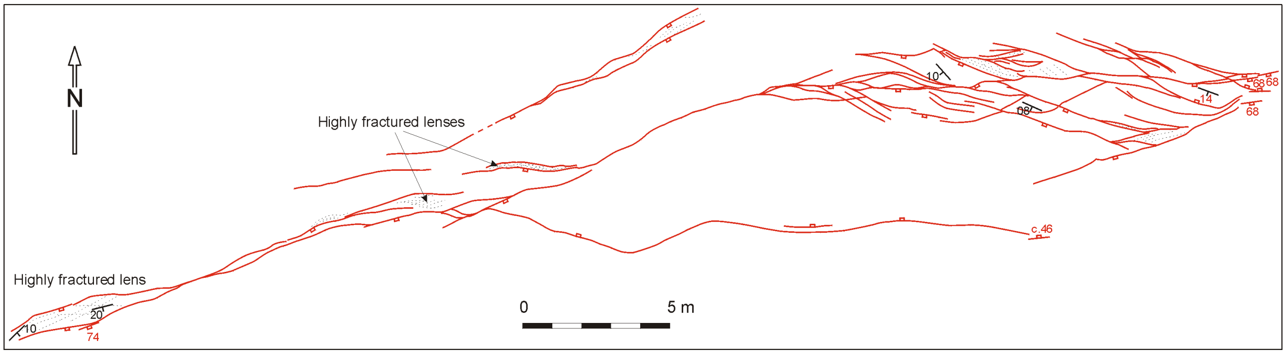


Figure 1. Map of a small normal fault trace (displacement = 0.8m) on a horizontal erosion surface within massive limestones, south of Fomm ir-riħ bay, Malta. The structure of the fault changes sharply in width, number of slip surfaces and content over small distances.

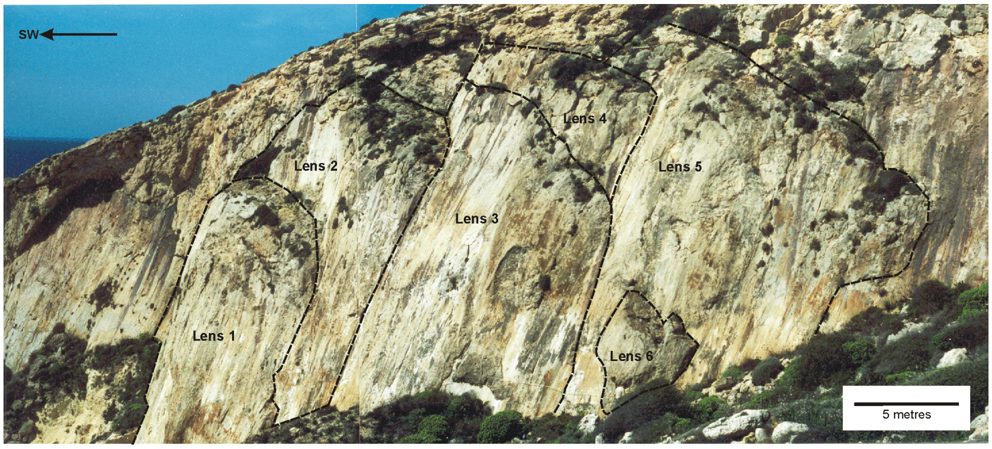
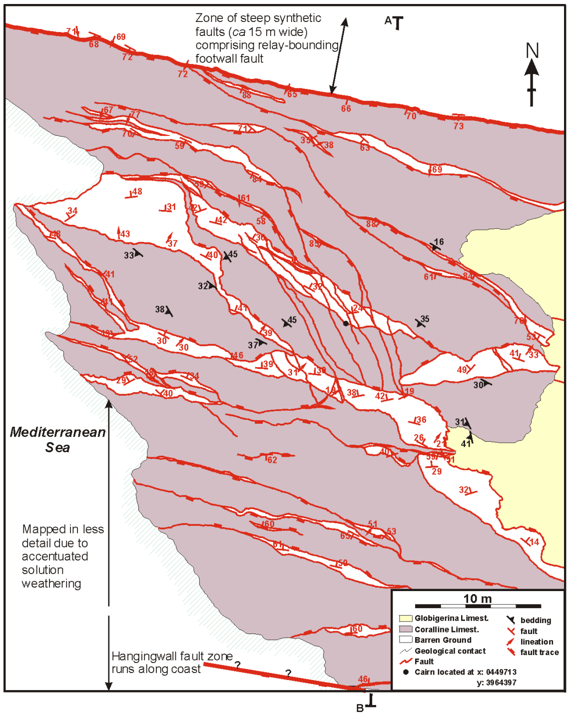


Figure 2. Complex fault zone structure, comprising stacked decametre-scale lenses of limestone, occupying a highly curved bend on the Magħlaq fault, Malta (displacement >220m).



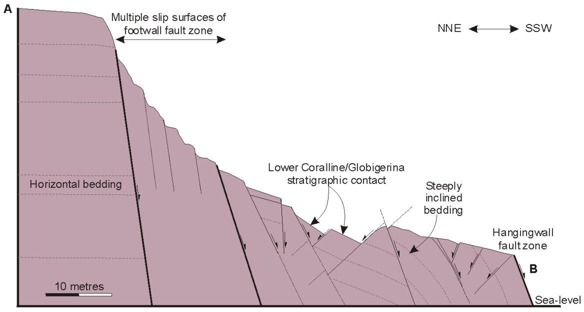


Figure 3. Map and schematic cross-section of part of a breached relay ramp within massive platform limestones along the Magħlaq fault, Malta. The relay is ca 45m wide at this point and is bounded by footwall and hangingwall faults with displacements of ca 30m and >100m, respectively. The relay zone is a highly deformed ramp cut by numerous faults, both synthetic and antithetic to the main fault zone dip. Synthetic faults tend to occur close to the ramp-bounding faults, whilst antithetic faults are distributed throughout the ramp, but are particularly well developed within the centre, where they comprise a hard-linked anastomosing network. Both fault sets interact to facilitate accommodation of rotational strains within the ramp.

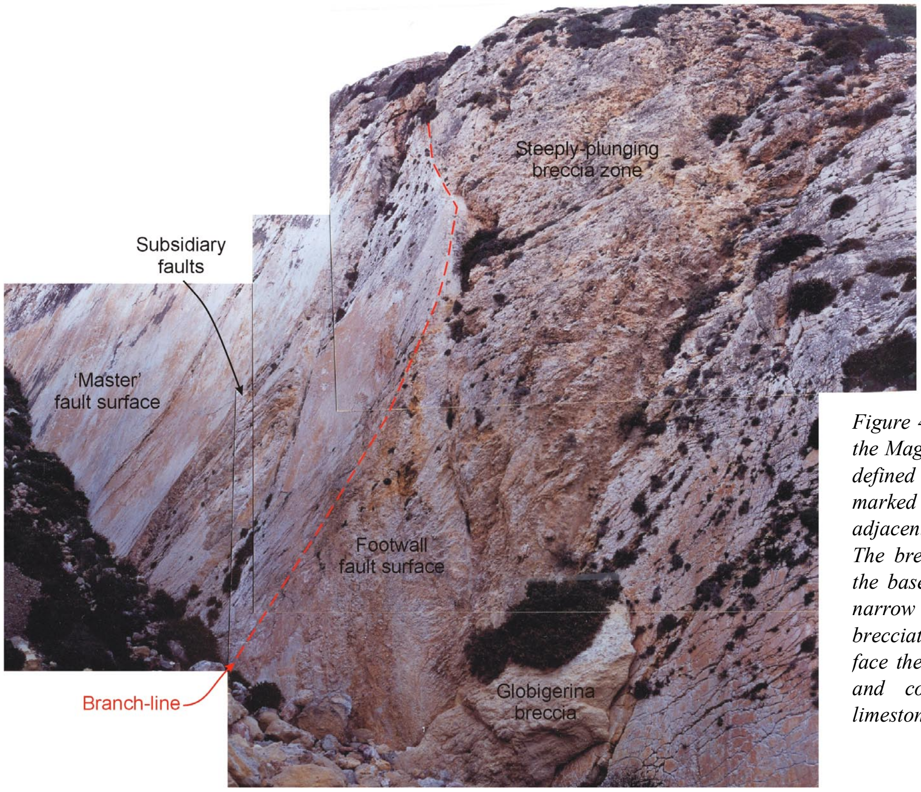


Figure 4. Steeply plunging branch-line along the Magħlaq fault, Malta. The branch-line is defined on the master fault surface as a marked linear zone of brecciated limestone, adjacent to a ca 4m offset of the fault surface. The breccia zone is vertically variable. At the base of the exposure, the branch-line is narrow (ca 1m wide) and intensely brecciated. However, higher up in the cliff-face the breccia zone widens to ca 8 metres and contains m-scale intact blocks of limestone in a weakly brecciated matrix.

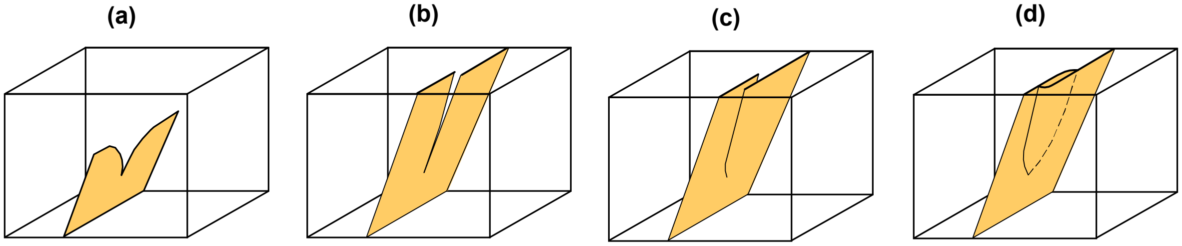


Figure 5. The process of tip-line bifurcation (see text).

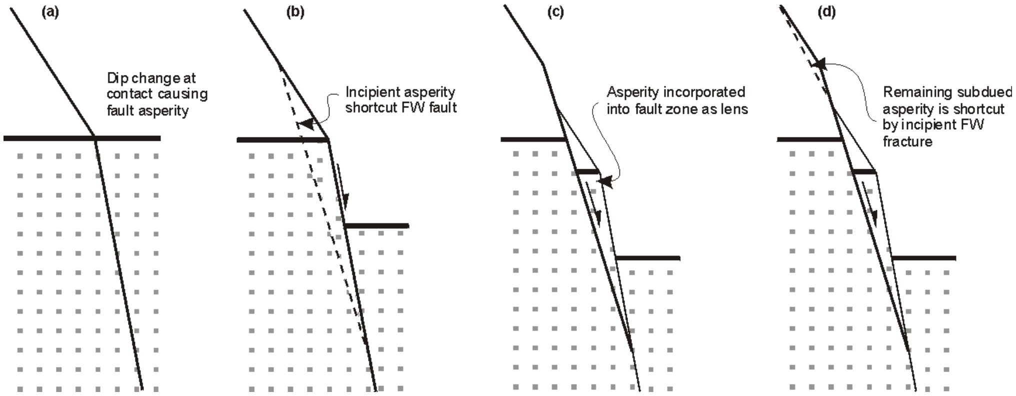


Figure 6. The process of asperity bifurcation (see text).