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Contemporaneous movement along crossing conjugate normal faults

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Abstract—A sandbox experiment is described in which conjugate normal faults cut each other in an 'X' configuration. Detailed measurements, using a stereoscopic technique, demonstrate synchronous movement along these opposing faults. Their mutual offset leads to generation of new fault segments, and finally to a complex but systematic interference structure. Since similar structures can be observed in the field, it is argued that contemporaneous operation of conjugate normal faults is also possible in large-scale crestal-extension structures over salt domes and deltaic rollover anticlines.

INTRODUCTION

ANDERSON (1951) demonstrated the relationship between the three fundamental stress regimes at the earth's surface and their associated faults, thus defining the basic categories of normal, reverse and wrench faulting. For each stress regime there are two possible fault plane orientations, forming a conjugate pair whose acute bisectrix gives the direction of maximum compressive stress.

Whether one or both fault sets actually develop will depend on such considerations as the symmetry of bedding planes with respect to the stress axes, or the presence of pre-existing zones of weakness which may control the position and movement of new faults. Operation of a single fault set causes rotation of the boundaries of the faulted material, or a bending of the fault planes, as shown by Freund (1974). Irrotational strain requires the operation of both sets of faults in conjunction, a concept known in the soil-mechanics literature as double gliding (De Josselin de Jong 1959). Nevertheless, as Freund (1974, p. 101) stated, "it seems geometrically impossible that the two sets of the conjugate faults operate simultaneously because they interfere mutually where they cross each other".

Many subsurface studies have documented conjugate sets of normal faults in extensional structures over salt domes and deltaic rollover anticlines (e.g. Behrmann 1949, Merki 1972, fig. 6). Where opposing faults cross, some interpretations (e.g. Fig. 1) indicate one set of faults to be consistently offset and thus entirely older than the conjugate set. Geometrical problems of interference are then non-existent but one is faced with the question of why the faults should operate consecutively in time. Because both sets require the same stress orientation, why should one become unstable with respect to the other?

An independent check on fault timing may often be made from stratigraphic data. In Fig. 1 for example, it may be seen that a few faults, both north- and south-dipping, were active until after the Early Miocene, although the majority appear to have ceased activity prior to the Late Oligocene. Yet on the interpretation, some of the pre-Late Oligocene faults (e.g. A and B) are shown as displacing post-Early Miocene faults (e.g. C and D), a rather unlikely relationship. Although the stratigraphic evidence suggests that both north- and south-dipping faults were active over the same time periods, the fault intersections have been drawn to show the north-dipping set as post-dating the south-dipping set.

Similar problems are encountered in reconstructing the complex patterns of extensional faulting over anticlinal crests in deltaic areas (Merki 1972). Thickening of sedimentary units across such faults often indicates contemporaneous operation of both conjugate sets. How should one then depict their deeper subsurface intersection?

The aim of this paper is to demonstrate that, on an experimental scale at least, crossing conjugate faults can operate contemporaneously, to produce characteristic interference structures. Where found in nature, such structures can form a criterion for recognition of contemporaneous movement. The experimental fault relationships should also serve as a basis for improved subsurface interpretation.

The advantage of experimental studies is that, by appropriate boundary displacements, conjugate shear planes or faults are readily developed, and their time relationships can be followed easily. In earlier experiments, conjugate sets of shears were produced by, for example, Hoeppener *et al.* (1969), Freund (1974) and Means (1977), using homogeneous modelling material and irrotational boundary conditions. In the clay-cake experiments of Hoeppener *et al.* (1969) the shears were closely spaced and displayed only minor displacements. Opposing conjugate shears showed little interference because they tended to occur in separate domains of the model.

In a plasticene model experiment by Freund (1974) there was clear cross-cutting and interference between the two sets of faults. He suggested that the two interfering faults moved alternately, so that first one was offset, and then the other, with new faults forming to replace those

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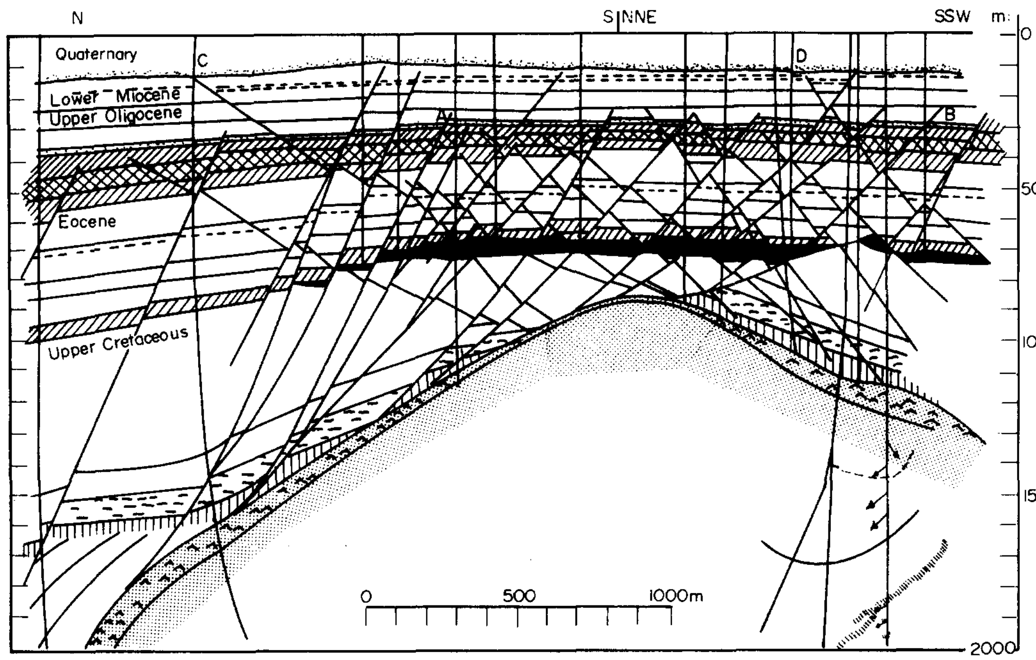

Fig. 1. Reitbrook salt dome, North Germany (after Behrmann 1949). Example of crossing conjugate normal faults over an anticlinal crest, illustrating a typical problem of subsurface reconstruction. Oil wells are shown as vertical lines, oil accumulations in black. The interpretation shows north-dipping faults consistently offsetting those dipping south. Nevertheless, some of these supposedly later faults (e.g. A and B) appear not to truncate the Upper Oligocene strata, whilst some south-dipping faults (e.g. C and D) displace the Lower Miocene.

offset to positions where they became locked (Fig. 2).

To study such fault relationships in more detail, sandbox experiments were carried out at Koninklijke/Shell Exploratie en Produktie Laboratorium in Rijswijk, using a stereoscopic technique to analyse the history of movement along the interfering fault zones. One of these experiments is described below.

EXPERIMENTAL APPARATUS

The equipment used was a glass-fronted sandbox (Horsfield 1977), containing densely-packed dry sand of grain-size 0.3–0.6 mm. The distance between front and rear walls was 10 cm. Conjugate normal faults were generated by withdrawing two lateral retaining walls whose initial separation was such as to lead to interference between the resultant faults.

The two walls were withdrawn at a constant rate of 1 mm/min, and the sand model was photographed at each 1 mm displacement increment. Faults in the sand were visible as offsets of the marker horizons (layers of dark-stained sand). Incremental fault displacements at each stage of the experiment could be subsequently established by stereoscopic comparison of pairs of successive photographs (Butterfield *et al.* 1970), the differential movements in the sand pack being visible as a variable relief of the pseudo-stereoscopic image. Measurement with a simple parallax bar gave displacements to an accuracy of ± 0.1 mm.

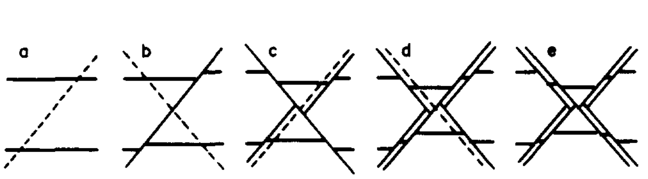

Fig. 2. Mechanism (after Freund 1974) to produce irrotational plane strain by the operation of conjugate faults in alternation. (a) Incipient fault (dashed line). (b) Slight displacement on the first fault and initiation of a conjugate fault. (c) First fault offset by the conjugate fault, becomes locked. (d) New fault, parallel to first, offsets conjugate. (e) New conjugate fault forms.

EXPERIMENTAL RESULTS

As the two sidewalls were slowly withdrawn, a normal fault developed upwards from the base of each wall, making an angle of 75° with the horizontal. Above the point of intersection of these faults, no fault displacement was apparent until the sidewalls had each moved about 4 mm. Subsequently the faults extended to the surface, forming an X-shaped configuration (Fig. 3a). The photogrammetrically-measured incremental throw on the faults at interval 4–5 is shown in Fig. 3(d). The displacements along fault pairs A_1 and B_1, C_1 and D_1 were almost identical, implying a synchronous movement rather than an alternation of opposing faults (cf. Freund 1974). The difference in throw between upper and lower segments can be largely explained by the different inclinations of these faults. Along the individual segments the throw was roughly constant, but showed a slight decrease near their terminations and crossover, an indication that the moving sand blocks were non-rigid near these points.

As the experiment progressed, new faults appeared and existing ones became inactive. The steep segments A_1 and B_1 were cut across by the less steep pair A_2, B_2 (Figs. 3b and e). From Fig. 3(e) it may be seen that the combined

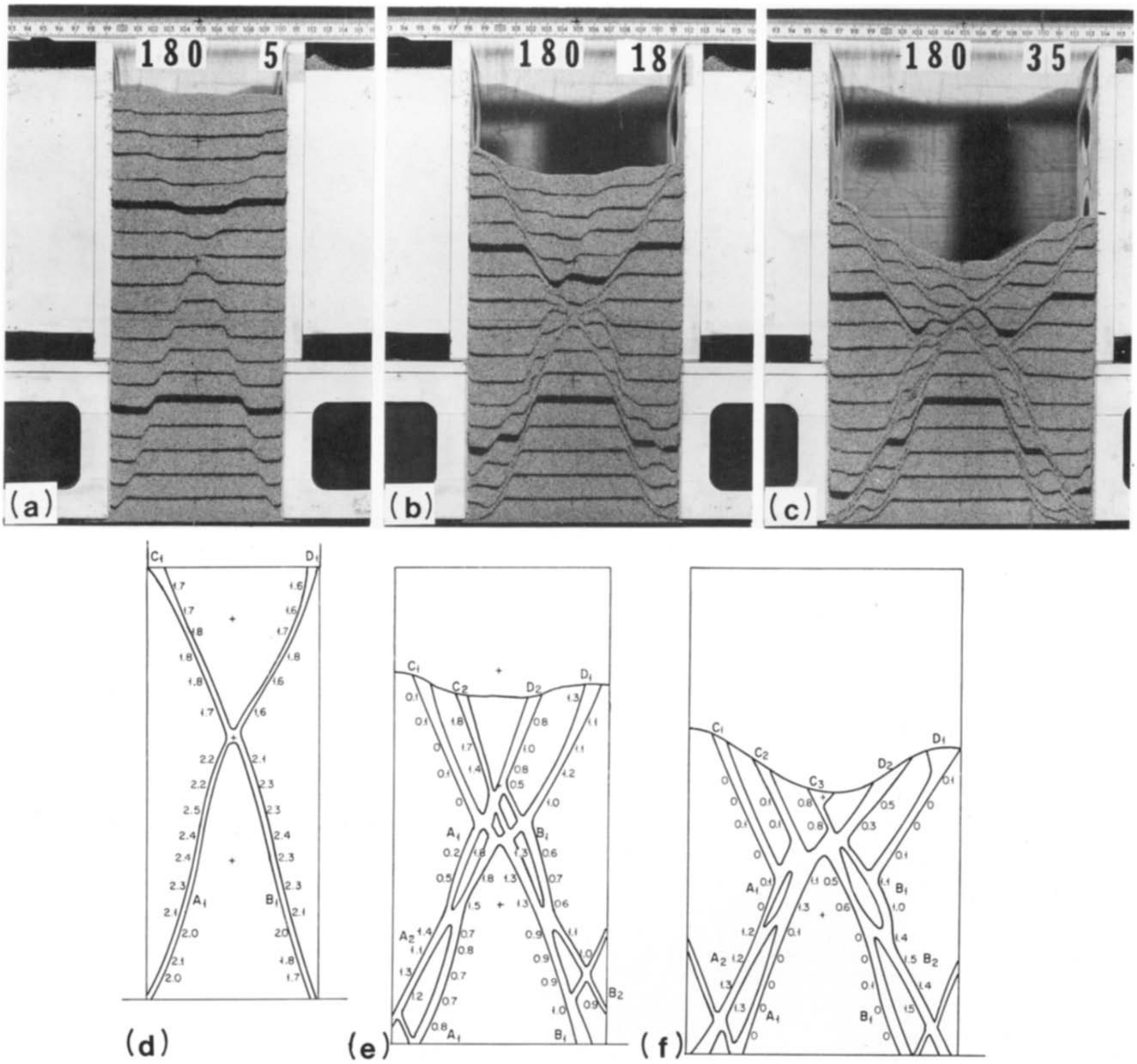

Fig. 3. Sandbox experiment demonstrating contemporaneous movement along crossing faults. The sandpack, with marker layers of dark-stained sand, is seen horizontally through a glass front wall. The lateral retaining walls are each constructed from two Teflon-coated blocks, fixed rigidly together. Photos (a), (b), and (c) show the faults after 5 mm, 18 mm, and 35 mm respectively, of outward movement of each retaining wall. The line drawings (d), (e) and (f) depict fault geometry corresponding to each photograph, together with values in mm of the stereoscopically-measured fault throw during the preceding 1 mm increment of outward movement of the walls.

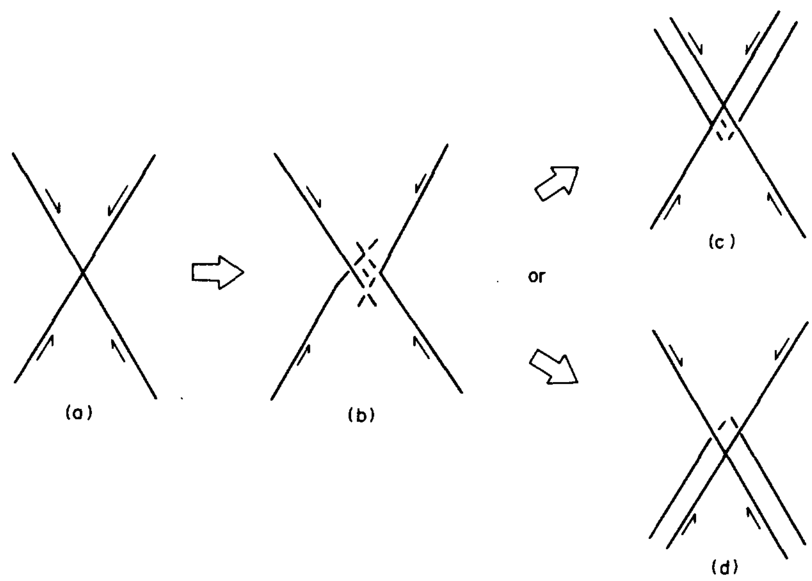

Fig. 4. Proposed mechanism of contemporaneous movement along crossing faults (compare with Fig. 2). (a) Initial formation of conjugate pair. (b) Movement along each fault causes offset of both faults. Further displacement leads to increasing small-scale deformation in the crossover region. (c) and (d) The original faults eventually break through to form new extensions. External constraints on the fault positions may determine which of the alternatives (c) or (d) actually develops. Continued displacement will generate an increasing number of new fault extensions.

incremental throw on faults A_1 and A_2 ($\sim$1.9 mm) in the interval 17–18 was roughly equal to that on B_1 and B_2. The upper portion of A_1 was almost inactive. Movement along C_1 and D_1 decreased with the appearance of C_2 and D_2, so that by stage 18 movement on C_1 had virtually ceased. The combined incremental throw on C_1 and C_2 (1.5–1.9 mm) was comparable to that on D_1 and D_2 (1.7–2.1 mm).

Deformation was stopped when the height of the sandpack had been reduced to 2/3 of its original value (Fig. 3c). By this stage, faults C_1, C_2, D_1, A_1 and the lower portion of B_1 were inoperative, the movement being concentrated on C_3, D_2, A_2, B_2 and the upper portion of B_1. Thus, even with total displacements in excess of 5 cm, all four arms of the basic 'X' configuration were still represented by at least one active fault segment. Despite the considerable total strain, large volumes of the sand remained neither distorted nor rotated.

On the basis of this and similar experiments, an alternative explanation (Fig. 4) to Freund's (1974) model of *alternating* crossing faults is proposed. The movement on the faults is considered to be *continuous* but with gradual offset of segments of each fault until these become so locked that generation of a new parallel branch, in a more favourable position for movement, becomes necessary. The eventual structure may be very complex but in its simplest development it could resemble Figs. 4(c) or (d).

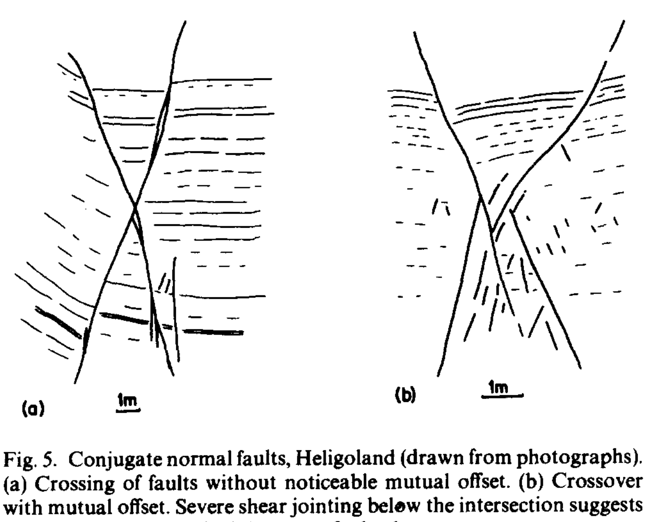

Fig. 5. Conjugate normal faults, Heligoland (drawn from photographs). (a) Crossing of faults without noticeable mutual offset. (b) Crossover with mutual offset. Severe shear jointing below the intersection suggests incipient new fault planes.

FIELD EXAMPLES

The suggested mechanism is based on small-scale experiments with cohesionless sand, a material whose behaviour is believed to simulate that of sedimentary rocks on a larger scale (Horsfield 1977). The structures observed have their counterparts in exposures of faults in consolidated sandstones, as may be seen on the North Sea island of Heligoland. This island, whose cliffs are formed of resistant Bunter Sandstone, owes its origin to the doming of underlying Zechstein salt. Extension of strata over the salt uplift has generated two conjugate sets of normal faults, downthrowing to the NW and SE respectively. These have been described in detail by Schmidt-Thomé (1937). Most have displacements of less than a metre, with a maximum of about 5 m.

Figure 5(a) shows the crossover of two small conjugate faults exposed along the southwest coast. Neither fault offsets the other and they could thus have operated over the same time period. Figure 5(b) shows what could be a more advanced stage of interference, where both crossing faults appear to be offset. Widespread jointing in the underlying horst suggests the initiation of new, downward extensions to the truncated faults, as in Fig. 4(d).

CONCLUSIONS

The Heligoland structures are interpreted to be of similar origin to those observed in sandbox experiments, caused by the contemporaneous operation of crossing conjugate faults. On still larger scales such fault interaction should be equally feasible, but would generate complex accommodation structures at fault crossovers. Although these might not be resolvable in the subsurface with seismic or well data (cf. Fig. 1), their presence should be anticipated. When dealing with subsurface interpretation of conjugate fault systems, one should not assume *a priori* that one set postdates the other.

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