Pergamon

Journal of Structural Geology, Vol. 17, No. 10, pp. 1351 to 1360, 1995
Elsevier Science Ltd
Printed in Great Britain
0191-8141/95 $9.50 + 0.00

0191-8141(95)00037-26

Strike-slip relay ramps

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(*Received* 29 *November* 1994; *accepted in revised form* 17 *March* 1995)

Abstract—Areas of reorientated bedding at contractional oversteps between strike-slip faults are here called *strike-slip relay ramps*. Metre-scale examples are described from the Jurassic sediments at East Quantoxhead, Somerset, U.K. Larger strike-slip relay ramps occur in the Rio de Peixe Basin, NE Brazil, along the Newport–Inglewood Trend, California, and in the Bovey Basin, SW England.

Although the geometry and development of strike-slip relay ramps are similar to those of relay ramps in normal fault systems, there are differences in the structures which accommodate the transfer of displacement between the overstepping faults. Whereas strike-slip relay ramps are typically transpressional, with pressure solution often occurring, relay ramps in normal fault systems are dominated by extension or transtension. Care needs to be taken when interpreting areas of reorientated bedding between overstepping faults, particularly when displacement directions are unknown, for example when using seismic data. This is because relay ramps can occur in both strike-slip and normal fault zones.

INTRODUCTION

A *relay ramp* is an area of reorientated bedding which transfers displacement between two normal faults which overstep in map view and which have the same dip direction (Larsen 1988). This paper describes the geometry and development of structures between overstepping strike-slip faults (Fig. 1), where bedding can be reorientated to accommodate a component of vertical displacement on the faults. They are similar to relay ramps (Fig. 2), and are here called *strike-slip relay ramps*. There has been considerable interest in relay ramps (e.g. Griffiths 1980, Larsen 1988, Peacock & Sanderson 1991, Schlische 1992) because of their role in hydrocarbon migration and entrapment (Morley *et al.* 1990, Peacock & Sanderson 1994), and because of their effects on erosion and sedimentation (Gawthorpe & Hurst 1993, Jackson & Leeder 1994).

Small, fully-exposed examples of strike-slip relay ramps in Somerset, U.K., are described in terms of the amount of linkage that occurs, i.e. the extent to which the overstepping faults are connected by faults cutting the relay ramp. The Somerset examples are used to deduce the evolution of strike-slip relay ramps, and are compared with much larger examples. Strike-slip relay ramps are compared with relay ramps in normal fault systems. Similar structures can occur between overstepping thrusts (e.g. Chadwick 1993, fig. 11), but these are not discussed in this paper.

STRIKE-SLIP RELAY RAMPS IN SOMERSET

Five areas which show strike-slip relay ramps at contractional oversteps (e.g. Fig. 3) have been mapped on the beach within 100 m of the steps at East Quantoxhead, Somerset (grid reference ST136443). They are exposed on bedding planes of Lower Jurassic limestones with a mean thickness of about 196 mm. The limestones occur between mudrock beds which have a mean thickness of about 500 mm (Peacock & Zhang 1994). The area is in the Bristol Channel Basin, which was effected by Mesozoic N–S extension (Chadwick 1986, Brooks *et al.* 1988, Donato 1988), which produced E–W striking veins and normal faults (Peacock & Sanderson 1992). The strike-slip faults discussed in this paper are conjugate about N–S, and developed during late Cretaceous or early Tertiary N–S contraction (McLachlan 1986, Beach 1989, Peacock & Sanderson 1992).

Mapping was undertaken on photographs taken using either a hand-held camera, or from heights of 2–4.5 m using a pole and tripod. Relative heights of points on bedding planes were measured to within 1 mm using a surveyors' level. Measurement errors and weathering of bedding surfaces caused errors of up to about 5 mm. Contouring of these spot heights was performed manually because of the complexity of the surfaces. Fault displacements can be measured using the widths of pull-aparts (Peacock & Sanderson 1995) and displaced E–W striking veins and normal faults. It is often difficult to measure the displacements on the larger faults, where pull-aparts have been destroyed. The maximum fault displacement in the areas mapped is probably no more than about 2 m.

Slickenside lineations are rarely observed on the mapped faults because of weathering, but they are common in the nearby cliffs. Slickenside lineations plunge at an average of 5° towards 208° for the sinistral faults (Fig. 4a), and at 12° towards 157° for the dextral faults (Fig. 4b). The area studied at East Quantoxhead shows bed dips outside the fault zones of about 5° towards 058° (Fig. 4c). The fault displacement directions

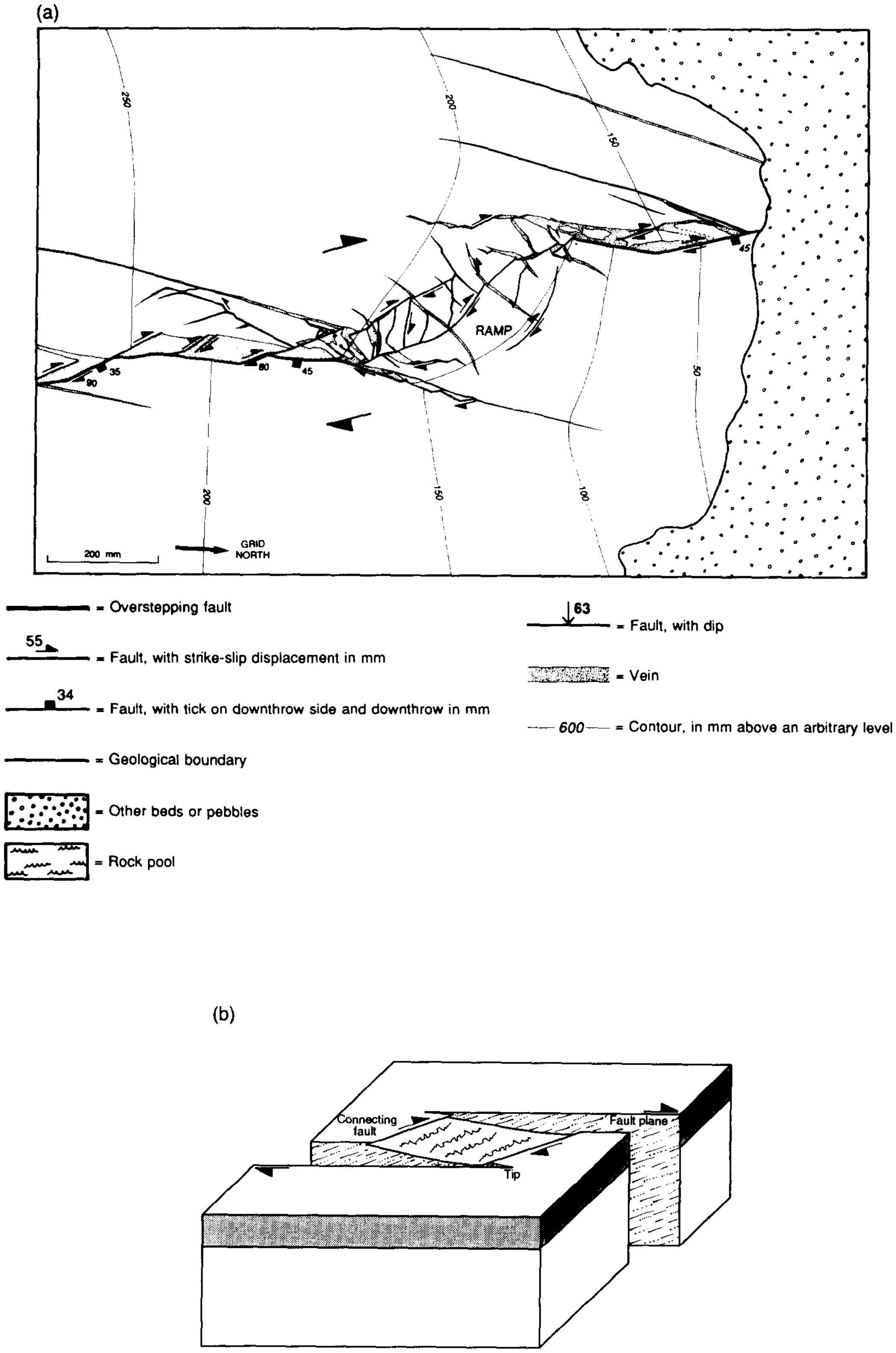

Fig. 1. (a) Map of a strike-slip relay ramp at East Quantoxhead, Somerset. The contours are for a limestone bedding plane in millimetres above an arbitrary datum level. Veins and antithetic faults are concentrated in the relay ramp, which occurs in a contractional overstep between two sinistral faults. (b) Block diagram showing the main features of a strike-slip relay ramp. Bedding is reorientated in the relay ramp to transfer the component of vertical displacement between the overstepping faults. Veins and faults can develop within the relay ramp, and may connect the overstepping faults. The overstepping faults may or may not meet at depth.

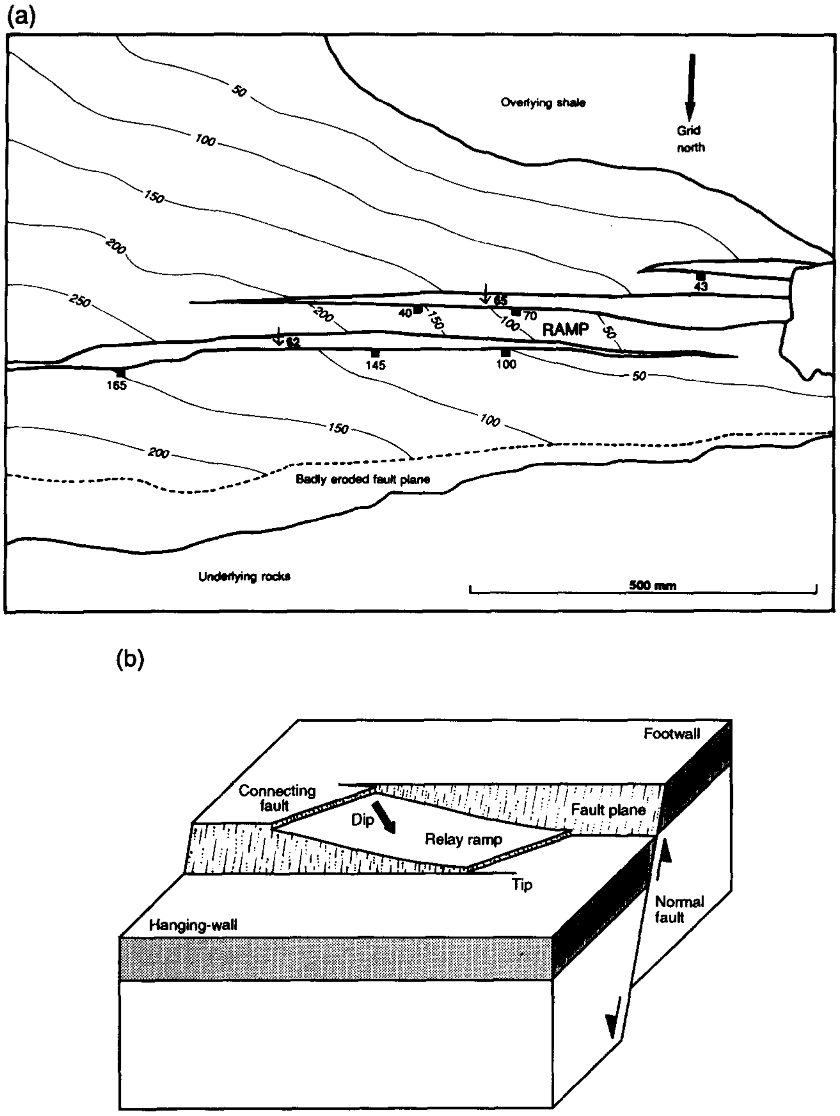

Fig. 2. (a) Map of a relay ramp between two overstepping normal faults, at Kilve, Somerset (grid reference ST149446). See Fig. 1(a) for key. The contours are for a limestone bedding plane in millimetres above an arbitrary datum level. Note that the map is a mirror image so it corresponds with the geometry of the structure shown in Fig. 1(a). (b) Block diagram showing the main features of a relay ramp between overstepping normal faults (see Peacock & Sanderson 1994).

are therefore oblique to the plane of bedding, causing some vertical separation of bedding. This is accommodated at fault oversteps by reorientation of bedding at strike-slip relay ramps.

Analysis of the traces and tips of the strike-slip faults suggests the following sequence of development. An array of en echelon veins developed in a limestone bed. The veins were then linked by shear fractures to form a zone of pull-aparts (Peacock & Sanderson 1995). The pull-aparts eventually linked to form a through-going fault. For movement to occur out of the plane of bedding, the fault must have propagated into the overlying and underlying mudrocks. Note that pull-apart zones are shown as faults in Figs 1(a) and 5 because of the shear that occurs.

DEVELOPMENT OF STRIKE-SLIP RELAY RAMPS

The examples of strike-slip relay ramps presented in Fig. 5 show a range of geometries with different amounts of linkage. The fault zone shown in Fig. 5(a) comprises several relay ramps, the widest of which does not have connecting faults linking the two overstepping faults. Other relay ramps in the fault zone shown in Fig. 5(a), and the relay ramps shown in Fig. 5(b), are extensively fractured, with veins and faults partially connecting the overstepping faults. The examples shown in Figs. 5(c) and 5(d) are completely linked, with fault-bound areas of reorientated bedding representing broken strike-slip relay ramps. Several characteristic features have been

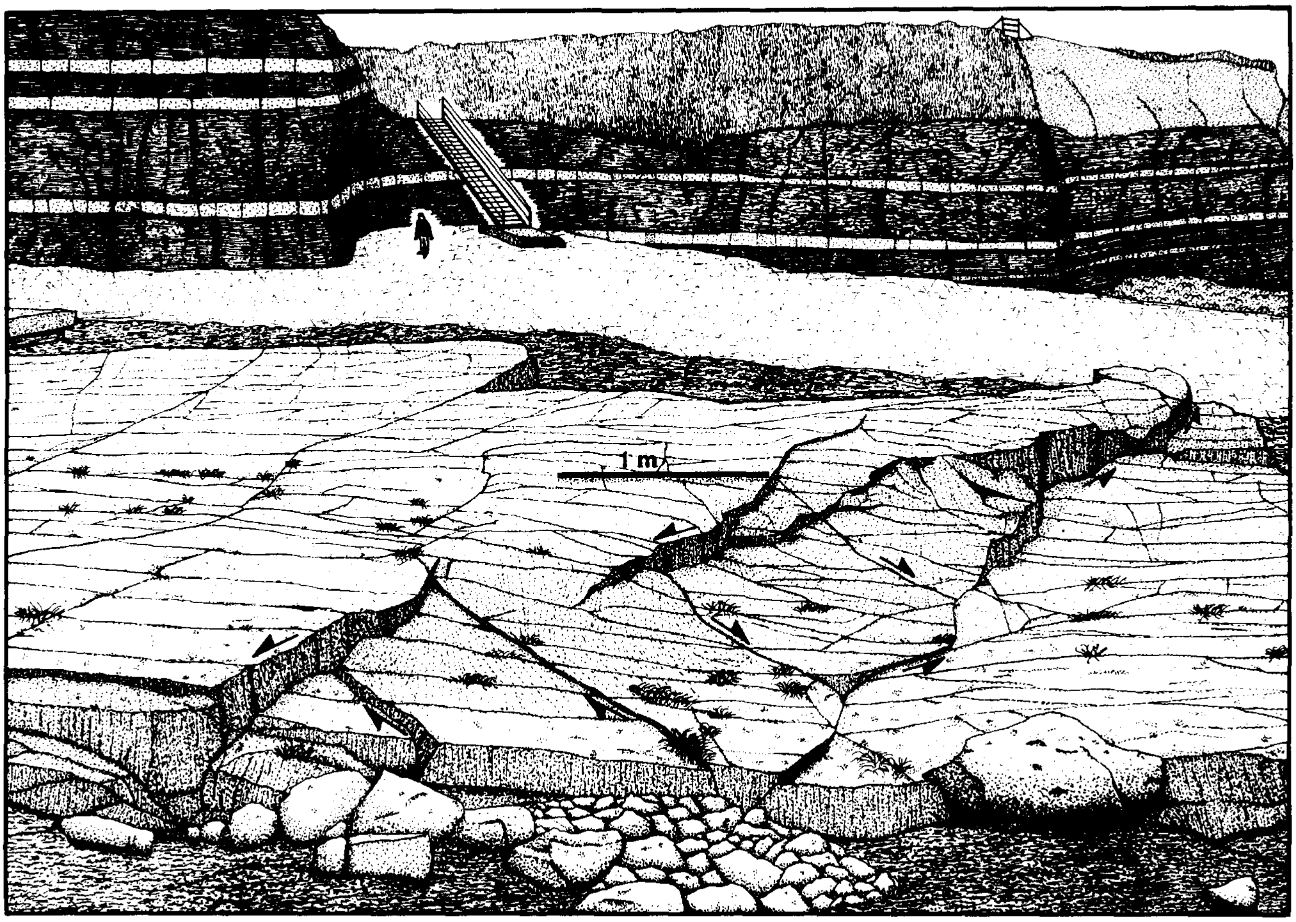

Fig. 3. Line drawing of a strike-slip relay ramp, viewed from the north. A map of this structure is shown in Fig. 5(b). The relay ramp occurs at a contractional overstep between two sinistral faults, and is perfectly exposed on a gently-dipping limestone bedding plane. For size, a 1 m ruler has been placed behind the relay ramp.

observed in the strike-slip relay ramps at East Quantoxhead:

(a) The fault zones consist of a series of en echelon fault segments trending at 15–25° to the zone, whose slip is synthetic to the zone. These correspond to Riedel shears (Tchalenko 1970).

(b) The relay ramps are contractional, being developed at contractional oversteps between strike-slip fault segments. The segments are right-stepping in left-lateral zones (Fig. 1a), and left-stepping in right-lateral zones (Fig. 5).

(c) Calcite veins extend from the faults into the wall-rocks, with the vein thickness decreasing away from the faults (Figs 1a and 5d). Many faults pass laterally into veins (Fig. 1a).

(d) Veins and antithetic faults occur within the relay ramps at high angles to the fault zones (Figs 1a, 5a & b). The antithetic faults are often sigmoidal (Figs 1a and 5c), indicating rotational strain in the relay ramps, with the sense of rotation consistent with that of the fault zone. They commonly show pull-aparts (Peacock and Sanderson 1995). Some antithetic faults extend out from the ramp (e.g. Figs 5b & c).

(e) Pressure solution seams are locally developed within the relay ramps (Fig. 5c).

(f) Synthetic faults link the en echelon fault segments in several of the zones (Figs. 5b, c & d). These synthetic faults cut and displace the earlier antithetic faults (Fig. 1a). Some strike-slip relay ramps (e.g. Figs 5a, b & c) have minor sinistral and dextral faults with dihedral angles of only a few degrees, suggesting stress reorientation during ramp development.

These structures suggest a sequence of development of the structure within strike-slip relay ramps. Early synthetic fault segments are followed by antithetic faults, and then by synthetic linking faults. This sequence has been widely reported from areas of wrench faulting (e.g. Tchalenko 1970, Wilcox *et al.* 1973). We emphasize here the importance of their localisation in strike-slip relay ramps, and the widespread development of antithetic faults in a contractional setting.

The evolution of strike-slip relay ramps is illustrated in Fig. 6. The development starts with two isolated or en echelon faults (Fig. 6a), and ends with the two faults having linked up to form a single fault with a contractional bend (Fig. 6d). Further displacement may obscure

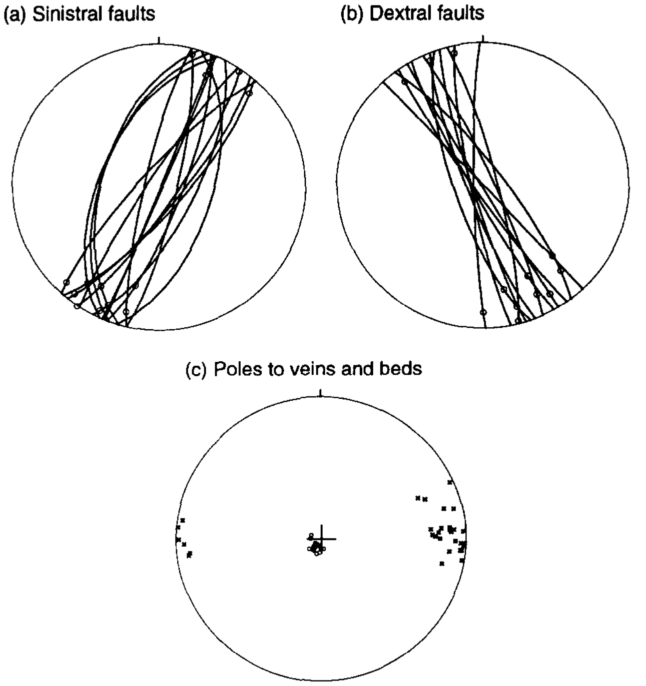

Fig. 4. Equal area stereograms for structures at East Quantoxhead, Somerset. (a) Sinistral strike-slip faults (great circles) have an average dip of nearly 90 towards 116°, and their slickenside lineations (dots) have an average plunge of 5 towards 208° (*n* = 15). (b) Dextral strike-slip faults (great circles) have an average dip of 87 towards 246°, and their slickenside lineations (dots) have an average plunge of 12 towards 157° (*n* = 12). The strike-slip faults indicate approximately N–S contraction. (c) Poles to N–S striking veins (crosses, *n* = 31) which also indicate N–S contraction. Poles to bedding (open circles, *n* = 20), which is oblique to the fault displacement directions.

the relay ramp, for example by the development of a strike-slip duplex at the bend (Woodcock & Fischer 1986).

LARGE STRIKE-SLIP RELAY RAMPS

The Rio do Peixe Basin, Brazil

Françolin *et al.* (1994) describe the faulting in the early Cretaceous Rio do Peixe Basin of NE Brazil (Fig. 7a). The basin is composed of three sub-basins separated by basement highs, with up to 2000 m of sediments. Sediments are Late Jurassic to Early Cretaceous, with the Antenor–Navarro Formation at the base and the Rio Piranhas Formation at the top. Françolin *et al.* (1994) show that E–W sinistral transtension, involving NNW extension and ENE contraction, controlled the deformation in the basin. The main fault is the sinistral Malta Fault, which strikes E–W and forms the southern boundary of two of the sub-basins. There are several NE-striking dextral faults, including the Portalegre and Rio Piranhas faults, which are conjugate to the Malta Fault. These faults are dominantly strike-slip, having slickenside lineations with pitches of 20° or less. They generally have a normal component, however, causing basin development. The master faults, including the Malta and Portalegre faults, have vertical offsets of up to several kilometres, and larger strike-slip offsets. Bedding mostly dips gently to the south or SE.

Françolin *et al.* (1994) show that the Santa Helena High, north of the western end of the Malta Fault, underwent initial transtension and later transpression, with thrusts occurring. They interpret the high as an area of crustal thickening at the conjugate intersection of the Malta and Portalegre faults. An alternative explanation is that the Santa Helena High is a strike-slip relay ramp between the Malta Fault and the E–W striking sinistral fault to the NW (Fig. 7a). These two faults are about 10 km apart and have an overlap of about 30 km. The conjugate Portalegre Fault, and the other dextral faults in the area, would have developed to accommodate the strains and rotation of bedding in the strike-slip relay ramp. The Sousa and Rio Piranhas formations (>500 m thick) are missing from the Santa Helena High, indicating at least 500 m of vertical displacement at the relay ramp. As with the Somerset examples (Figs. 5b & c), some of the antithetic faults (e.g. the Portalegre Fault) extend out of the strike-slip relay ramp.

The Newport–Inglewood Trend, California

The Newport–Inglewood Trend (Harding 1973) occurs on the edge of the Miocene to Holocene Los Angeles Basin. It consists of en echelon periclines and en echelon dextral strike-slip faults, with a lateral displacement of up to about 750 m. The Newport–Inglewood Trend is dominated by strike-slip displacements, with slickenside lineations in cores having low angles of pitch. The main periods of faulting were in the Miocene and Pleistocene. Topographic highs occur at contractional oversteps along the strike-slip faults because the zone is still active (Harding 1973, fig. 6). Secondary normal faults occur at extensional oversteps and bends, with thrusts occurring at contractional oversteps and bends (e.g. Fig. 7b). A strike-slip relay ramp occurs at a contractional overstep in the area mid-way between the Inglewood and Rosecrans oilfields, this being indicated by a change in the orientations of structure contours. The overstepping faults are about 3 km apart (measured perpendicular to their strikes) and they appear to underlap.

Strike-slip relay ramp in the Bovey Basin, SW England

The Bovey Basin (described by Bristow & Robson 1994) is a 7 km wide E–W and 5 km long N–S pull-apart basin, which contains over 1000 m of Palaeogene clays, sands and lignites. It developed at an extensional overstep between the northern segment of the Sticklepath–Lustleigh Fault Zone (SLFZ) and a fault system which includes the southern segment of the SLFZ, the Bickington Thrust and the Liverton branch of the SLFZ (Fig. 7c). Bristow & Robson (1994) believe that the SLFZ has a few hundreds metres of post-Variscan dextral displacement. A possible strike-slip relay ramp occurs at the contractional overstep between the southern segment of the SLFZ and the Liverton branch, in the SW of the

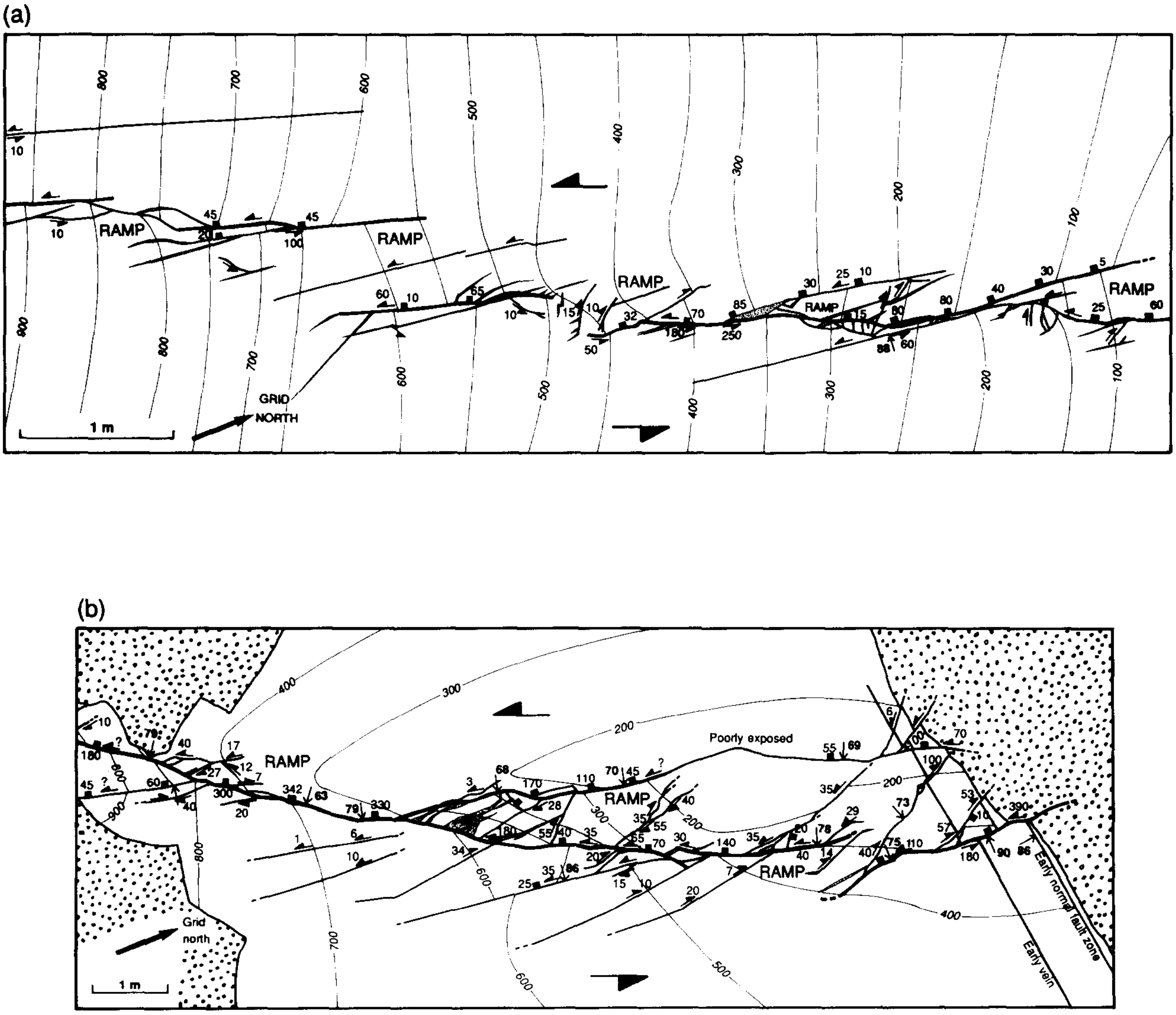

Fig. 5. Maps of strike-slip relay ramps developed within sinistral fault zones at East Quantoxhead. See Fig 1(a) for key. The contours are for limestone bedding planes in millimetres above arbitrary datum levels. (a) A set of right-stepping faults have produced five strike-slip relay ramps, with different stages of linkage. Some overstepping faults are unconnected. Veins, antithetic faults and synthetic faults are common in the relay ramps. (b) Three strike-slip relay ramps occur, each having different amounts of linkage. There is an area with solution seams near the southern end of the area, near the breached relay ramp. (c) Complex deformation occurs within the zone, with up to 20° rotation of bedding occurring. (d) This zone consists of a set of anastomosing faults, with areas of reorientated bedding representing strike-slip relay ramps. Extensive veining occurs in the wall-rocks.

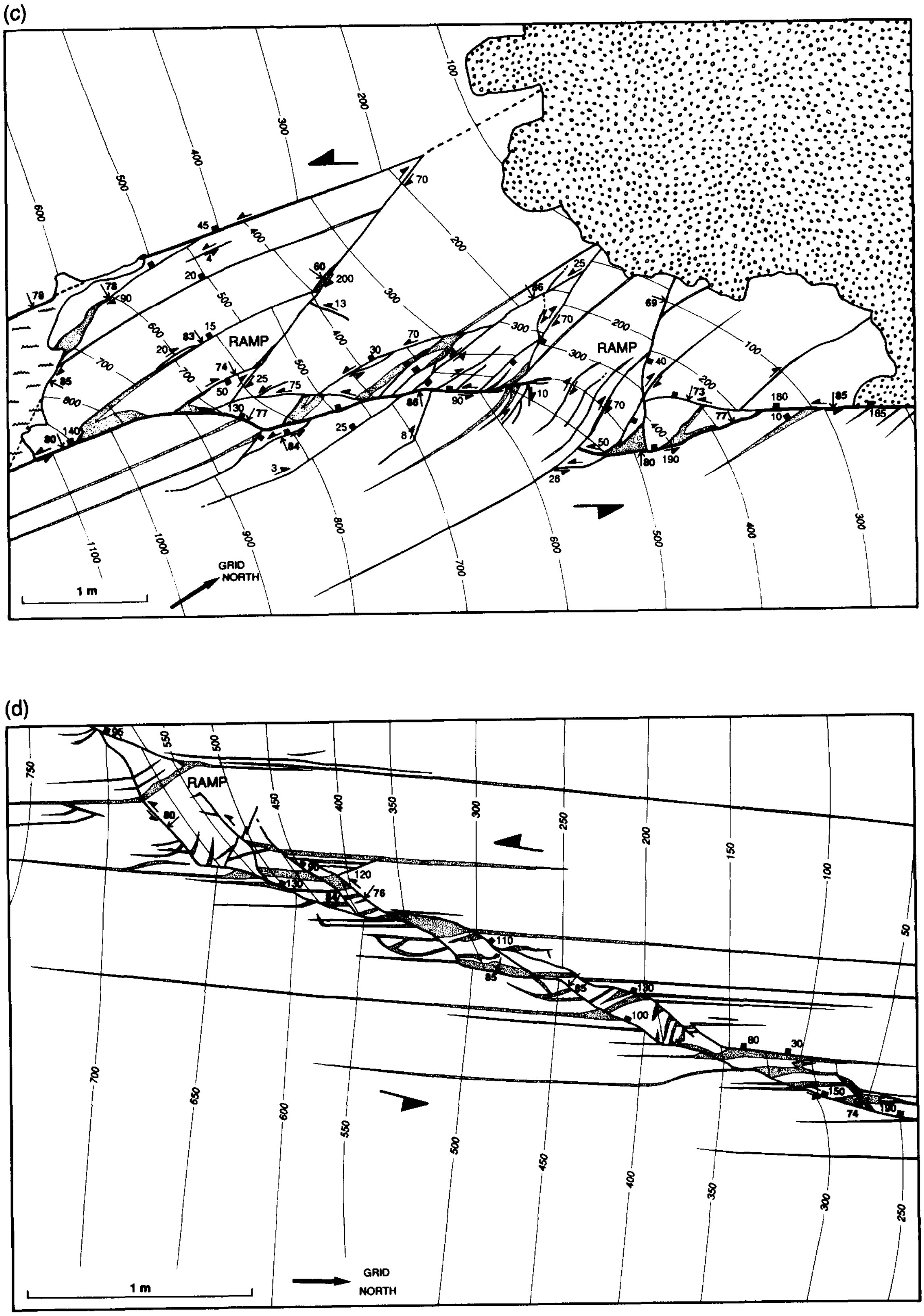

Fig. 5. Continued.

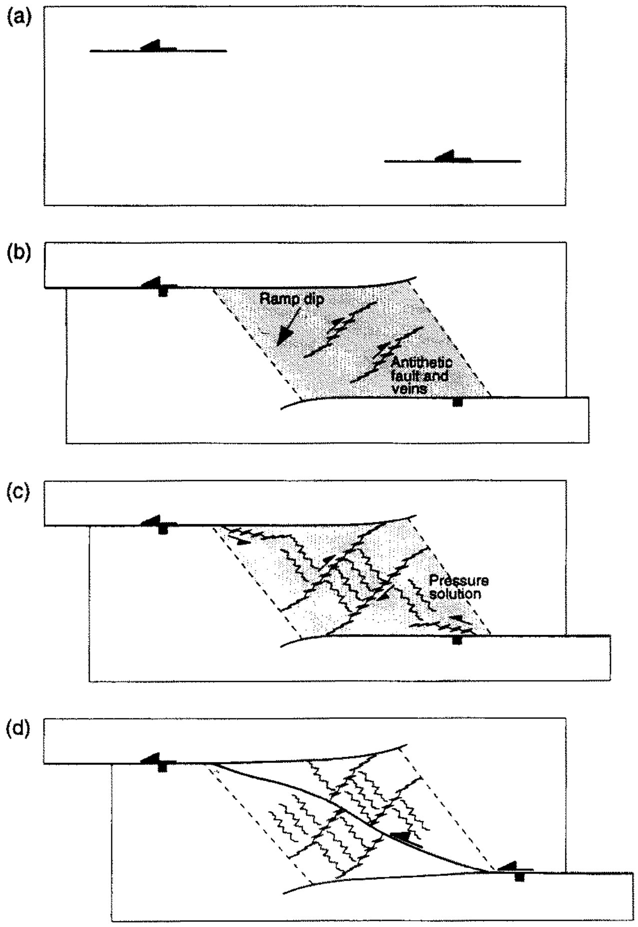

Fig. 6. Schematic map views of the development of a strike-slip relay ramp at a contractional overstep between two sinistral faults (cf. Peacock 1991b, fig. 13). Fault displacement is slightly oblique to bedding, causing some dip-slip (stratigraphic) separation. Ticks are on the down-thrown side of faults. (a) Stage 1: two sub-parallel, non-coplanar, non-interacting strike-slip faults initiate, possible as part of an array of Riedel shears. (b) Stage 2: the faults interact and a strike-slip relay ramp develops in the contractional overstep to accommodate the dip-slip separation (e.g. Fig. 5a). Some veins, antithetic (dextral) faults and pressure solution can occur in the relay ramp. Interaction may cause the propagation directions of the sinistral faults to change. (c) Stage 3: further rotation and deformation causes the two overstepping sinistral faults to start linking up across the relay ramp (e.g. Figs. 5a & b). (d) Stage 4: the relay ramp is completely broken, being replaced by a single, composite fault with a contractional bend (e.g. Figs. 5c & d). The relay ramp may be preserved as an area of folding and fracturing in one or both walls.

basin near Ringslade. Features of this relay ramp include:

(a) A NE-wards dip of Palaeogene beds (Bristow & Robson 1994, fig. 8), indicating rotation of bedding towards the basin to accommodate the component of vertical displacement caused by basin subsidence.
(b) The reactivation of the Variscan Bickington Thrust at the relay ramp.
(c) Minor faults with apparent strike-slip displacements.

COMPARISON WITH RELAY RAMPS IN NORMAL FAULT SYSTEMS

Strike-slip relay ramps occur where fault displacement is at a low angle to the plane of bedding, and are usually dominated by local transpression. In contrast, relay ramps in normal fault zones occur where fault displacement is at a high angle to the plane of bedding, and are dominated by extension or transtension. Strike-slip relay ramps also have similarities with bridges between overstepping veins, which are blocks of rock which rotate to transfer displacement between vein segments (Peacock 1991a).

The development of strike-slip relay ramps (Fig. 6) is similar to the development of relay ramps in normal fault systems (Peacock & Sanderson 1994, fig. 3). In both cases, two originally separate faults propagate towards each other and interact to form a relay ramp, which is by-passed if the faults link up. It is possible that the stages of strike-slip relay ramp development (Fig. 6) show a spatial distribution up and down the dip of the fault zone, which would be similar to the model for relay ramps in normal fault systems proposed by Peacock & Sanderson (1994, fig. 12). A spectrum can occur, from strike-slip relay ramps at contractional oversteps, to relay ramps between thrusts, to strike-slip relay ramps at extensional oversteps, to relay ramps between normal faults.

Basins can develop on the down-thrown sides of both large-scale strike-slip relay ramps (Fig. 7) and large-scale relay ramps in normal fault systems (Peacock & Sanderson 1994, figs. 14e and 16). Because relay ramps connect basins with the highs at the basin margins, they can be important locations for hydrocarbon migration and entrapment (e.g. Peacock & Sanderson 1994). The relay ramps in the Newport-Inglewood Trend (Fig. 7b) may have influenced hydrocarbon migration out of the Los Angeles Basin.

Because the overall geometry and development of relay ramps are similar in strike-slip and normal fault zones, it could be difficult to use relay ramp geometries to distinguish between different types of fault systems. This would be a problem when limited data are available, as on seismic profiles, where there is no information about displacement directions. Care needs to be taken, therefore, when using relay ramp geometries to infer fault displacement directions.

CONCLUSIONS

Detailed mapping of small strike-slip fault zones at East Quantoxhead has revealed several features which may be typical of other fault zones, including much larger structures.

(1) *A strike-slip relay ramp* is an area of reorientated bedding which connects the wall-rocks at oversteps between two strike-slip faults when the displacement direction is not in the plane of bedding (Fig. 1). A relay

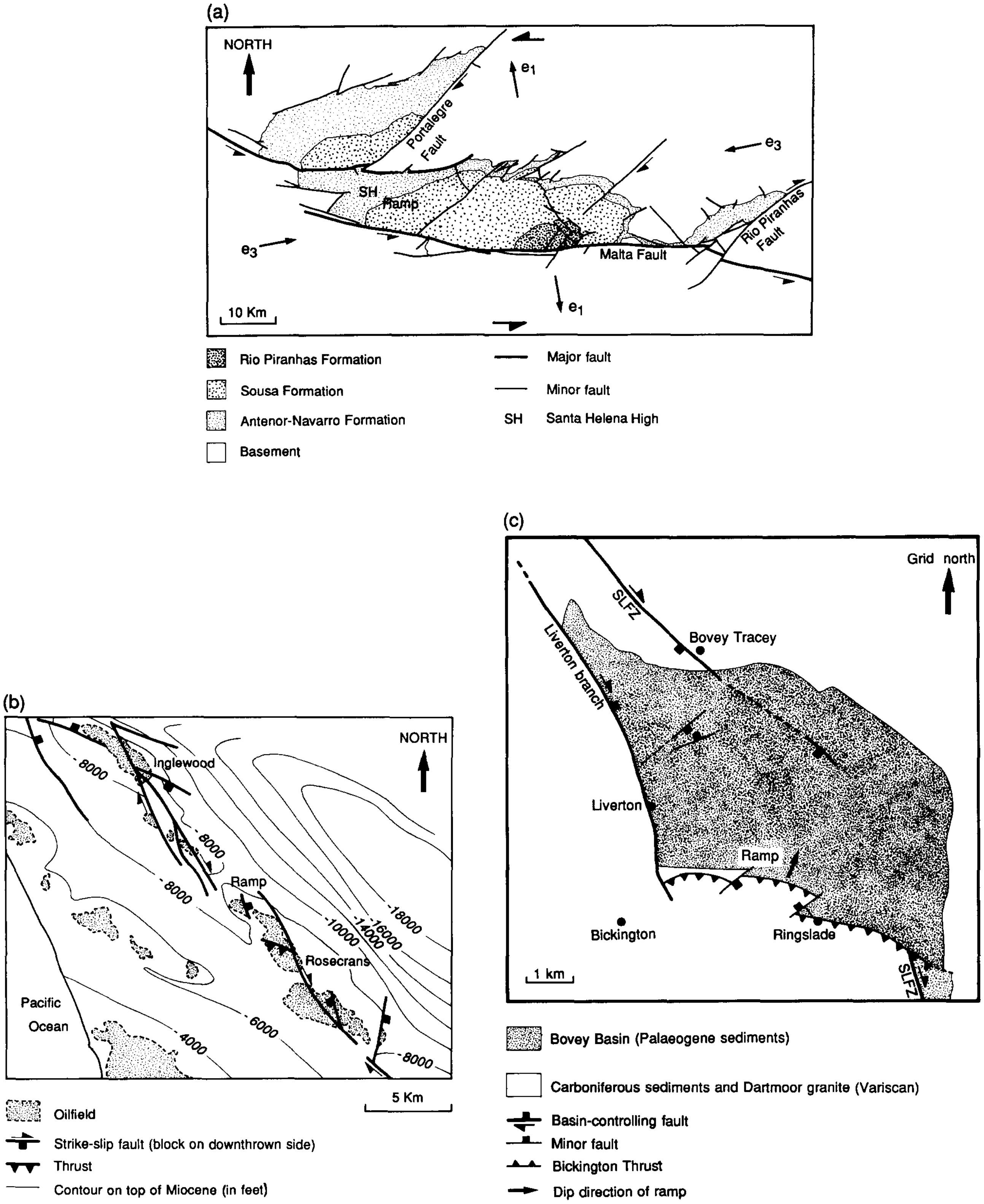

Fig. 7. Large strike-slip relay ramps. (a) Faulting in the Rio do Peixe Basin, NE Brazil (modified from Françolin *et al.* 1994, fig. 10). The longest sinistral faults ('major' faults) are interpreted as being dominant because they form the southern edge of the basin. The relay ramp is the Santa Helena High, which developed at the contractional overstep between the Malta Fault and another E–W striking sinistral fault to the NW. Antithetic (dextral) faults, including the Portalegre and Rio Piranhas faults, occur at the contractional overstep. The orientations of the principal strain axes, inferred by Françolin *et al.* (1994), are shown. (b) The Newport–Inglewood Trend (modified from Harding 1973, figs. 7 and 12b) is a zone of dextral transpression involving en échelon folds and strike-slip faults. A strike-slip relay ramp and thrusts are developed in a contractional overstep between two segments. (c) Map of the Bovey Basin (based on Bristow & Robson 1994, figs. 2 and 3). The Palaeogene pull-apart basin developed at an extensional overstep along the Sticklepath–Lustleigh Fault Zone (SLFZ). A probable strike-slip relay ramp developed at the contractional overstep between the southern segment of the SLFZ and the Liverton branch. It accommodates the vertical displacement associated with the basin. The relay ramp is characterised by thrusting, minor faulting and the dip of bedding into the basin.

ramp is necessary to accommodate the vertical separation of beds.

(2) The folding and rotation that occur at contractional oversteps are typically accommodated by small-scale synthetic and antithetic strike-slip faults, by veins, and by pressure solution. These structures indicate that transpression typically occurs in strike-slip relay ramps.

(3) Four stages in the development of strike-slip relay ramps can be determined (Fig. 6). Non-interacting faults develop at stage 1. At stage 2, the faults have propagated towards each other and start to interact, with a relay ramp developing to transfer displacement between the overstepping faults. The relay ramp can be accommodated by veining and small-scale faulting. Strains have increased in the relay ramp at stage 3, and a fault (or faults) cuts across the relay ramp to link the overstepping faults. At stage 4, the relay ramp is by-passed and a single fault with a contractional bend has developed.

(4) Larger strike-slip relay ramps occur in the Rio do Peixe Basin, Brazil, along the Newport–Inglewood Trend, California, and in the Bovey Basin, SW England. They have similar geometries to the small-scale examples from Somerset.

(5) Care needs to be taken in interpreting the rotation of bedding in fault zones, particularly when fault displacement directions are unknown, because relay ramps can occur in both extensional and strike-slip regimes.

Acknowledgements—Funding was provided by the University of Plymouth and the University of Southampton. Dwight Bradley, Richard Lisle and Ray Wood are thanked for their careful reviews, and Mark Swanson is thanked for his helpful comments. Meriel FitzPatrick gave valuable help with the diagrams.

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