Pergamon

Journal of Structural Geology, Vol. 20, No. 4, pp. 489 to 490, 1998

0191-8141/98 $19.00 + 0.00

PII: S0191-8141(97)00099-0

Brevia

Large lateral ramps in the Eocene Valkyr shear zone: extensional ductile faulting controlled by plutonism in southern British Columbia: Reply

PHILIP S. SIMONY

Department of Geology and Geophysics, University of Calgary, Calgary, AB, Canada T2N 1N4

and

SHARON D. CARR

Ottawa Carleton Geoscience Centre and Department of Earth Sciences, Carleton University Ottawa, Ontario, Canada K1S 5B6

(*Received* 29 *September* 1997; *accepted in revised form* 13 *October* 1997)

We are pleased that our paper elicited an interesting discussion from a group working in the field of extensional faulting, Peacock and others. We trust that we did not mislead anyone by our usage of the term 'ramp'. We meant to imply only a geometric not a mechanical analogy to large thrust ramps, and we will begin by addressing the question of terminology. Classic fault terminology involves much reference to the present-day horizontal; the angle of dip, the rake of slip and the map pattern are all important elements. This terminology is practical for simple faults with moderate to steep dips but it may lead to difficulties with sub-horizontal faults, particularly where faults have been tilted or folded. It is of interest, therefore, that the descriptions of ramps by Boyer and Elliot (1982) and Butler (1982) and earlier workers, show that a ramp is simply a portion of a fault surface with an orientation that is distinctly different from that of the main fault surface. In a *lateral* ramp, the angle measured in the main fault surface between the ramp edges and the dominant slip direction is small. Used in this way the term ramp is independent of the notion of strike, dip, rake, shear sense, etc., and can be applied to any fault or shear zone system. This is elegantly illustrated by Twiss and Moores (1992, fig. 4.25, p. 68). In the case of the sub-horizontal and warped ductile Valkyr shear zone, the classic 'along-strike bend' map pattern is cryptic and we chose not to use that term.

With respect to the ramps of the Valkyr shear zone, the key observation is that the position and geometry of the Valkyr shear zone and of its lateral ramps is controlled by the location and orientation of the bounding surfaces between rock masses with strongly contrasting rheologies. The Arrow Lake ramp is located where stiff Jurassic tonalite was induced to shear laterally past hot ductile Eocene leucogranite along a south-dipping boundary that linked the northern segment of the Valkyr shear zone to a deeper southern segment. Motion on the shear zone segments and on the linking ramps continued for four million years during which time leucogranite sheets were injected and the rheological contrast was maintained. The ramps of the Valkyr shear zone are therefore very different from those formed by the breaching of relay ramps.

The expression 'breached relay ramp' (used by Peacock *et al.*, and references therein) describes a very specific structural configuration; unless the relay ('relais' of Goguel, 1952, fig. 68, p. 125) ramp is breached, there is no fault ramp or along-strike bend. The fault overstep zone, the ramp and the breaching fault must all be present, although Larsen (1988, fig. 9a, p. 7) illustrates a relay ramp where there is no overstep. Many faults and ductile shear zones, including the Valkyr shear zone, formed by the linkage of shorter segments; however, relay ramps are but one important structure involved in the linkage process. We agree with Peacock *et al.* that in our presentation of alternative interpretations and of ramp propagation (Simony and Carr, 1997, pp. 780–781), we could have discussed the relay ramp alternative; however, our observations indicate that the necessary elements are clearly not present.

Peacock *et al.* suggest that the 'ramp foliation' in the Arrow Lake ramp is a reoriented regional foliation and constitutes a relay ramp. This is an intriguing idea but our 'ramp foliation' occurs only in small domains isolated within the regional foliation, and is only present in close proximity to the Arrow Lake Ramp to which it is therefore related. We document (Simony and Carr, 1997, p. 780) that a zone of overstepping is unlikely at the Arrow Lake ramp; although there is a breaching structure localized at a south-dipping rheological boundary, there is no relay ramp.

In the vicinity of the smaller southern Murphy Creek ramp (Simony and Carr, 1997, figs 3, 4 and 5) there is a zone of reoriented layering, breached by the ramp, an excellent candidate for a ductile breached relay ramp except that the map (Simony and Carr, 1997, fig. 3) shows that there is no zone of overstepping and that the reorientation of the layering is, in all probability, related to intrusion of the Trail pluton some 110 Ma prior to activation of the Valkyr shear zone segments.

The block diagram (their fig. 1) suggests that a breached relay ramp about 6 km across and 6 km high was propagated between two fault or shear zone segments that did not merge in the down-dip direction; it propagated from the brittle regime into the ductile regime for about 18 km to form a ductile ramp where the overstep zone that caused the relay ramp in the brittle field need not be present. The probability of a structure propagating, or merely continuing for a certain distance along its length, must somehow be, in part, a function of the ratio of the size of the structure to the required propagation distance. In their fig. 1, that ratio is 6:18. In the case of the Arrow Lake Ramp at least 25 km separates Arrow Lake from the nearest possible brittle regime, up and to the west. The ratio is therefore 2.5:25. The lower probability implied by this smaller ratio is further reduced by the fact that the slip vector in the brittle zone of their fig. 1 is approximately sub-parallel to the tip lines of the overstepping faults and, with the fault, at high angle to layering, while deep in the ductile regime the slip lines are still parallel to the tip lines of the upper and lower shear zones but the shear zones and the slip vector lie within the layering. Furthermore, in typical core complex detachments there is no single unique brittle fault that passes smoothly into the ductile regime as shown in fig. 1 of Peacock *et al.* Instead, as shown by Lister and Davis (1989, and references therein), there are many different brittle faults and they have a variety of complex kinematic and temporal relationships to the detachment. It would seem improbable, therefore, that along-strike bends caused by the breaching of relay ramps in the brittle field somehow propagated into the ductile regime to form the Valkyr shear zone ramps.

We propose that there are several types of lateral ramps and along-strike bends that may be formed by the linkage of fault and shear zone segments of every class. Here we identify three distinct types.

(1) Ramps may be formed by linkage across overstep or transfer zones as they are strained during propagation of the segments. Breached relay ramps are one important example.

(2) Ramps may be formed by the reactivation of a pre-existing transverse structure, such as an old fault, that lies in an orientation that is suitable to link fault segments as they propagate.

(3) Ramps may be formed at the site of an important transverse rheological boundary that is suitably oriented to localize a shear zone that links the propagating segments. Carbonate platform edges are one example and the thermo-mechanically localized ramps of the Valkyr shear zone are another.

Relay ramps are structures of the relay (relais) or transfer zone and are to be expected with type (2) and type (3) lateral fault ramps where the transverse structure was not immediately and efficiently activated. In these cases the relay ramp would be completely incidental to the localization of the lateral fault ramp.

REFERENCES

Boyer, S. E. and Elliot, D. (1982) Thrust systems. *Bulletin of the American Association of Petroleum Geologists* **66**, 1196–1230.

Butler, B. W. H. (1982) Terminology of structures in thrust belts. *Journal of Structural Geology* **4**, 239–245.

Goguel, J. (1952) *Traité de tectonique*. Masson et Cie, Paris.

Larsen, P. H. (1988) Relay structures in a Lower Permian basement-involved extension system, East Greenland. *Journal of Structural Geology* **10**, 3–8.

Lister, G. S. and Davis, G. A. (1989) The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A. *Journal of Structural Geology* **11**, 65–94.

Simony, P. S. and Carr, S. D. (1997) Large lateral ramps in the Eocene Valkyr shear zone: extensional faulting controlled by plutonism in southern British Columbia. *Journal of Structural Geology* **19**, 769–784.

Twiss, R. J. and Moores, E. M. (1992). *Structural Geology*, Freeman and Co., New York.