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Duplex structures in the Lewis thrust sheet, Crowsnest Pass, Rocky Mountains, Alberta, Canada

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Abstract—The Lewis thrust sheet of the southern Canadian Rocky Mountains contains many spectacular examples of small-scale duplex structures. This paper presents the results of a detailed analysis of such structures found in the Mississippian carbonates of the Banff Formation at Crowsnest Pass, southwestern Alberta.

Foreland dipping, hinterland dipping and antiformal stacked duplexes are found in the hangingwall of the Lewis thrust. Out-of-sequence thrusts, back thrusts and folds that push out of the plane of the cross-section, termed lateral lobes, give rise to complex internal geometries. Dominant slip vectors are towards 080–090° but the complex fault geometries have generated significant variations in slip away from this direction. The duplex structures occur as discrete thrust fault-bounded packages with each package having different slip vectors. The panels above and below the duplex structures show consistent slip vectors towards 080–090° whereas the duplexes exhibit a wide scatter of slip vectors from 350–160°. The stacking of duplexes with many horses can be likened to the stacking of many inverted soup bowls, herein termed turtle back structures, and will involve a wide scatter of slip directions, particularly if the horses are of limited lateral extent. Such a stacking mechanism involving out-of-section movement invalidates the assumption of two-dimensional plane strain in the plane of the cross-section that contains the regional tectonic transport direction. Correctly balanced cross-sections cannot be constructed through such stacked duplex structures as described in this paper.

INTRODUCTION

The Canadian Rocky Mountains and Foothills are one of the premier examples of a cordilleran foreland fold and thrust belt. Classic studies of thrust fault geometries by Douglas (1950), Bally *et al.* (1966), Dahlstrom (1969, 1970), Price & Mountjoy (1970), Price (1981) and Thompson (1981) have demonstrated the large-scale structural features of this well-exposed thrust belt.

The southern Canadian Rocky Mountains fold and thrust belt is composed mainly of west dipping panels of massive Palaeozoic carbonates, shaly carbonates and shales (Cambrian–Mississippian) and Mesozoic clastics of the foreland basin bounded by major east to northeast verging thrust faults. In the Main Ranges of the Rocky Mountains the fault bounded panels are dominantly of Palaeozoic strata, whereas the Mesozoic clastics become involved in the thrusting further to the east in the Front Ranges and the Foothills (Price & Mountjoy 1970, Price 1981). The regional tectonic transport is assumed to be towards the east and northeast with at least 200 km accumulated displacement in the Rocky Mountains and Foothills (Price 1981).

The study area lies in the Front Ranges of the southern Canadian Rocky Mountains at Crowsnest Pass in southwest Alberta near the British Columbia border (Fig. 1). Here the thrust belt includes several thick west dipping (30–45°) fault bounded panels of Cambrian–Mississippian carbonates (Price 1962, 1981). The dominant thrust sheet is the Lewis thrust (Fig. 1) which in the Crowsnest Pass area brings the carbonate succession, internally repeated by thrust faults, over the Upper Cretaceous Belly River Formation sandstones (Figs. 1 and 2). The carbonates are generally resistant units which erode to form rugged peaks up to 3000 m high, whereas the Mesozoic clastics are recessive and form valleys between the thrust sheets.

The area was mapped at a scale of 1 : 126,720 by Price (1962) and a detailed analysis of some of the mesoscopic fabric elements was also carried out by Price (1967). Since this early work a new road cut on Highway No. 3 has provided 0.7 km of continuous section striking 070° (subparallel to the direction of thrusting) through the upper plate of the Lewis thrust system (Fig. 2).

This paper reports the results of a detailed study of the internal structures within the hangingwall of the Lewis thrust sheet at Crowsnest Pass. Duplex structures (Dahlstrom 1970) which cause repetitions of strata and are a significant deformation mechanism in thrust belts, are spectacularly exposed on the roadcut at Crowsnest Lake on Highway No. 3 (Fig. 2). A detailed cross-section at Crowsnest Lake was mapped at a 1 : 150 scale, and a 1 : 10,000 scale structural map was made of the Crowsnest Pass area (Figs. 2 and 4). In particular the geometries and kinematics of the mesoscopic duplexes indicate that the movement patterns and internal deformation within the hangingwall of the thrust sheet are far more complex than hitherto realized.

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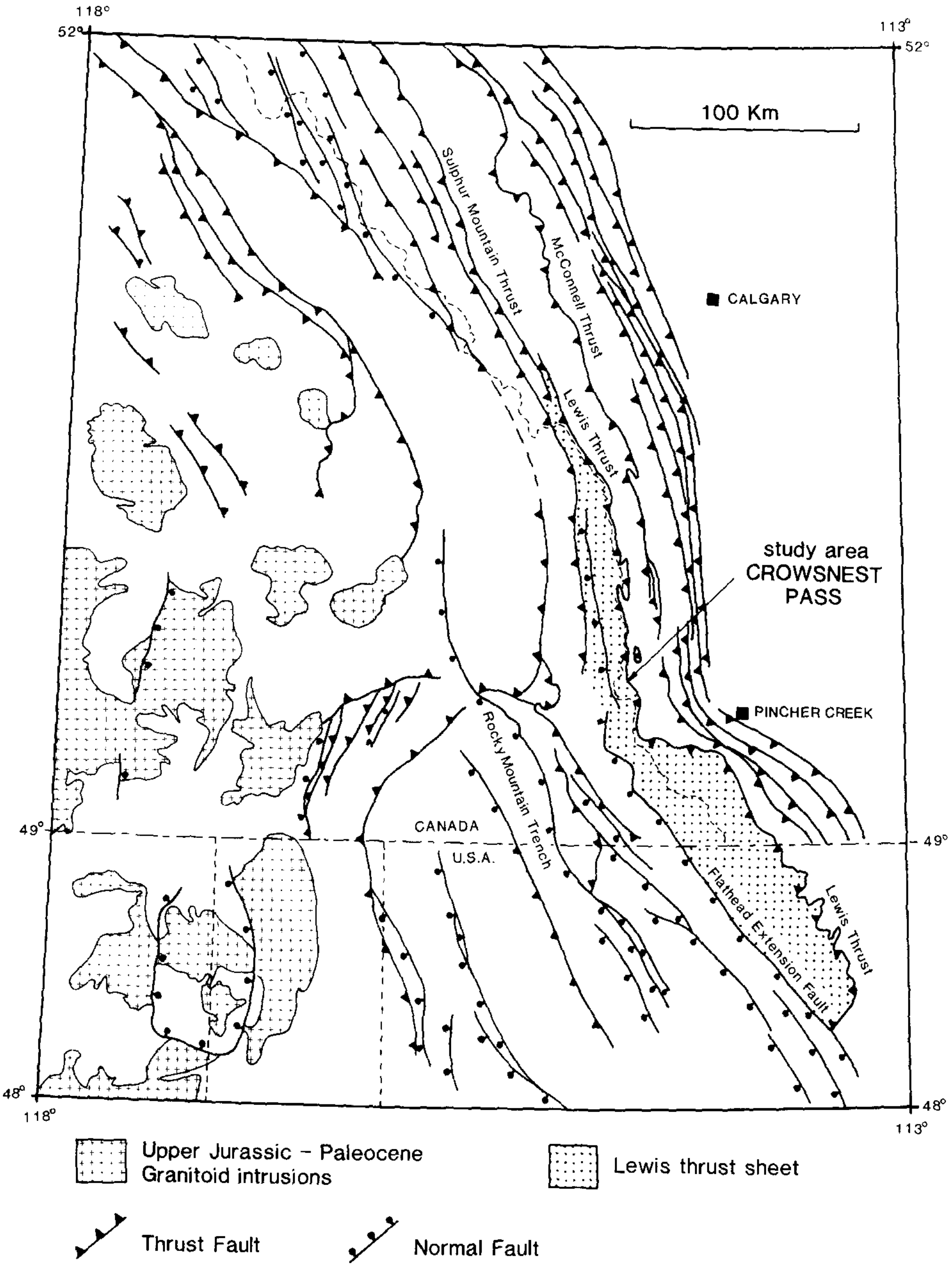

Fig. 1. Location of the Lewis thrust sheet and Crowsnest Pass in the Canadian Rocky Mountains (after Price 1981).

GEOLOGY OF THE LEWIS THRUST SHEET AT CROWSNEST PASS

Stratigraphy

The stratigraphy of the Front and Main Ranges of the southern Canadian Rocky Mountains has been described in detail by Price (1962) and will be briefly reviewed here. Figure 3 is a summary tectono-stratigraphic column of part of the Lewis thrust sheet at Crowsnest Pass. The basal section of the Lewis thrust sheet comprises some 600 m of Cambrian and Devonian carbonates, of which the massive dolomite-mottled limestones of the Palliser Formation (Fig. 3) form distinct cliffs. Conformably overlying the Devonian carbonate succession are the Mississippian Exshaw, Banff and Livingstone Formations (Fig. 3). The Exshaw is a black, platy, non-calcareous shale and the overlying Banff is a laminated, medium bedded cherty limestone and silty limestone. The Livingstone Formation is a prominent cliff-forming massive crinoidal limestone. The stratigraphic positions of thrust faults are shown in Fig. 3 with the most abundant thrusts in the Upper Palliser, Exshaw and Banff Formations.

Structure

The structure of the Crowsnest Pass area is dominated by a homoclinally west dipping panel of Cambrian through Mississippian carbonates thrust over the Upper Cretaceous strata on the Lewis thrust. Detailed mapping has revealed a complex array of faults in the hangingwall of the Lewis thrust (Fig. 2). In the immediate hangingwall there is a poorly exposed duplex of Fairholme

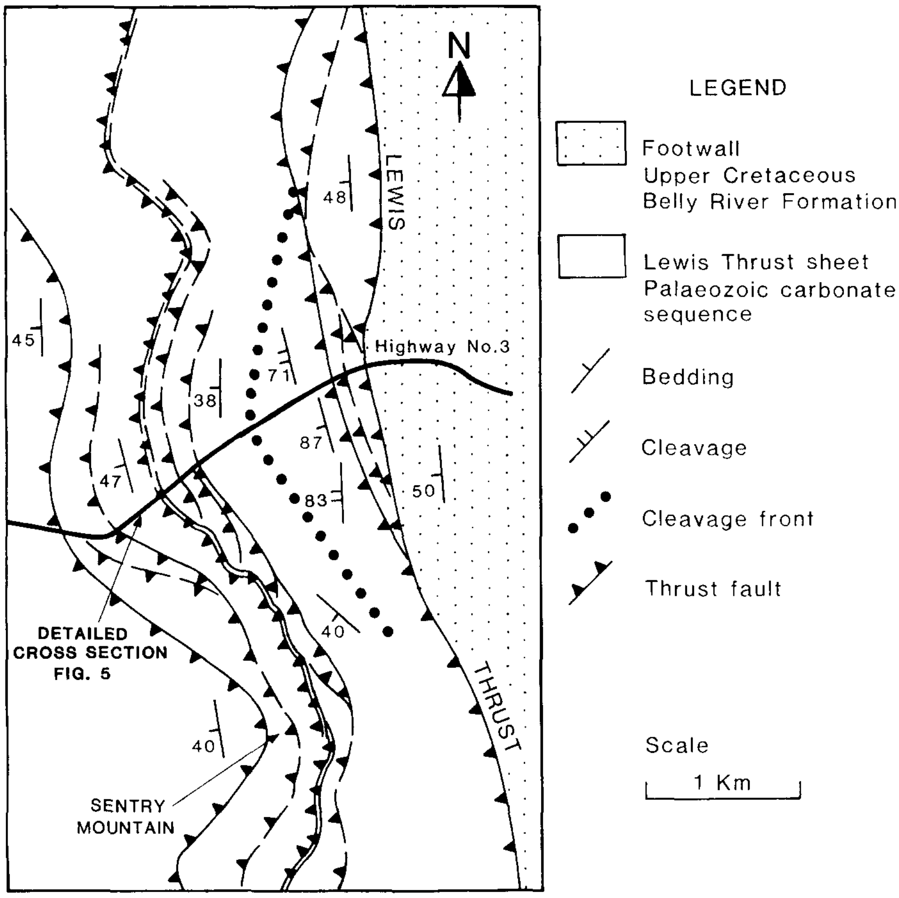

Fig. 2. Simplified sketch map of the Lewis thrust sheet at Crowsnest Pass, south west Alberta.

strata. A pronounced cleavage front is developed in the Mount Hawk Formation, such that strata to the east have a poor to moderately well developed pressure solution cleavage whereas strata to the west are uncleaved (Fig. 2). The exposure of the cleavage front may be due to uplift on a frontal ramp on the Lewis thrust or to local pinning of the thrust during progressive deformation. Further west and higher in the hangingwall to the Lewis thrust, a complex series of duplex structures are found in the Palliser, Banff and Livingstone Formations. These structures are well exposed on the north flank of Sentry Mountain (Fig. 4). In particular the duplexes in the Palliser and Banff Formations are exposed in the highway section (Fig. 5) and have been mapped and studied in detail. Major thrust faults repeat the Exshaw shales in Sentry Mountain and have been traced south of Sentry Mountain. In particular some of these thrusts cause substantial tectonic thickening of the Banff Formation (Fig. 4). In subsequent sections we shall describe the duplexes in the Banff and Palliser Formations in detail.

DUPLEX STRUCTURES

Terminology

The terminology of thrust systems has been reviewed by Boyer & Elliott (1982). They emphasized the importance of linked thrust systems, in particular duplexes. Duplexes are characterized by repetitions of strata on sigmoidal faults that are linked to a floor thrust and to a roof thrust (Fig. 6). Individual fault blocks within the duplex system are termed horses.

Boyer & Elliott (1982) classified three main types of duplex:

(a) the hinterland-dipping duplex (Fig. 7a) in which the horse blocks and the sigmoidal faults are all dipping opposite to the direction of thrust transport, that is into the hinterland of the thrust belt;

(b) the antiformal stack in which the horses of the duplex become pushed up over a ramp in the floor thrust and folded into an antiformal structure (Fig. 7b) and

(c) the foreland-dipping duplex in which the individual horses and the sigmoidal duplex faults are dipping in the direction of thrust transport, that is towards the foreland of the thrust belt (Fig. 7c).

In all of the above cases the sigmoidal faults linking the floor thrust to the roof thrust of the duplex system are contractional (i.e. they shorten the stratigraphic datum) and the duplex system represents an important mechanism for shortening in the thrust system. In the examples described below idealized duplex systems are not always found and the system, becomes 'less linked' with out-of-sequence thrusts that cut already folded strata and cut down the stratigraphic section.

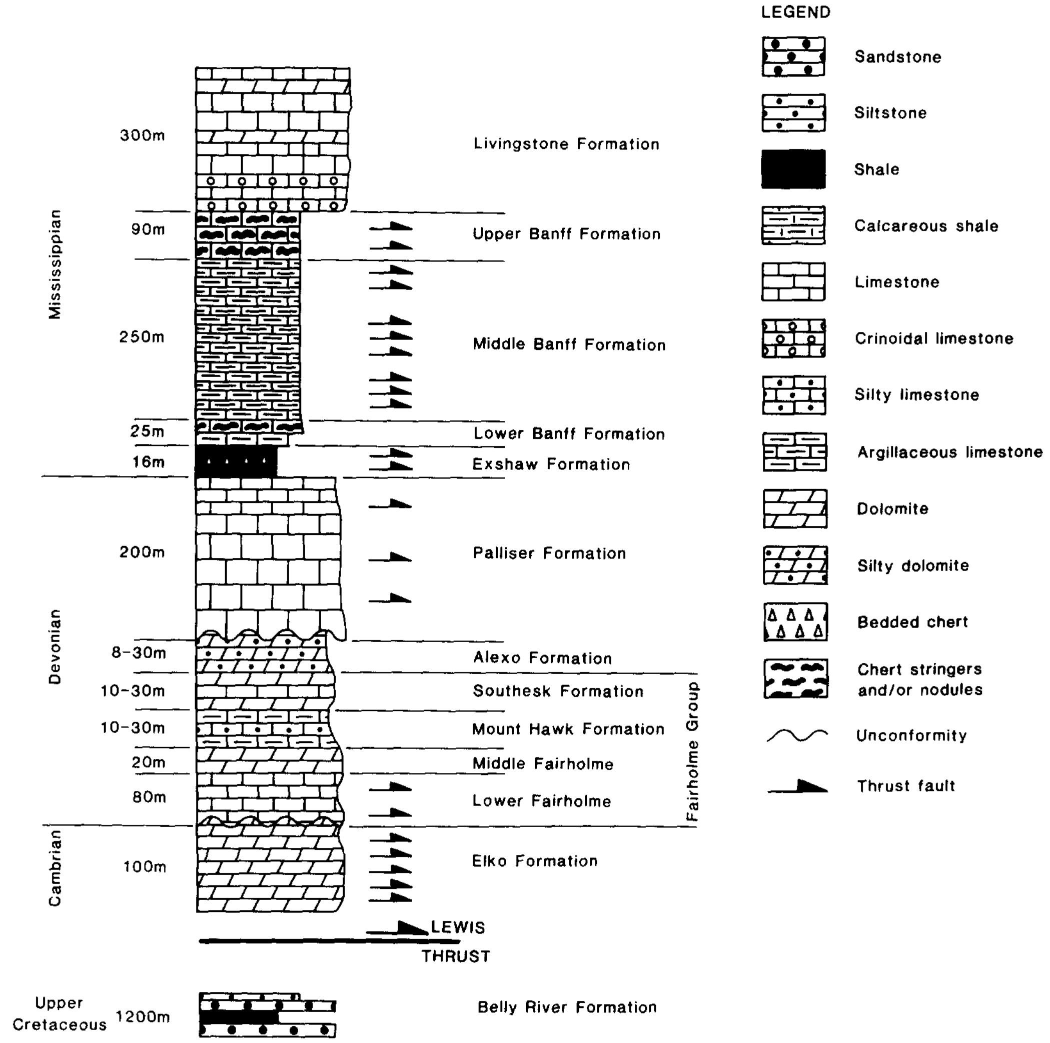

Fig. 3. Stratigraphic column of units in the Crowsnest Pass area (stratigraphic nomenclature after Price 1962). The stratigraphic positions of important thrust faults are shown.

DUPLEX SYSTEMS AT CROWSNEST PASS

A detailed cross-section through the Palliser–Banff Formations at Crowsnest Lake is shown in Fig. 5. This section along the highway is parallel to the regional tectonic transport direction for the Crowsnest Pass area as determined from measurements of slickenside and slickolite orientations.

The Palliser Formation is repeated on a number of thrust faults and in a major antiformal stack with a hangingwall syncline (Fig. 5). The thick massive bedded units of the Palliser Formation (Fig. 3), clearly control the spacing of duplex faults and the wavelength of the antiformal fold. Incomplete exposure of the antiformal stack has prevented a more detailed analysis of this structure.

The duplex structures in the Banff Formation (Fig. 5) are spectacularly exposed in the highway section at Crowsnest Lake. At least eight duplexes are found in this section (Fig. 5) and they include foreland and hinterland dipping duplexes and antiformal stacks (Fig. 5). Here we describe three examples of duplex structures. In each case they were mapped at a scale of 1 : 150 and the bedding, fracture, fold axial plane and slip vector (grooving, slickensides and slickolites) orientations were recorded. Slip normals, defined as the normal to the slip vector in the slip plane, are used to indicate the axes of rotation on curved fault planes.

Internal duplex

Within the Middle Banff Formation an excellent example of a 14 m long duplex is exposed in the road cut at Crowsnest Lake (Fig. 8). This is termed an internal duplex as it is contained entirely within one formation and repeats one individual bedding unit within that formation. Twenty seven individual horses have been identified within this duplex. It occurs in the footwall of a larger duplex system which has partly developed into an antiformal stack (Fig. 9). Individual horses are bounded by sigmoidal faults which are asymptotic to both the floor and roof thrusts. The floor and roof thrusts have straight, smoothly varying trajectories (Fig. 9). Individual horse blocks commonly have a spacing of 30–60 cm but this can vary greatly.

Structural data collected from this exposure reveal

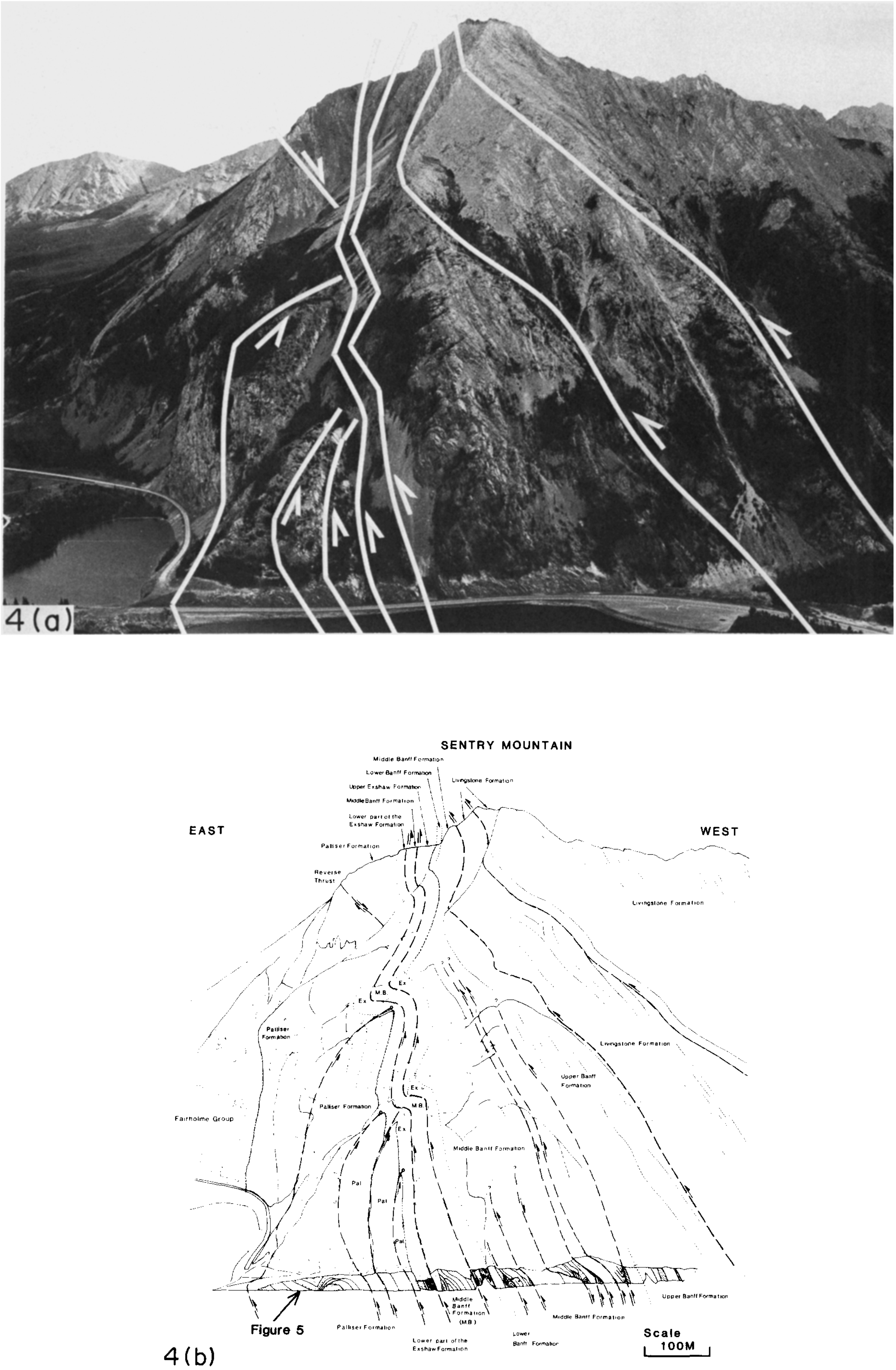

Fig. 4. (a) Photograph of the north flank of Sentry Mountain (Fig. 2) showing the major units in the hangingwall of the Lewis thrust. The mountain consists mainly of carbonates of the Palliser, Banff and Livingstone Formations. (b) Sketch of Fig. 4(a) showing the major structures in Sentry Mountain. The stratigraphy key is as for Fig. 3.

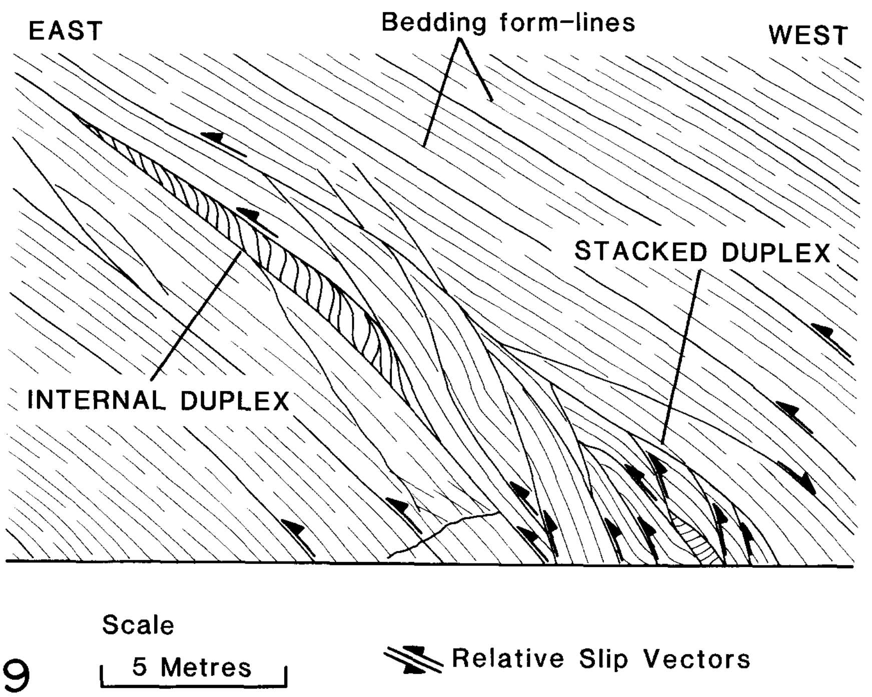

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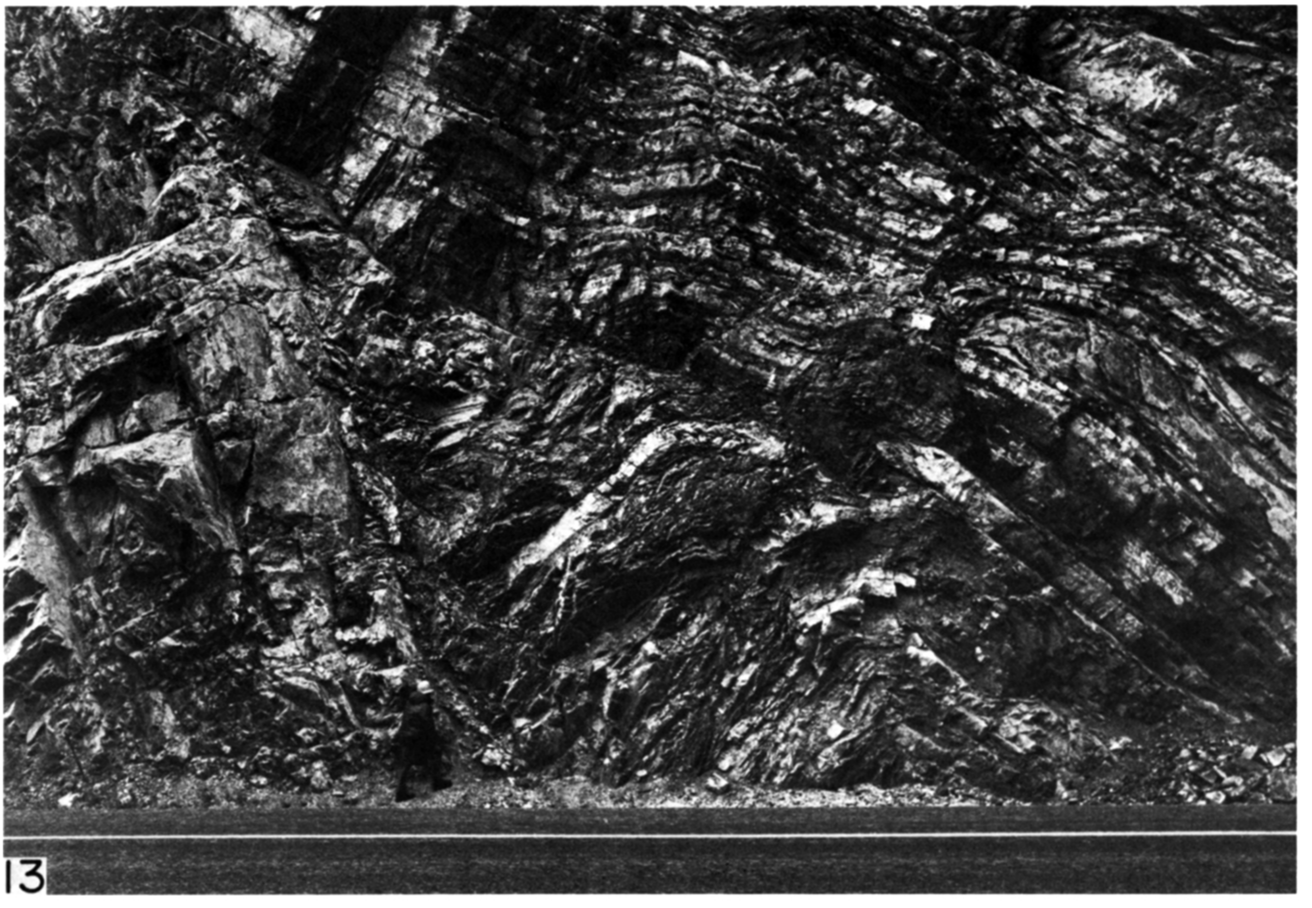
Fig. 8. Photograph of an internal duplex in the Middle Banff Formation, Crowsnest Pass.

Fig. 9. Detailed cross-section of the internal duplex (Fig. 8) and associated structures.



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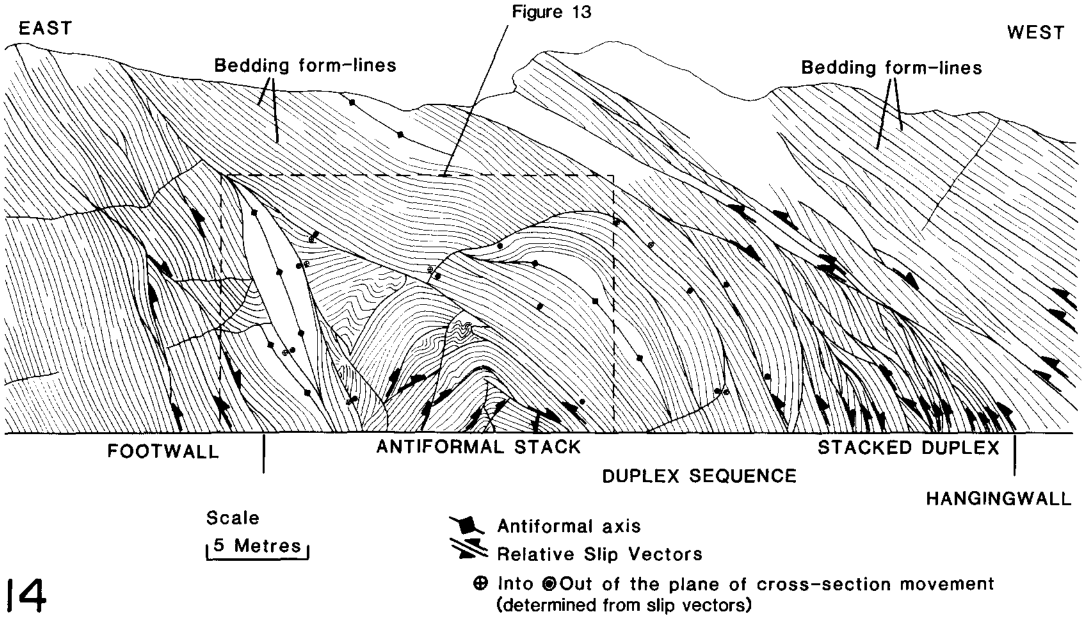

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Fig. 13. Photograph of an antiformal stack within the Middle Banff Formation.

Fig. 14. Detailed section through the antiformal stack (Fig. 13) and the associated stacked duplexes in the Middle Banff Formation.

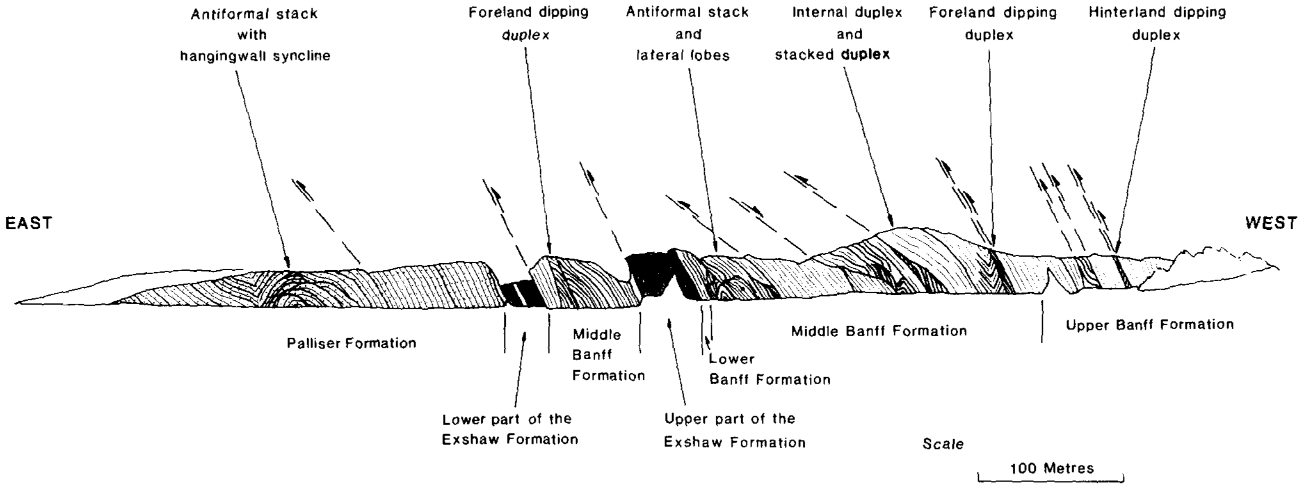

Fig. 5. Detailed cross-section through the Lewis thrust sheet along Highway No. 3 at Crowsnest Lake, Crowsnest Pass, Alberta. The plane of the cross-section is sub-parallel to the regional tectonic transport direction.

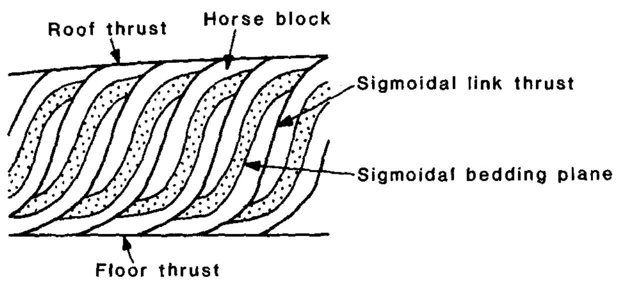

Fig. 6. Idealized duplex structure showing the floor and roof thrusts linked by sigmoidal link thrusts which bound individual horses.

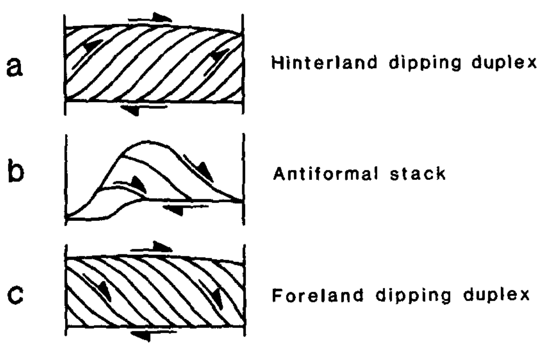

Fig. 7. Terminology used to describe duplex structures (after Boyer & Elliott 1982): (a) hinterland dipping duplex; (b) antiformal stacked duplex; (c) foreland dipping duplex.

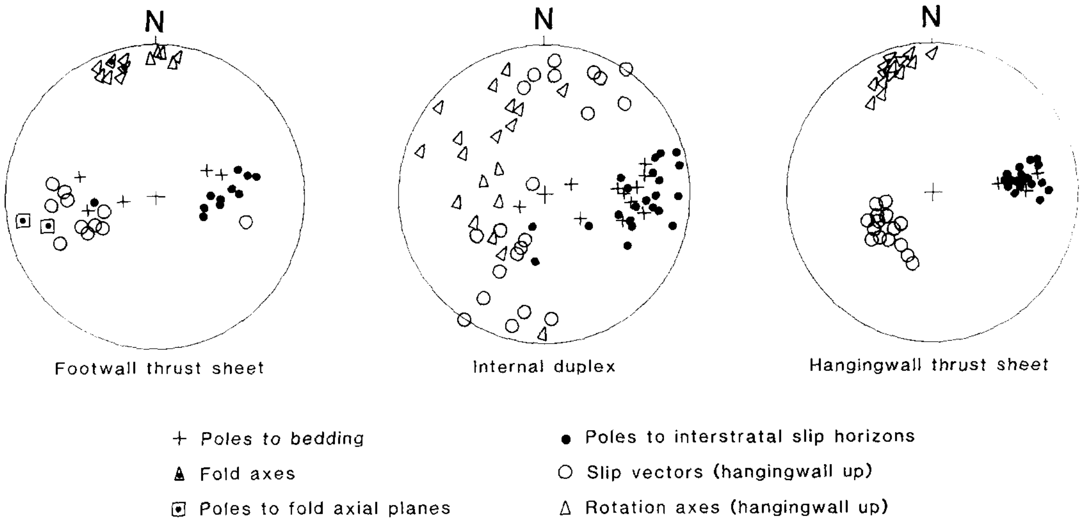

Fig. 10. Structural data from the area shown in Fig. 9.

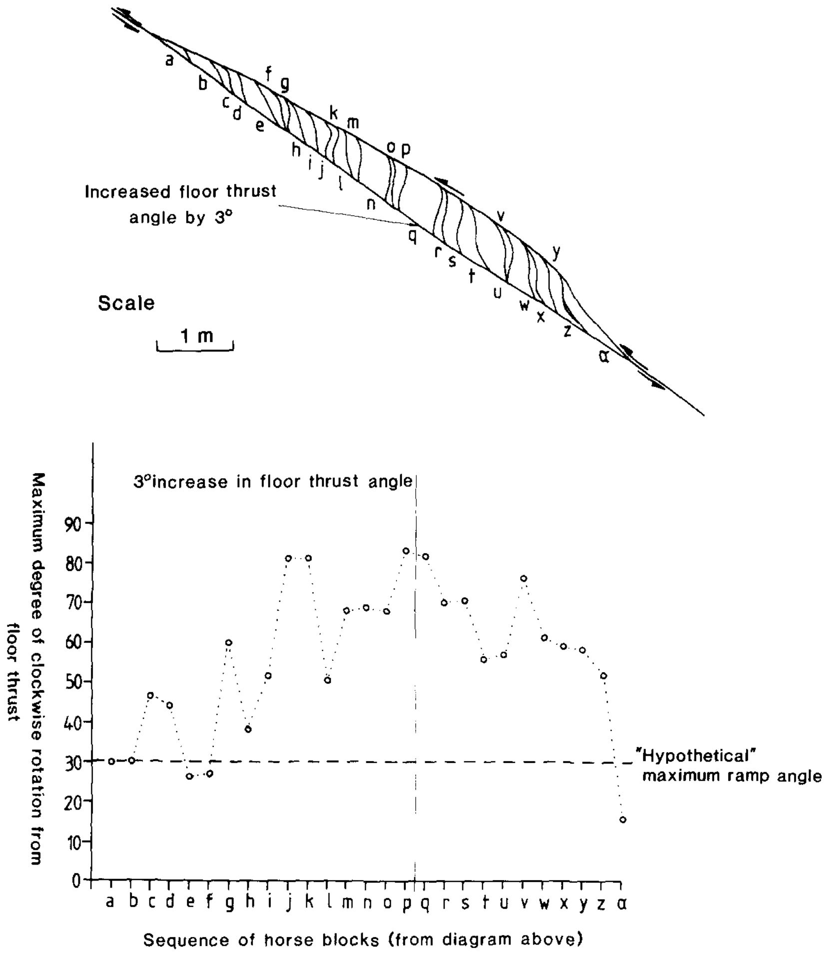

Fig. 11. Angular variation of the link thrusts plotted with respect to position in the duplex shown in Figs. 8 and 9.

complex relationships (Fig. 10). The footwall and hanging wall thrust sheets show consistent slip directions towards 080° whereas in the duplex itself considerable variation in slip vectors is found. The nature of the rotation of the horse blocks in the duplex is illustrated in Fig. 11, in which maximum angle of the sigmoidal link faults is plotted with respect to the floor thrust. This clearly shows that the maximum fault angles are developed in the central part of the duplex and that these angles decrease towards both the leading edge and the trailing edge of the duplex (Fig. 11).

Into- and out-of-section thrusts

Within the Banff Formation at Crowsnest Pass/ Crowsnest Lake there are many examples of thrust packages and duplex structures for which the slip vector determinations and fault geometries indicate significant movement out of the plane of the cross-section, that is not in the direction of regional tectonic transport. Total displacements on individual faults are difficult to determine because of the lack of distinctive marker units but the exposed fault geometries indicate that in some cases the out-of-section movement totals several to tens of metres, whereas the movement in the direction of regional tectonic transport is of the order of tens of metres. One such section is shown in Fig. 12 which shows a complex array of thrust faults and folded horse blocks. Many of the thrusts are out-of-sequence in that they truncate fold hinges and already folded layers. In the plane of the cross-section many individual faults cut both up and down the stratigraphic section (Fig. 12) indicating local extension and movement at an angle to the plane of

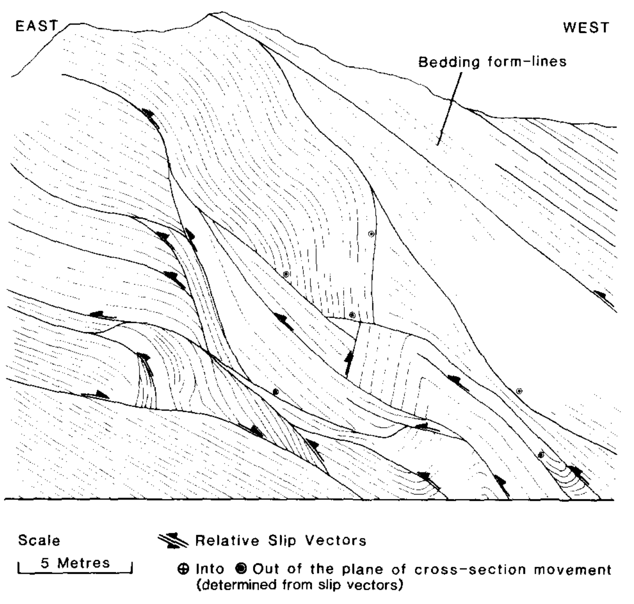

Fig. 12. Detailed cross-section through a region of stacked duplexes showing complex thrust geometries; thrusts cut both up and down the stratigraphic section and thrust movement is both into and out of the plane of the cross-section.

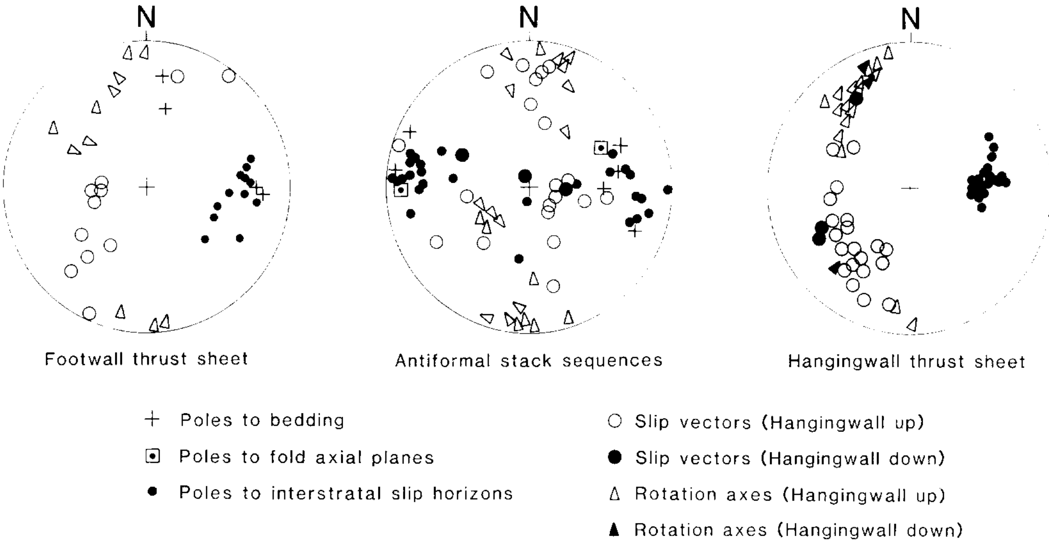

Fig. 15. Structural data collected from the detailed section shown in Fig. 14.

the cross-section. The geometries of this package are more complex than that required by simple ramps in a duplex system.

Antiformal stack

Many of the duplexes in Fig. 5 are pushed up into antiformal stacks such as those shown in Figs. 13 and 14. Complex geometries with tight folds and back thrusts are developed. In particular there are several folds which push out of the plane of the cross-section (Fig. 13) and these are termed lateral lobes. Clearly there is considerable movement out of the plane of the section. Slip vector determinations using slickensides and grooving reveal a complex movement pattern (Fig. 15). The footwall package shows dominant slip towards 045–055°, whereas the antiformal stack sequences show extremely widely scattered slip vectors with a marked component of slip towards 000–010° (Fig. 15). The hangingwall thrust sheet shows slip vectors distributed in the plane of the bedding and trending dominantly towards 045°. This complex movement pattern is interpreted to indicate accommodation slip at the edges of lateral ramps and at the edges of antiformally stacked duplexes.

DISCUSSION

The duplexes illustrated in this paper exhibit a number of characteristics that may be pertinent to the study of other duplexes. The simple hinterland dipping duplex (Figs. 8 and 9) exhibits the following features:

(a) the floor and roof thrusts as defined have smooth trajectories similar to duplex structures described by Cooper *et al.* (1983);

(b) the link thrust faults are sigmoidal and asymptotic to the floor and roof thrusts and

(c) the individual horse blocks are sigmoidal but partial horses (blocks bounded by faults that do not link directly between the floor and roof thrusts) are also developed.

The variations in the maximum angle of the link faults are largely a result of early faults being rotated by forward propagating later faults. In this mesoscopic example of a duplex (Fig. 11) the variation in angle of the link faults may have arisen in a number of ways. The rearward decrease in the link fault angle may have been caused by:

(a) variation of slip of the individual horses with a decrease in slip towards the rear of the duplex;

(b) layer-parallel shortening of the duplex after the formation of the duplex thus steepening the link fault angles;

(c) simultaneous but heterogeneous slip on effectively all of the faults in the duplex at the same time, with a greater rate of slip in the central portions of the duplex leading to steepening of the link faults in this part of the duplex, and

(d) hindward accretion of the horses of the duplex giving less steeply dipping faults at the rear of the duplex.

Exact fault displacements cannot be determined for this duplex and hence we cannot distinguish between the mechanisms proposed above. The low fault angles and smooth trajectory of the roof thrust at the rear of the duplex would tend to suggest that at least some of the horses were accreted from the rear by the development of hanging wall shortcuts (Knipe 1985) in the roof thrust.

These geometric relationships are also found in the large duplexes in the Rocky Mountains as described by Fermor & Price (1976) and by Dahlstrom (1970) for the Cate Creek window in the Lewis thrust sheet.

The smooth trajectory of the roof thrust and its large displacement (tens of metres) may possibly be interpreted to indicate that the roof thrust was active throughout the whole of the duplex formation and that only part of the displacement was partitioned into the duplex through the mechanism of footwall collapse. If this were not the case then we would expect uneven slip on the duplex link faults to deform the inactive portion of the roof thrust and hence create an irregular final roof thrust trajectory.

The complex geometries shown by stacked duplexes

(Figs. 5, 12 and 14) give rise to back thrusts, accommodation folds and significant movement out of the plane of tectonic transport. The dominant slip vector is towards 080–090° but considerable variation is observed. Slip vectors towards 000–010° appear to be associated with folds that move out of the plane of the cross-section (termed lateral lobes).

These features indicate significant internal rotations in the thrust sheets in response to the accommodation of the duplex stacking. The limited lateral extent of horses and the consequent oblique fault surfaces produce local movement in and out of the plane of the cross-section. These structures may be likened to a series of nested turtle backs or soup bowls (herein termed turtle back structures) in which individual horses have been shuffled over each other to give a wide scatter in slip directions.

This study has demonstrated that the internal deformation of the Lewis thrust sheet is complex and that considerable out-of-section movement has occurred. Thus two-dimensional plane strain and conservation of area in the plane of the cross-section cannot be assumed. Such an assumption is often made in thrust belts in order to construct balanced cross-sections (Dahlstrom 1969) and in this case it is clearly invalid. Hence we would urge caution in attempting to construct two-dimensional balanced sections in such areas as Crowsnest Pass where duplex faulting is well developed and where the duplexes clearly have a limited strike extent. One notes that in this area there is no evidence of lateral or oblique ramps and their associated folds (Fig. 2) and hence the tectonic thickening in this section arises largely from the formation of multiple small scale duplexes within the Banff Formation. This style of deformation probably occurs elsewhere in the Rocky Mountains but is difficult to identify in weathered outcrops.

CONCLUSIONS

The following conclusions can be drawn from this study.

(1) Significant complex internal deformation of the Lewis thrust sheet occurs by the formation of duplexes within the Banff Formation.

(2) For duplexes with roof thrusts that have smooth trajectories, the roof thrust may have been active throughout the formation of the duplex.

(3) In stacked duplexes there can be considerable movement out of the plane of the cross-section. Significant internal rotation and widely scattered slip vectors occur as a result of geometric accommodation of the duplex stack.

(4) In such situations as described above two-dimensional plane strain cannot be assumed in order to construct balanced cross-sections.

(5) Determination of the orientation of the regional slip vector needs to take into account the mesoscopic deformation of the outcrop from which slip data are obtained. In less well-developed areas than that described in this paper significant errors may be introduced.

(6) Finally we would conclude that even though the structures we describe in this paper are only a few tens of metres in size they show considerable geometric similarities to larger structures described elsewhere in the Rocky Mountains. We suggest that the features described in this paper may occur also at larger scales and that such complexity of deformation may also be present in larger scale structures.

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