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Fault-related folding in the Ramshorn Peak area, Idaho–Wyoming thrust belt

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Abstract—The Ramshorn Peak area of the Idaho–Wyoming thrust belt lies in the toe of the Prospect thrust sheet along the eastern margin of the exposed part of the thrust belt. The terrain is folded with axes trending N–S and wavelengths ranging from 3 to 4.3 km. Thrusts occur exclusively along the eastern part of the map area where the toe of the Prospect thrust sheet is thinnest. The easternmost thrusts are backthrusts.

Monoclinally folded rocks are thrust on less deformed rocks south of Ramshorn Peak. This fold and fault complex is interpreted to have formed by thrusting over a large oblique and small forward step. The oblique step is responsible for the formation of the monocline in the hanging wall of the thrust. All faults and associated folds are rotated by subsequent buckle folding.

Second- and third-order folds (folds at the scale of the Ramshorn Peak fold and fault complex and smaller) appear to be isolated features associated with faults (fault-related folds rather than buckle folds) because they are not distributed throughout the map area. These folds were probably initiated by translation and adhesive drag. The early folding was terminated by large translation over a stepped thrust surface which caused additional folding as the hanging wall rocks conformed to the irregular shape of the footwall. The Rich model is utilized to explain the Ramshorn Peak complex because the fold is of monoclinal form and is an isolated feature rather than part of a buckle fold wave-train.

INTRODUCTION

THE RAMSHORN Peak area lies at the eastern margin of the exposed Idaho–Wyoming thrust belt (Fig. 1). Within this area there occurs a fold above a thrust fault with a relatively undeformed footwall. The fold and fault complex is well exposed on the east face of a 304-m high ridge, just south of Ramshorn Peak. The Ankareh, Nugget, and Twin Creek Formations (Triassic and Jurassic) are thrust on Twin Creek Formation (Figs. 2, 4 and

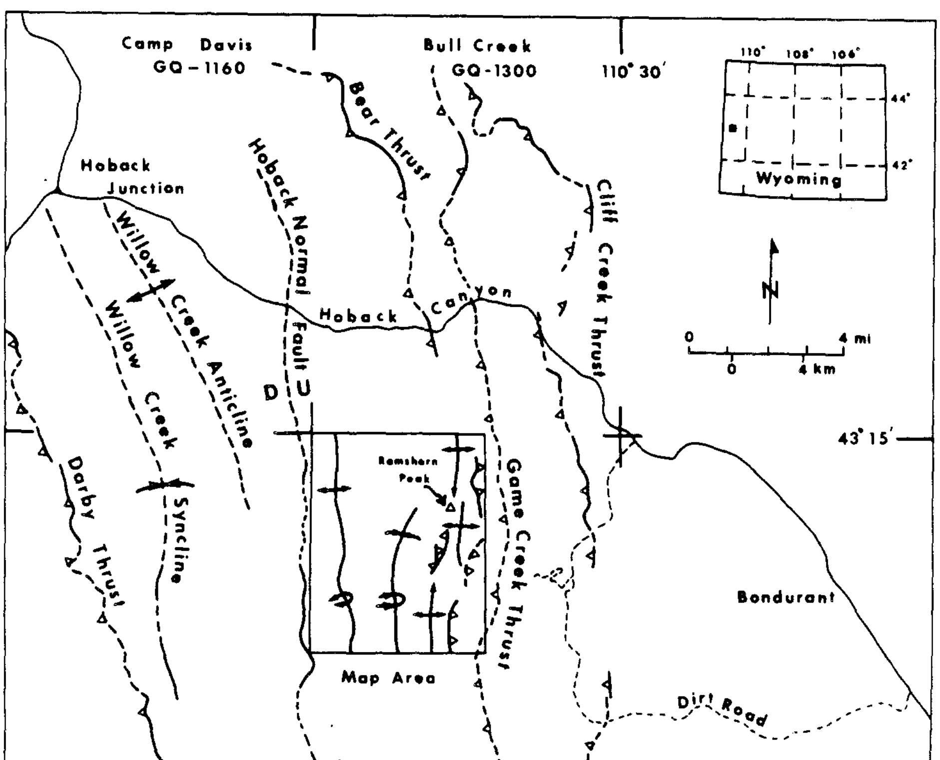

Fig. 1. Location of Ramshorn Peak map area, Teton, Lincoln and Sublette Counties, Wyoming. U.S. Geological Survey quadrangle names and geologic map accession numbers shown. Regional geology from U.S. Geological Survey geologic maps.

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EXPLANATION

Jsp	Stump and Preuss Sandstones (Upper Jurassic)
	Twin Creek Limestone (Upper and Middle Jurassic)
Jtu	Upper Part
Jtgs	Gypsum Spring Member
JTrn	Nugget Sandstone (Jurassic? and Triassic?)
Tra	Ankareh Shale (Upper and Lower Triassic)
Trt	Thaynes Formation (Lower Triassic)
Trw	Woodside Formation (Lower Triassic)
Trd	Dinwoody Formation (Lower Triassic)
Pp	Phosphoria Formation (Permian)
PPMw	Wells Formation (Permian, Pennsylvanian and Mississippian)
Mm	Madison Group (Upper and Lower Mississippian)
	Contact - Dashed where approximately located, dotted where inferred
	Thrust Fault - (includes fault later overturned into normal fault orientation) Dashed where approximately located, dotted where inferred solid teeth where fault contact is exposed
	Anticline
	Overturned anticline
	Syncline
	Overturned syncline
60	Strike and dip of beds
75	Strike and dip of overturned beds
	Strike of vertical beds
	Horizontal beds
	Photo view direction

Table 1. Explanation of symbols in geologic map of the Ramshorn Peak area (Fig. 4).

5; Table 1). The Nugget and Twin Creek Formations are folded; the Nugget Formation occurs as a monoclinal flexure with the short limb terminating at the thrust fault. At the northern end of the ridge, the fault and hanging wall beds are truncated at a saddle in the crest of the ridge, leaving only footwall beds exposed as one follows the strike of beds north towards Ramshorn Peak. All beds, in both hanging wall and footwall, dip W.

The Ramshorn Peak fold and fault complex is on the limb of a larger fold. The larger folds, with wavelengths ranging from 3 to 4.3 km, dominate the map pattern in the surrounding area. Two large anticlines trend roughly N–S near the east and west borders of the map area, with a S-plunging syncline between them. According to the cross sections of Royse *et al.* (1975) and Schroeder (1973), the rocks in the area are allochthonous above the Prospect (Cliff Creek or Jackson) thrust. The fold train is terminated on the western margin of the map area by the Hoback normal fault and on the eastern margin by the Prospect thrust.

The origin of the first-order folds is not clear. They may be buckle folds with a short wave-train, or they may be related to faulting at depth in a manner similar to the model described in this paper. Most likely, they formed from a combination of processes (Allmendinger 1981, Berger & Johnson 1980, 1982). Certainly, buckle folding was operative because the wavelength of the first-order folds increases in response to the fault-thickened section at Ramshorn Peak.

The purposes of this paper are to describe the Ramshorn Peak fold and fault complex, to relate it to structures mapped in the surrounding area and to present a model for the formation of the complex. The model incorporates the theoretical work of Berger & Johnson (1980, 1982). The theoretical work evaluates the effect of translation and adhesional drag, processes that are inferred to have been operative in the Ramshorn Peak fold and fault complex. The model does not incorporate buckling effects because the second-order ramp fold of the Ramshorn Peak complex is an isolated feature occurring in association with a thrust fault. The fold does not occur everywhere in the area, as would be expected if it

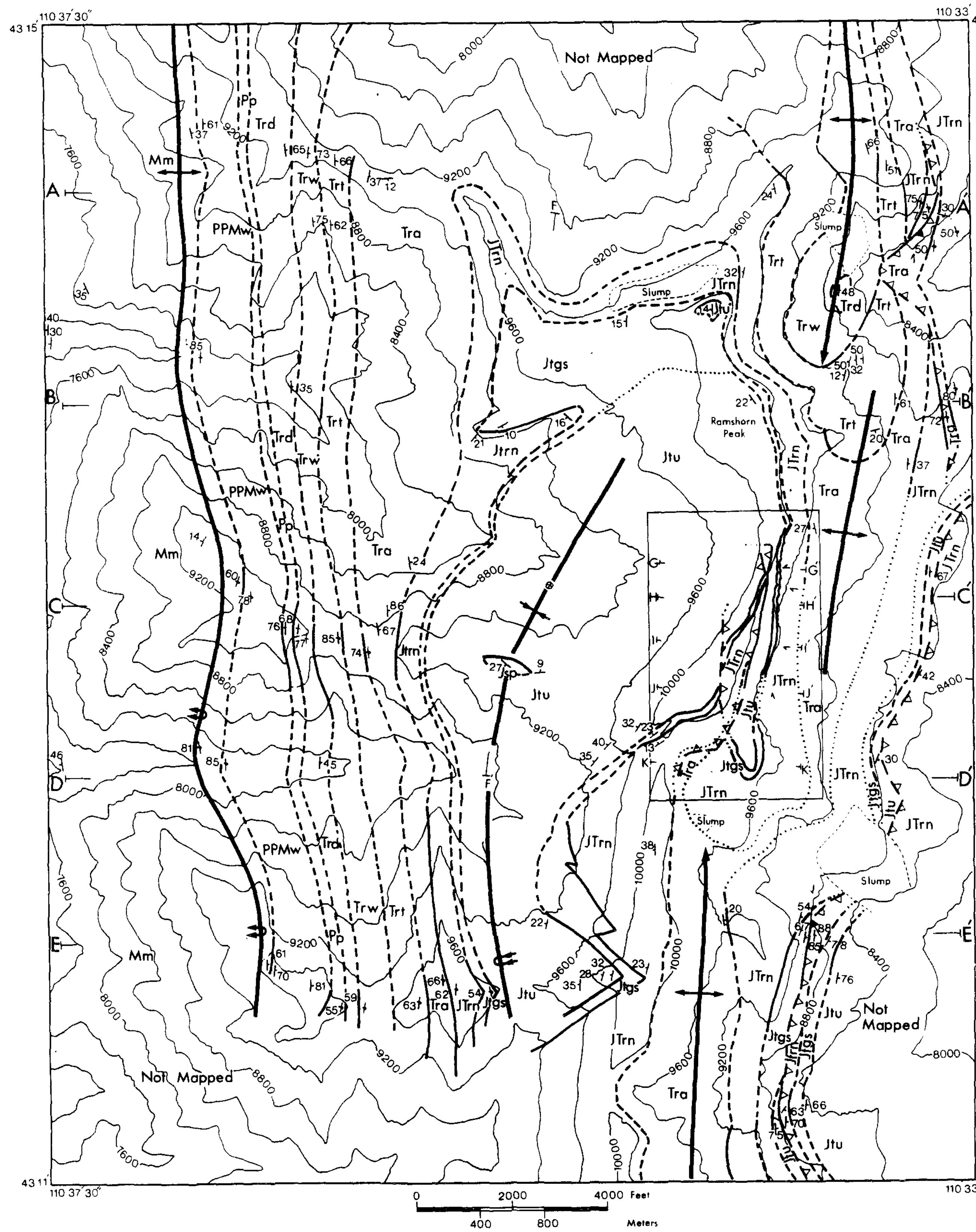

Fig. 4. Geology of Ramshorn Peak map area. See Table 1 for explanation of symbols. Contours are in feet.

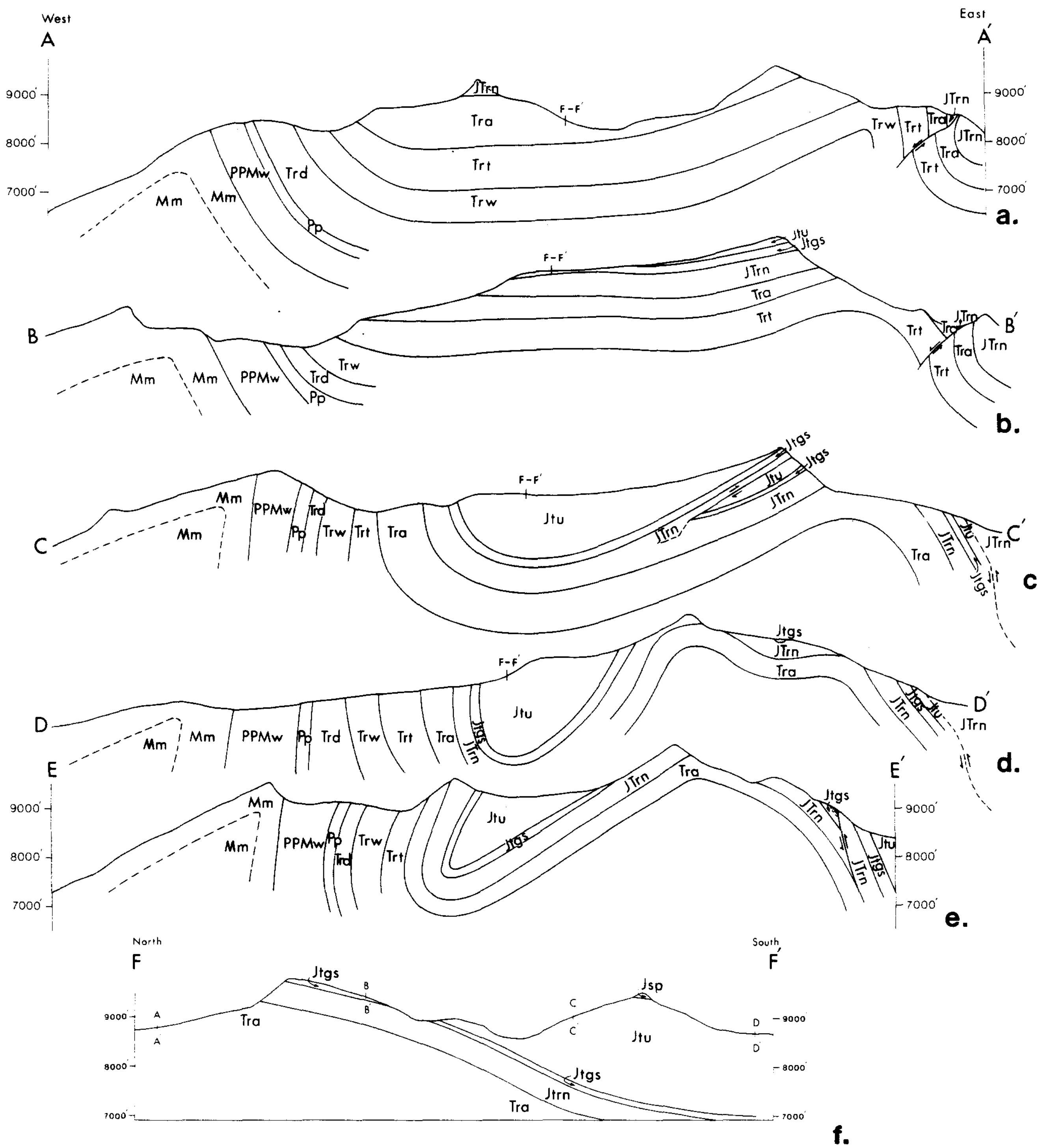

Fig. 5. Geologic structure sections [(a), (b), (c), (d) and (e) normal to structural trends, (f) parallel to structural trends] of the Ramshorn Peak area. See Table 1 for explanation of symbols. Location of section indicated on Fig. 4.

were a buckle fold formed by compression of a multilayer with thickness and viscosity contrasts. The association of an isolated, monoclinal fold with a relatively far-travelled thrust suggests that the Rich (1934) model of deformation should be utilized.

STRATIGRAPHY

In the Ramshorn Peak area, the rocks (Table 1) range in age from Mississippian (Madison Limestone) to Jurassic (Stump and Preuss Sandstones). Wanless *et al.* (1955) measured 1448 m of section for that interval from exposures in nearby Hoback Canyon and adjacent areas. In general, the map units are the same as those of Schroeder (1973). The Gypsum Spring Member of the Twin Creek Formation was mapped here as a separate unit, however, distinct from the Twin Creek Limestone. The Gypsum Spring Member is characterized by a thick, resistant, solution-breccia at the base, red shale in the middle and, following the usage of Wanless *et al.* (1955), gray shale at the top. The top of the Gypsum Spring Member is defined as the base of the first thick, gray limestone.

The pre-Nugget Triassic rocks are divided into four

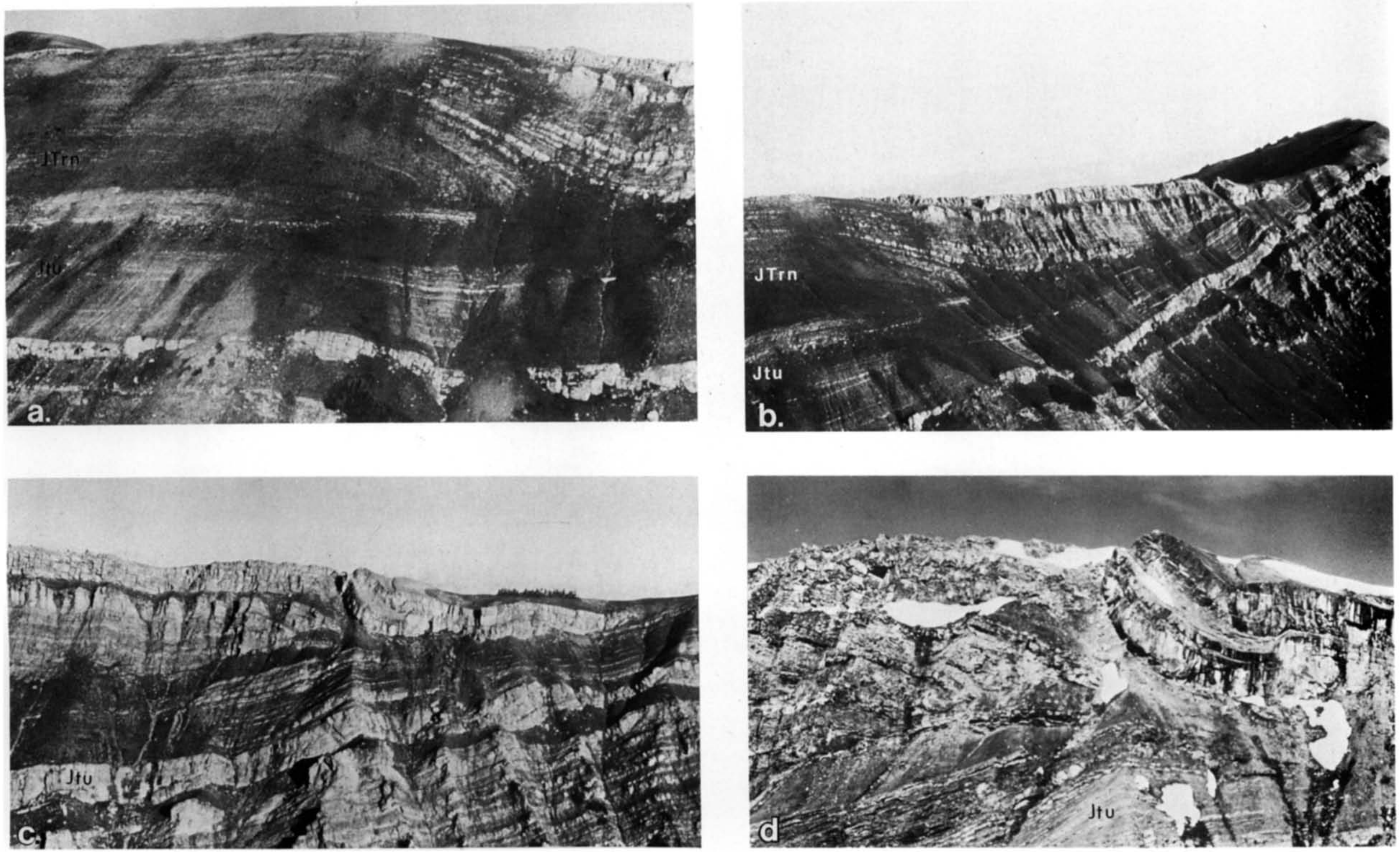

Fig. 2. Photographs taken from a helicopter at Ramshorn Peak fold and fault complex. See Table 1 for explanation of symbols. Arrows on Fig. 4 show photo view directions. Trees at ridge crest on Fig. 2(c) are approximately 3 m high. (a) Monoclinally folded Nugget and Twin Creek Formations in fault contact above Twin Creek. View looking west. Photograph by Nick Woodward. (b) View looking north-northwest. Note shallow saddle and aberrant block at north end of the thrust sheet. Ramshorn Peak is at the north end of the ridge. Photograph by Nick Woodward. (c) Northern termination of the thrust sheet. View looking west. Photograph by Nick Woodward. (d) Detailed view of the thrust termination and the aberrant block. View looking west. Photograph by Ken Young.

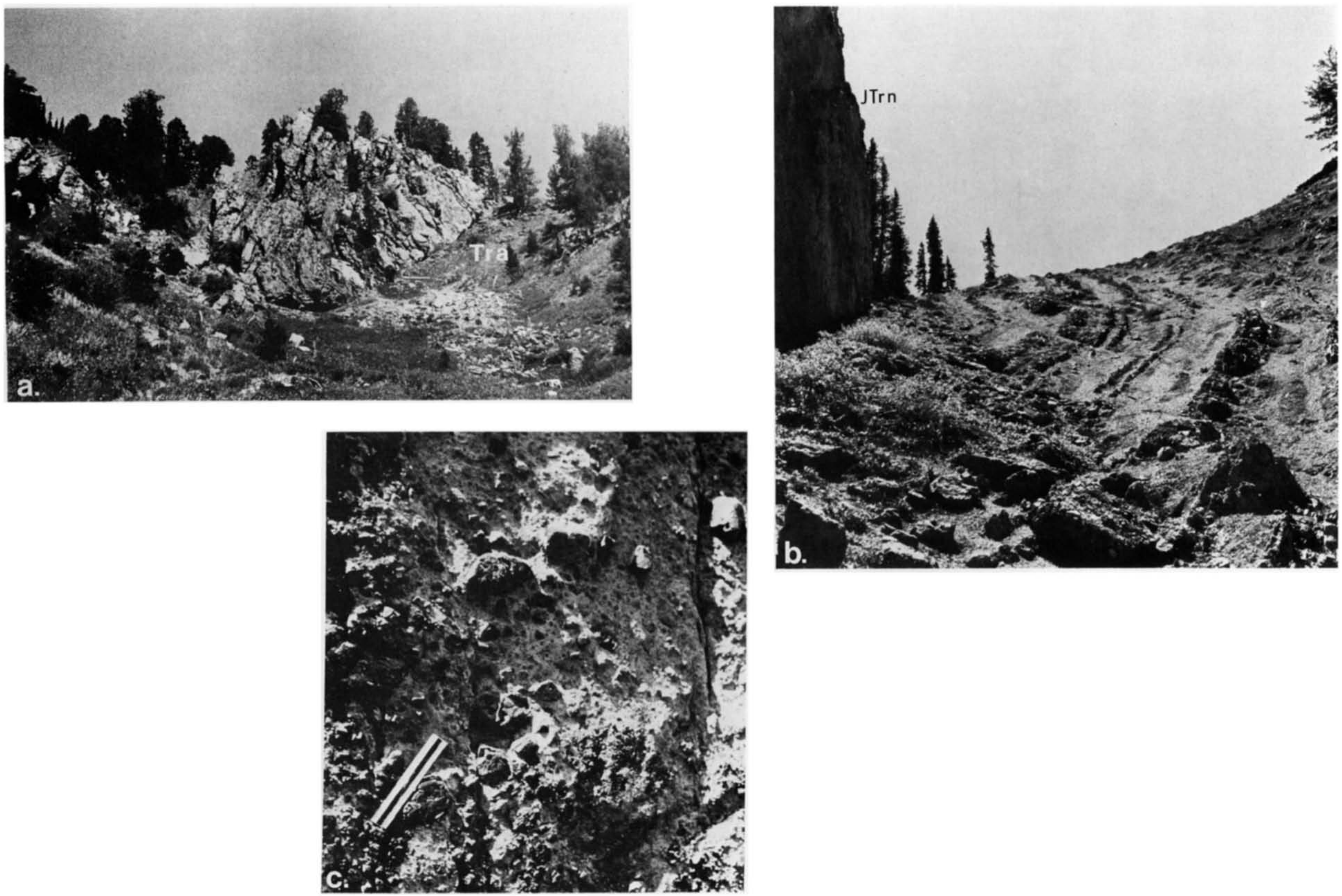

Fig. 3. Backthrusts on the east margin of the map area. (a) Vertical Nugget Formation in fault contact with overturned Ankareh Formation in the northeast part of the Ramshorn Peak map area. View looking north. Note flexure of Nugget bedding surfaces at the fault. (b) Vertical Nugget Formation in fault contact with Gypsum Spring Member in the southeast part of the Ramshorn Peak map area. View looking south. Note flexure of Gypsum Spring beds at the fault. (c) Brecciated Nugget Formation at the fault contact shown in Fig. 3(b). View looking east. Ruler is 15 cm.

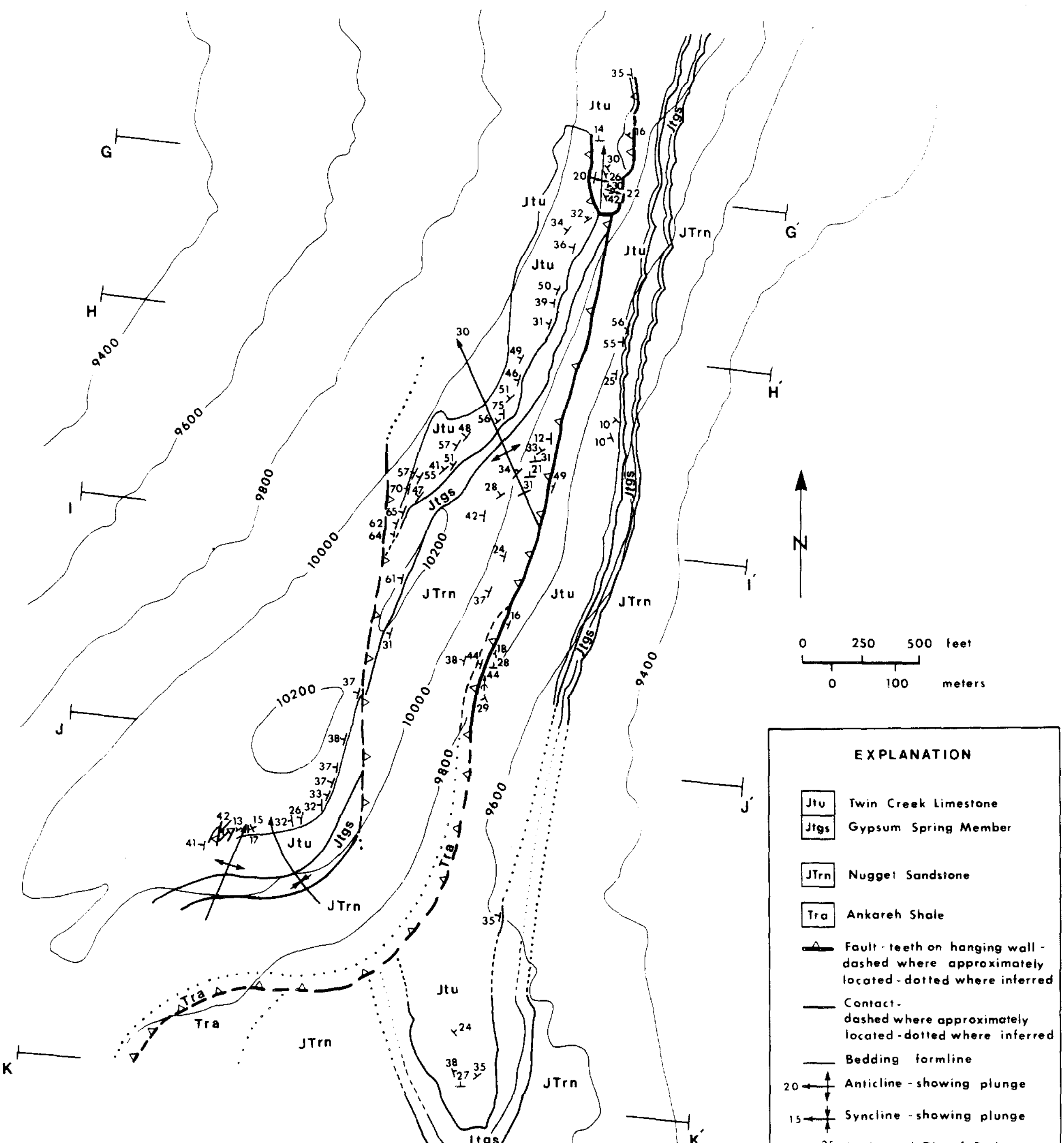

Fig. 6. Detailed geology of the Ramshorn Peak fold and fault complex. Boxed area in Fig. 4 shows location. Contours are in feet. Form lines are the trace of bed surface visible on air photographs.

map units: Dinwoody, Woodside, Thaynes and Ankareh Formations. Contacts between these units are picked at the first or last red bed. The red beds may be discontinuous, leading to variations in the thicknesses of the map units, although the overall thickness of the Triassic remains constant (Corbett, personal communication 1981).

RAMSHORN PEAK FOLD AND FAULT COMPLEX

The trace of the thrust fault climbs in altitude more than 129 m from south to north along the cliff face. At the southern margin of the detailed map area (Fig. 6), the thrust crops out at an altitude of approximately 2956 m and places upper Ankareh Formation on lower Twin Creek Limestone. At the northern end of the detailed map area, the thrust becomes parallel to bedding at an altitude of approximately 3072 m. The hanging wall beds are flexed downward and are terminated against the fault so that the fault successively truncates younger beds from south to north in its hanging wall. Along strike from south to north, the fault places Nugget on lower Twin Creek, Gypsum Spring on lower Twin

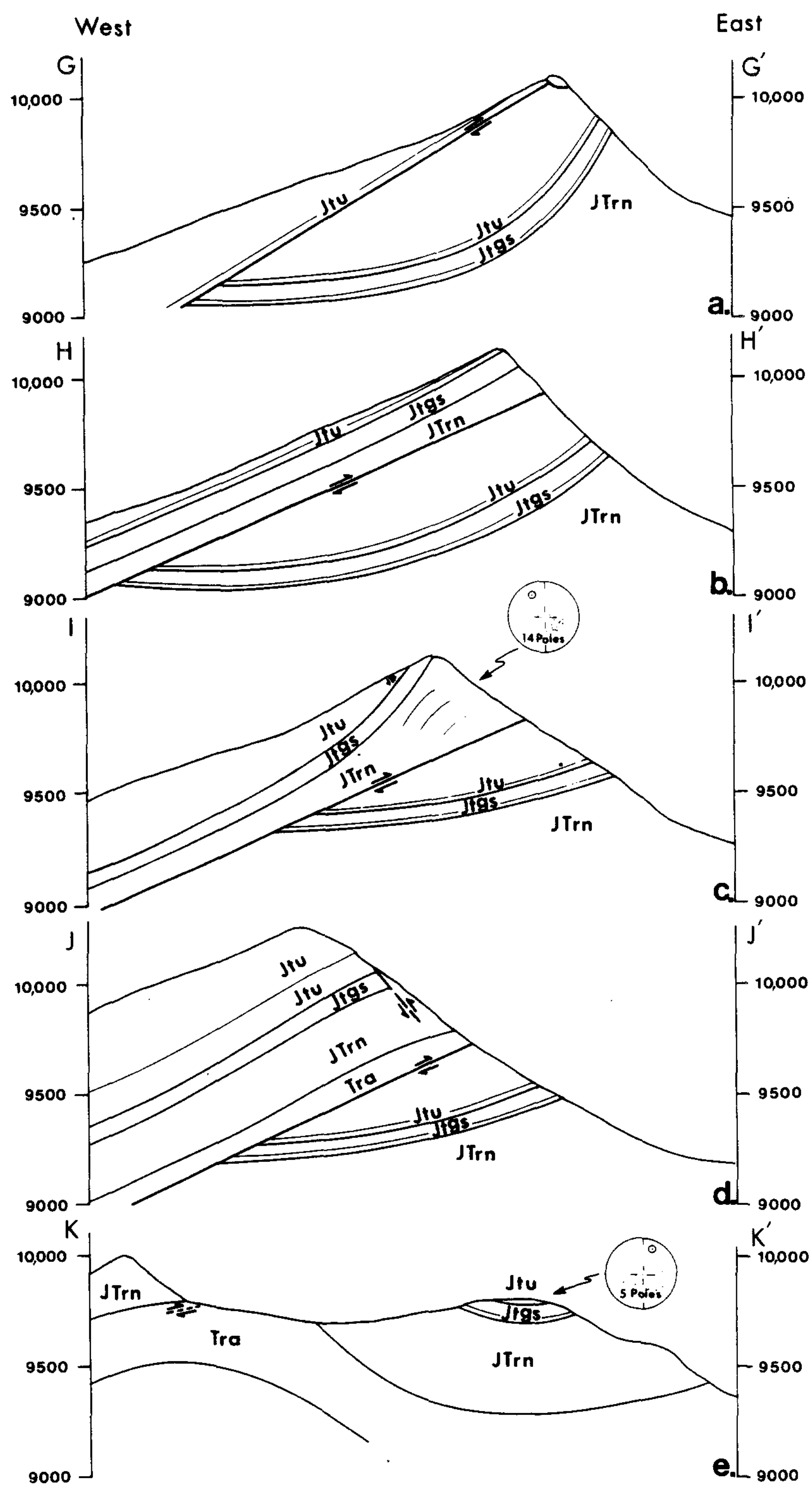

Fig. 7. Detailed geologic structure sections of the Ramshorn Peak fold and fault complex. Location of sections indicated on Fig. 6. Stereogram shows poles to bedding and Pi axis.

Creek, and finally places lower Twin Creek on lower Twin Creek (Figs. 6 and 7).

The hanging wall rocks are monoclinally folded around a fold axis plunging N33°W/30°N. When viewed down the plunge of this fold axis (Fig. 8), the terminations of the Ankareh, Nugget and Gypsum Spring are apparent. Smaller flexures occur on the short limb of the monocline in the Nugget, Gypsum Spring and Twin Creek. Minor folding with different plunge directions and a regional change in strike disturb the bedding lines in the southern end of the down-plunge projection.

In the vertical cross sections (Fig. 7), the fault is inferred generally to dip parallel to the layering in the hanging wall rocks. The fault cannot dip more gently than the beds or it would be exposed on the dip slope to the west. The fault cannot dip more steeply than the hanging wall beds because then it would be exposed in the northern part of the detailed map area. An exception

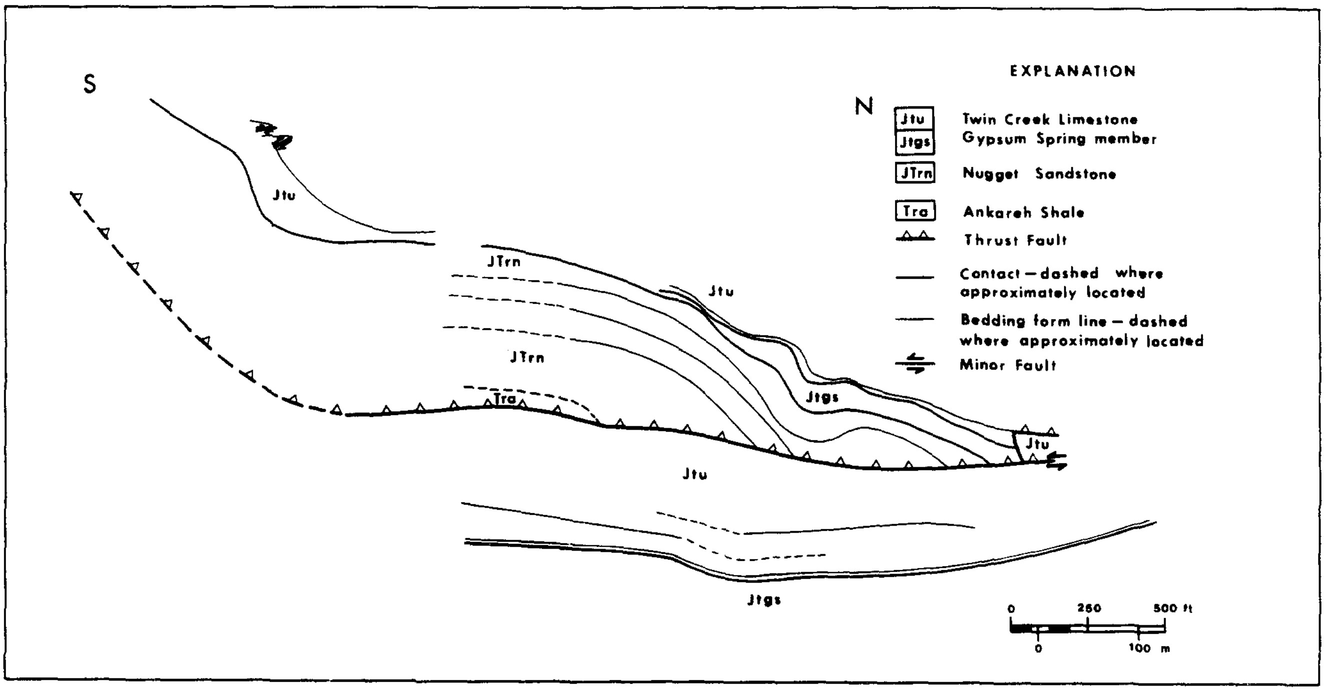

Fig. 8. Detailed geologic structure section of the Ramshorn Peak fold and fault complex viewed down the plunge of the monoclinal fold axis (N33°W/30°N). Form lines are the trace of master bed surfaces visible on air photographs.

is shown in Fig. 7(c), where the beds are distinctly steeper at the ridge crest, reaching a maximum dip of 70°. The steep dip is either a result of the termination of a minor fault visible on the next cross section to the south (Fig. 7d) or represents minor folds that formed before the Ramshorn Peak fault, exposed on the cliff face, duplicated the section.

The major thrust sheets of the region were translated to the east. The map geometry in the Ramshorn Peak region suggests transport normal to the outcrop trend of the fault. Para-autochthonous rocks occur to the north and south of the detailed map area, eliminating these regions as source areas for thrusting. A thrust sheet translated to the west would probably have to have arisen from the limb of the large anticline to the east, and subsequently have been eroded from the crest of that anticline leaving a small remnant preserved near Ramshorn Peak on the cliff face. This direction of faulting is unlikely because it requires the fault to crop out on the dip slope of the Ramshorn Peak fold and fault complex.

A small, aberrant block of Twin Creek Formation occurs in the northern part of the detailed map area (Figs. 2d, 6 and 7a). The block is faulted and rotated down so that it dips E although it is contiguous with west-dipping Twin Creek. This aberrant block is underlain by a fault-zone approximately 0.3–0.6 m thick, consisting of red shale with blocks of gypsum and limestone with diverse bedding orientations. The block is shortened in the N–S direction as evidenced by contraction faults and minor folds with a N74°W axial trend.

The footwall rocks of the Ramshorn Peak fold and fault complex are distinguished by their overall uniform trend, parallel to the trend of the fault. One small fold is apparent on the down-plunge view (Fig. 8) and there is a marked steepening of dip from south to north along strike. Prominent in the map (Fig. 6), although poorly exposed, is a small, N-plunging syncline that marks the southern terminus of the rocks that lie in the footwall of the Ramshorn Peak complex. The axis of the syncline trends N–S. Ankareh through Twin Creek Formations crop out in the syncline.

DEFORMATION IN THE TOE OF THE PROSPECT THRUST SHEET

Faults with significant displacement occur exclusively at the eastern margin of the map area (Figs. 4 and 5), and two of them are well exposed. Cross-sections by Royse *et al.* (1975) and Schroeder (1973) suggest that the Prospect thrust sheet thins from west to east across the Ramshorn Peak map area. Thus, the faults occur where the thrust sheet toe is thinnest.

Overturned Ankareh and vertical Nugget Formations are in fault contact in the northeastern part of the map area (Figs. 3a, 4, 5a & b), where the fault can be traced for approximately 1500 m across a valley with the same beds in contact on both sides of the valley (Figs. 5a & b). The exposed fault surface is striated and decreases in dip downward. The Nugget Formation is brecciated near the fault, but the main bedding surfaces are coherent and show a small flexure near the fault (Fig. 3a). The fault has the orientation and relative displacement of a normal fault. However, it accommodated shortening parallel to layers. The fault probably began as a reverse fault or as a step in a thrust fault before dips on the limb of the fold became large, and the fault was rotated to its present, normal-fault orientation by further folding. According to this interpretation, the block on the east was translated to the west, so the fault is interpreted to be a backthrust.

The Nugget Formation has been faulted onto the

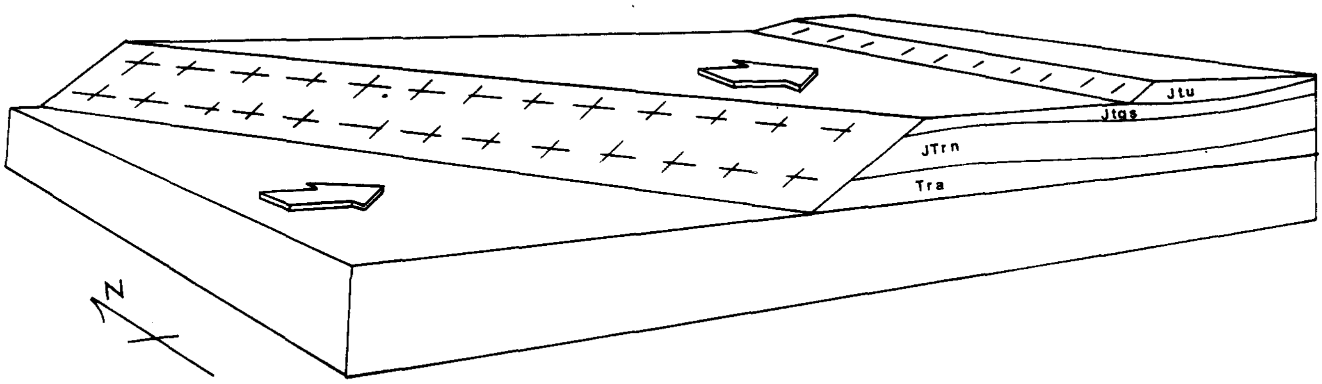

Fig. 9. Model of the footwall rocks in the Ramshorn Peak fold and fault complex.

Gypsum Spring Member in the southeastern part of the map area. The fault surface is nearly vertical, and there is a minor flexure of the Gypsum Spring beds (Figs. 3b, 4 and 5e). The Nugget Formation at the fault contact is brecciated (Fig. 3c) in a zone approximately 10 m thick. The sense of asymmetry of the flexure indicates that the block on the east was thrust over rocks on the west side of the fault. It is not likely that the fault formed with its present vertical orientation because the regional E–W horizontal compression (Allmendinger 1982) would cause it to lock. The fault is probably a backthrust, formed before dips on the limb of the fold became large, and was rotated to its present orientation by further folding.

DISCUSSION

The isolated, monoclinal form of the fold in the hanging wall of a thrust in the Ramshorn Peak area suggests application of the Rich (1934) model in order to gain insight into the structural geometry. In the Rich model, folding occurs due to fault-duplication of beds. In this fault-related (no buckling) folding process, the axis of the fold will parallel the axis of the ramp in the thrust surface. Thus, the monocline in the hanging wall of the Ramshorn Peak fold and fault complex formed as a result of thrusting over a ramp oriented N30°W and oblique to the slip direction. An oblique ramp is utilized by Elliott & Johnson (1980) to explain the oblique map pattern of the Dundonnell structure along the Moine thrust. Figure 9 is an idealized block diagram that shows the form of the footwall rocks after faulting (the hanging wall rocks are omitted from the diagram). The fault step has a minimum height equal to the thickness of duplicated beds. Thus, the height of the thrust ramp is approximately equal to the thickness of the upper Ankareh, Nugget and Gypsum Spring.

The aberrant block in the northern part of the detailed map area is folded about a N–S axis, suggesting an additional step in the detachment surface. This thrust ramp would be oriented N–S (Fig. 9) and is normal to the inferred direction of translation of the hanging wall beds. The aberrant-block fold is the sole surviving remnant of the beds truncated at the leading edge of the small step in the thrust. The stiff limestone at the base of the Twin Creek is cut off only by the second step and has rolled over to form a fold in response to translation over the second thrust ramp. The distance (parallel to the direction of transport) between the two thrust ramps may be determined by the map distance along the fault between the successive beds cut off by each ramp. In Fig. 10, a map view of the two thrust ramps, the distance between the ramps is measured as the distance between the upper Ankareh Formation (truncated at the base of the first ramp) and the top of the Gypsum Spring Member (truncated at the base of the second ramp). Because the second step is small, equivalent to the thickness of the limestone at the base of the Twin Creek, the second step should have little effect on the orientation of the monoclinal fold formed in response to translation over the first step. The exposure in the cliff face (Fig. 2) south of Ramshorn Peak is a section slightly oblique to the thrust ramps. It preserves a small segment of the leading edge of the thrust and a complete section of the rocks that have been cut off and translated over both thrust ramps.

In Fig. 10, the direction of thrusting is shown by the arrow and the thrust ramps are the hachured surfaces. Line XY and Line X'Y' show the pre-thrusting and present positions of the rocks exposed on the cliff face.

The map distance between the exposure on the cliff and the inferred thrust ramps in the footwall may be determined by examination of the surrounding area. There is a marked change in structural style between the cross-sections in Figs. 5(d) and (e). The syncline in the footwall is present in both cross sections, but the thrust has died out into an anticline along its trend. Gardner & Spang (1973) have investigated such a change in structural style along strike using clay models. In their models, an anticline has formed parallel to and along strike with the thrust ramp. The large, oblique thrust ramp is placed parallel with the anticline in Fig. 5(e). Thus, using geometric constraints based on field mapping, the inferred positions of the thrust ramps may be fixed in map view (Elliott & Johnson 1980).

Relationship between folding and thrusting

Dahlstrom (1970) provided a firm conceptual foundation for the sequence of fold and thrust belt structures. He suggests a scenario for a single thrust sheet that

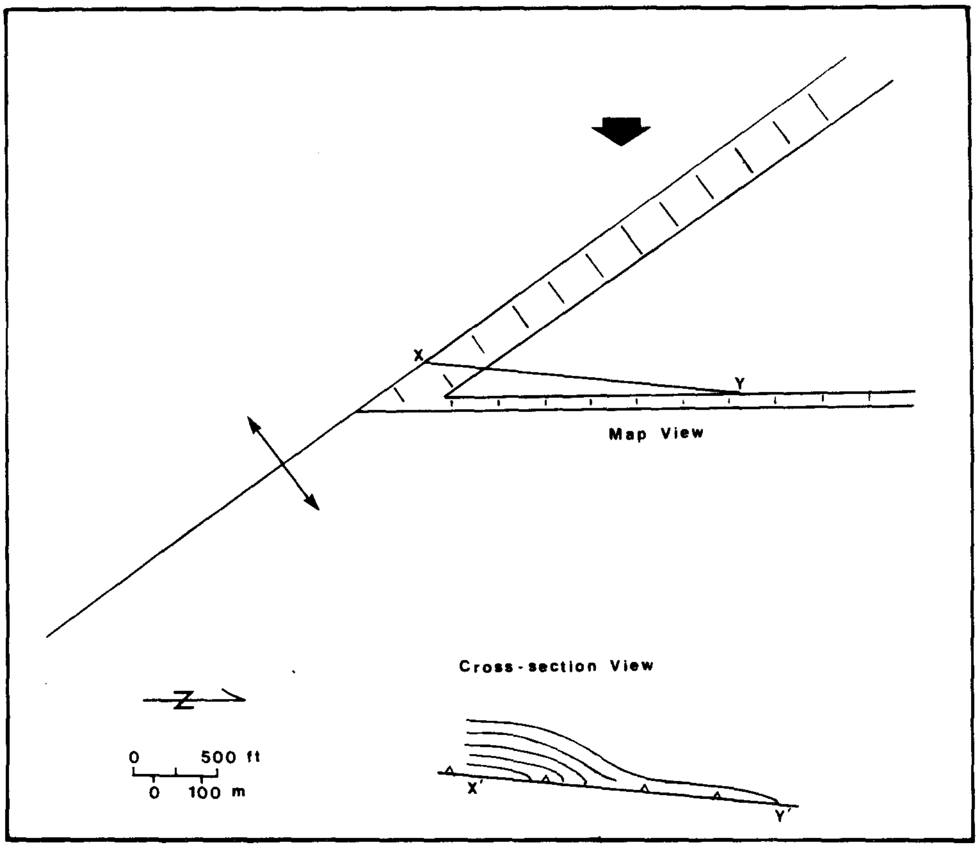

Fig. 10. Sketch map showing the spatial relations between the folds and thrust ramps. Hatchured surfaces are thrust ramps. Line XY and line X'Y' show prefaulting and present positions, respectively. Arrow indicates direction of translation of hanging wall. Scale is the same as in Fig. 6.

involves folding accompanied by minor thrust faulting, then major faulting. Additional folding due to the necessity to conform to the footwall surface (Rich 1934) may or not result, depending on the amount of translation and the height of asperities in the footwall ramp. Regional shortening and/or translation along deeper thrust sheets may also impress additional folding. At this stage, additional deformation may be superimposed from a wide variety of sources (Allmendinger 1981).

A similar scenario was constructed by Berger & Johnson (1980, 1982). They noted that minor folding results from minor translation over a flat surface, solely as a result of adhesional drag on the décollement (Berger & Johnson 1982; Fig. 2a). No lateral shortening is imposed. Fischer & Coward (1982) proposed a similar mechanism to account for folds that they inferred to have formed before translation of the thrust sheet. Berger & Johnson (1980, Fig. 5) could not derive a flat-topped, yet distinctly asymmetric anticline (such as the Powell Valley anticline of the Pine Mountain thrust sheet) by incorporating only translation and adhesional drag at the thrust ramp. They suggested (page T21) that folding and minor faulting occurred first at the thrust ramp, *followed* by additional folding as a result of a large amount of translation over a thrust surface with distinct asperities. The initial folding at the thrust ramp may result from a variety of mechanisms, including buckling, minor tectonic overlapping as a result of minor faulting (complex translation) (Berger & Johnson 1980, fig. 5a), simple translation (no tectonic overlapping) and adhesional drag (Berger & Johnson 1982, fig. 2) or complex translation and adhesional drag (Berger & Johnson 1980, fig. 5c). No folding would result from simple translation alone.

In the Ramshorn Peak complex, minor folding (third-order) is inferred to have occurred before translation over the thrust ramps. This is evidenced by third-order folding in the hanging wall of the Ramshorn Peak complex (Fig. 7c) (allowing the fault to cut down section). The minor pre-translation folding is shown schematically as folded footwall in Fig. 9. Like the second-order Ramshorn Peak fold, the third-order folds appear to be relatively isolated features associated with thrust faults, rather than buckle folds. These folds are probably fault tip-line folds as identified by Elliott (1976), formed by high adhesional drag with little or no translation (Berger & Johnson 1980, fig. 5d).

In summary, the Ramshorn Peak fold and fault complex has many of the elements recognized by Dahlstrom (1970), Elliott (1976) and Fisher & Coward (1982) for the larger thrust sheets. The major difference is that the Ramshorn Peak complex suffered less deformation prior to translation along faults, primarily because buckle folding was inhibited. The complex is somewhat unusual in that the main footwall ramp is relatively large, giving rise to a relatively large fold, yet not so large as to prevent the hanging wall from reaching and passing the top of the footwall ramp. Perhaps the oblique ramp offered less resistance to translation than a forward ramp. Similarly, the Ramshorn Peak complex is situated in the distal portion of the thrust belt so that later deformation only rotated the structures but did not obscure them.

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REFERENCES

Allmendinger, R. 1981. Structural geometry of Meade Thrust Plate in northern Blackfoot Mountains, southeastern Idaho. *Bull. Am. Ass. Petrol. Geol.* **65**, 509–525.

Allmendinger, R. 1982. Analysis of microstructures in the Meade plate of the Idaho–Wyoming foreland thrust belt, U.S.A. *Tectonophysics* **85**, 221–251.

Berger, P. & Johnson, A. M. 1980. First-order analysis of deformation of a thrust sheet moving over a ramp. *Tectonophysics* **70**, T9–T24.

Berger, P. & Johnson, A. M. 1982. Folding of passive layers and forms of minor structures near terminations of blind thrust faults—application to the central Appalachian blind thrust. *J. Struct. Geol.* **4**, 343–353.

Dahlstrom, C. D. A. 1970. Structural geology in the eastern margin of the Canadian Rocky Mountains. *Bull. Can. Petrol. Geol.* **18**, 332–406.

Elliott, D. 1976. The energy balance and deformation mechanisms of thrust sheets. *Phil Trans. R. Soc.* **A283**, 289–312.

Elliott, D. & Johnson, M. R. W. 1980. Structural evolution in the northern part of the Moine Thrust Belt, NW Scotland. *Trans. R. Soc. Edinb.: Earth Sci.* **71**, 69–96.

Fischer, M. W. & Coward, M. P. 1982. Strains and folds within thrust sheets: an analysis of the Heilam Sheet, Northwest Scotland. *Tectonophysics* **88**, 291–312.

Gardner, D. & Spang, J. 1973. Model studies of the displacement transfer associated with overthrust faulting. *Bull. Can. Pet. Geol.* **21**, 534–552.

Rich, J. L. 1934. Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky, and Tennessee. *Bull. Am. Ass. Petrol. Geol.* **18**, 1584–1596.

Royse, F., Jr., Warner, M. & Reese, D. 1975. Thrust belt structural geometry and related stratigraphic problems, Wyoming, Idaho, and northern Utah. In: *Deep Drilling Frontiers of the Central Rocky Mountains* (edited by Bolyard, D.), Rocky Mountain Association of Geologists, 1975 Symposium, Denver, Colorado, 41–54.

Schroeder, M. 1973. Geologic map of the Clause Peak Quadrangle, Lincoln, Sublette and Teton Counties, Wyoming. Geolog. Quad. Map, U.S. geol. Surv., GQ-1092.

Wanless, H., Belknap, R. & Foster, H. 1955. Paleozoic and Mesozoic rocks of Gros Ventre, Teton, Hoback and Snake River Ranges, Wyoming, *Mem. geol. Soc. Am.* **63**, 1–90.