

BALANCED CROSS-SECTION ACROSS THE SOUTHERN UTAH OVERTHRUST BELT (OTB)

By

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القطاعات المتوازنة حول حزام الصدوع الفوق دسر بجنوب يوتا

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تتيح القطاعات المتوازنة الفرصة لدراسة وفهم المناطق ذات التراكيب الجيولوجية المعقدة ، وقد تم عمل دراسات حقلية تفصيلية وتحليل تركيبية بتطبيق التقنية الهندسية المتوازنة لرسم قطاعات عرضية حول الطيه المحدبة الرئيسية لمسافة أكثر من ٧٠ ميل في الجزء الجنوبي لحزام الصدوع الفوق دسر من ولاية يوتا . وقد تم رسم القطاعات العرضية باستخدام نموذجين : قطاعات تعتمد على برامج كمبيوتر في المناطق المعتدلة التشوه ، وقطاعات تم رسمها بالاعتماد على نماذج معادلات رياضية في المناطق الشديدة التشوه . ولقد تم رسم أربعة قطاعات عرضية وقد استنتج ان الطيات قد تكونت نتيجة وجود صدع اندفاعي قاعدي انفصالي يرتبط مع صدع ذو انحناء ، ويفصل الصدع القاعدي الانفصالي المناطق الاستراتيجرافية الضعيفة نسبيا (الجبس والطفل) ولكنه يتواجد أيضاً في مستويات استراتيجرافية عالية مما يسبب تعقيد شكل الطيه وذلك في المناطق شديدة التشوه . وكذلك استنتج اختلاف شدة التشوه في منطقة الدراسة ، حيث تكون أكثر نشاطا في الوسط والشمال وأقل تشوها في الجزء الجنوبي .

Key Words: Balanced cross section, Southern Utah

ABSTRACT

Balanced cross-sections are offering the chance of better understanding of areas of complex geological structures that are insufficiently understood.

Detailed field study and structural analysis by employing geometric balancing techniques is used to construct cross-sections along the major fold, the Virgin - Kanarra anticline, over a distance of 70 miles in the southern part of the Utah OTB. Two models were used to construct the cross sections: a) A computer modeling program, used to draw cross-sections in the mildly deformed areas. b) A manual mathematical method, used in the strongly deformed areas.

Four cross-sections are presented illustrating that: 1) The folds are caused by steps in a basal detachment thrust that links with a break thrust. The basal detachment in southwest Utah preferred the stratigraphic zones of relative weakness (shale, gypsum), but detachment also exist at high stratigraphic levels and complicate the fold shape in the highly deformed areas. 2) Along the major fold, the intensity of deformation is variable, with stronger activity in the middle (e.g. Spring Creek) and the northern portions and less deformation in the southern part.

INTRODUCTION

The overthrust belt (OTB) of Utah, also known as the Sevier orogenic belt [1] occupies an elongate north-east trend-

ing belt, that runs for approximately 360 miles (600 km) long by 75 miles (125 km) wide. The area under study is located in southwest Utah (Fig. 1). It lies in the transition zone between the Basin and Range Province to the west and

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the Colorado Plateau to the east. It extends from Parowan Gap in the north to St. George in the south, passing through Cedar City along interstate 15. It is the eastern edge of the OTB, where folding and coeval thrust faulting of the sedimentary strata constitute the main structures.

The rocks exposed in the study area range in age from Permian to Quaternary (Table 1). The dominant sedimentary rocks are Mesozoic in age, which include limestone, sandstone, siltstone, shale and gypsum with minor conglomerate units.

The present work deals mainly with the structural geometries in the leading-edge folds of the OTB in southwest Utah, which affords an excellent opportunity for detailed structural analysis, where the rocks are well exposed. These exposures allow fitting of various theoretical models to each sub-area. These models in the form of series of detailed cross-sections running across the major fold, the Virgin - Kanarra anticline, that reveal the shape, size and timing of deformation of the hidden structure.

It is worth to mention that although the area has been studied by the previous workers, but none of them dealt with the detailed structure.

METHODS OF STRUCTURAL ANALYSIS

A. BALANCING TECHNIQUES

The concept of balanced cross-sections was first discussed in detail by Dahlstrom [2]. General methods of section balancing are now well established and have been discussed by several authors [2-5]. Balancing technique is a method of constructing the checking cross-sections for geometric acceptability. Balancing simply means that a cross-section is retrodeformable [6]. A balanced cross-section is a deformed-state cross-section that is both admissible and viable [7], but are not necessarily geologically correct.

Balancing techniques employ geometric models, which allow the structural interpretation or analysis to be translated into an understanding of the structural history. They were based on combination of data and assumptions, and the construction of the cross-sections was based on the following: 1) conservation of bed thickness, 2) conservation of bed length, 3) conservation of areas, 4) no distortion where the beds are horizontal, 5) the line of the cross-section is parallel to the transport direction, 6) all geometric methods are based on parallel folding, where parallel folding requires that the two axial angles at each plane are equal.

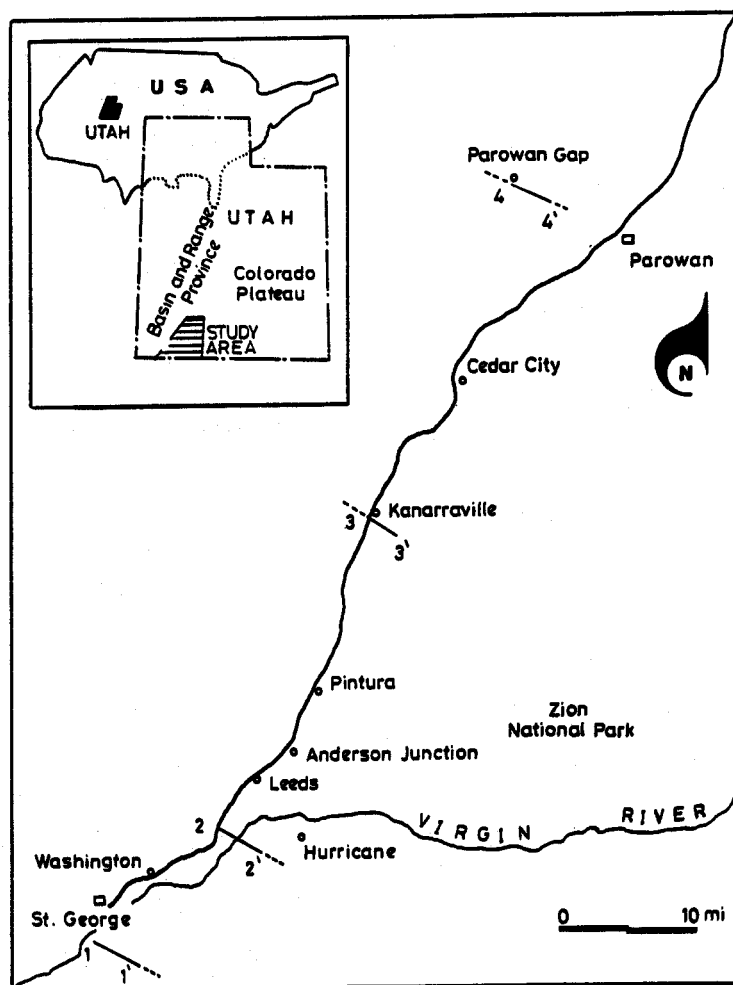


Figure 1. Index map showing the location of cross-sections.

Table 1
The different stratigraphic Formations in the study area

FORMATION	SYMBOL	THICKNESS"FT"
CENOZOIC		
Alluvium	Qal	
Basalt	Qb	
Claron Formation	Tc	2320
MESOZOIC		
Iron Springs Formation	Kis	3500
Navajo Sandstone	Jc	1200
Upper Keyenta	Jn	1700
Kayenta Formation Shurtz Tongue	Jku	450
Lower Kayenta	Jnu	400
MOENAVE FORMATION		
Springale Member	Jm	
Dinosaur Canyon Member	Jms	110
CHINLE FORMATION		
Petrified Forest Member	TRc	
Shinarump Member	TRcp	300
MOENKOPI FORMATION		
Upper red member	TRm	
Shnabkaib Member	TRmu	515
Middle red member	TRms	350
Virgin Member	TRmm	370
Lower red member	TRmv	130
Timpoweap Member	TRml	454
PALEOZOIC		
Kaibab Formation	TRmt	200
Toroweap Formation	Pk	400
Queantoweap Formation	Pt	453
Pakoon Formation	Pq	330
Callville Formation	Pp	465
Redwall Formation	P	900
Devwall Formation	M	850
Devonian	D	1533
Ordovician	O	933
Cambrian	C	1133
Precambrian	PC	

Dahlstrom [2] and Royse, Warner, and Reese [8] have emphasized that thrust faulting and folding in the Canadian Rockies and the eastern Idaho/western Wyoming thrust belt indeed took place without appreciable volume change. Furthermore, they demonstrated that bedding was neither thickened nor thinned significantly during deformation. Jamison [9] mentioned that bedding maintains constant thickness in the kink-hinge models except in the forelimb of the fold. In his view the forelimb is allowed to thicken or thin without limit.

The procedure of cross-section balancing has proven to be most valuable in the study of deformed belts in which deformation is largely confined to layer of rock that lie

above a subhorizontal detachment fault or decrement [10-12] Redgers, [11,12]. Deformation involving detachments occurs both in fold-thrust belt [13], in which shortening of the crust is accommodated by the formation of thrust faults and associated folds [3], and in extension or rift terraces, in which crustal thinning is accommodated by the formation of normal faults and associated folds [14-16]. Balancing techniques may be restricted to one simple geological environment, the marginal part of an orogenic belt [2]. The methods of cross-section balancing can also be applied in areas of thrust basement or metamorphic rocks [17]. Boyer [18] and Boyer and Elliott [13] constructed a balanced cross-section in the metamorphic rocks and basement of the Blue Ridge. This present work focuses on cross-sections of fold-thrust belts, for most cross-section balancing studies to date have been applied for these belts [4].

Balancing of cross-sections can be checked by using area balance [3,19,20] and/or bed-length balance [2,19]. Balancing can quickly be checked by measuring and comparing all bed lengths at various stratigraphic levels. The bed lengths should be the same. Where possible, the authors used bed-length balance because it is easy and quick.

B. KINK-STYLE METHOD

The Busk [21] and kink methods are two objective geometric techniques used to project surface data on fold geometry to depth. Both methods assume that the layers are of constant thickness. If the bed thickness is constant (parallel fold), the axial surface bisects the angle between the fold limbs into equal axial angles.

Folds could be drawn as sinusoidal and projected to depth from surface data using the methods of Busk [21]. However, Fail [22,23]; Laubscher [24,25] and Roeder et al. [26] have shown that folds in most fold and thrust belts possess kink-band geometries, with sharp narrow hinges and long planar limbs [27].

The kink method assumes that the folds are parallel (i.e. have constant layer thickness measured perpendicular to bedding), have straight limbs and sharp angular hinges (kink, or chevron folds). Reconstruction a cross-section and preserving bed lengths presumes parallel folding. Dahlstrom [2,28] described concentric folding as the operative fold-style, but included simply curved folds, chevron folds and box folds within his "concentric" style. In many localities folds that develop in fold-thrust belts are not smooth concentric curves in profile but rather are subdivided into several dip domains [22,29] in which the beds have a uniform dip. In such regions, the fault-related folds are said to have a kink-style. The kink methods is motivated by the fact that detailed measurements show that many large folds in sedimentary rocks are composed of a series of sharp bends [30].

The authors used the kink-style folds method in constructing the cross-sections because the kink method allows them to construct cross-sections of angular folds rapidly and reliably. The required data to draw cross-section by using kink-style folds are: 1) strike and dip, 2) stratigraphic thicknesses, 3) formation contacts, 4) fault positions, and 5) well and seismic data, if available.

It is easier to draw a cross-section if the fold are kink style, because limbs of the folds can be drawn as straight-line segments, and if there is no thinning or thickening of beds, the distances between contacts can easily be kept constant. In addition, it is easier to measure or calculate bed lengths, bed areas and amount of shortening and to determine the cut-off angles on kink-style cross-sections. For this reason, all the cross-sections drawn by the authors are drawn with the kink-style method.

RESULTS OF THE STUDY

The principal product of this study is a detailed set of four parallel balanced cross-sections constructed across the major fold of the study area, the Virgin-Kanarra anticline, over a distance of 70 miles, the sections running in NW-SE direction (Fig. 1). Some of the cross-sections were constructed utilizing published maps, but they were field checked by the author (Noweir) along the line of the cross-section. The author also had some difficulties because drill hole and seismic information were scarce. So, these sections represent the author's best interpretations of the available data. Therefore, details of the cross-section can be expected to change with more complete information, although the major features are expected to be correct. In the construction of the balanced cross-sections, the authors employed stratigraphic and structural relationships observed at the surface [31-34] to elucidate the stratigraphic and structural configurations which may exist in the subsurface.

The section construction is based upon two procedures: first, a commercial computer cross-section modeling program "MacthrustRamp" which enables the authors to draw rapidly cross-section in mildly deformed areas; second, a manual mathematical model, which enables the authors to draw cross-section in strongly deformed areas. The computer modeling program utilizes parallel folding deformation models, fault-bend and fault-propagation folding based upon Suppe's equations [30-35]. The authors used only the fault-propagation folding module (FaultProp model) to construct cross-section in less deformed areas. We also used the dip domain geometry [29] in which the beds have a uniform dip in order to maintain constant layer thickness throughout the structure. It should be noted that all the cross-sections constructed using the computer modeling program are reclassified by the author's fault-propagation folding (Type I). These cross-sections are : Webb Hill, St. George and Purgatory. On the other hand, all the propagation folding (Type II) [36]. These cross-sections are: Spring Creek-Kanarraville and Parowan Gap.

BALANCED CROSS-SECTIONS

a. Cross-section 1-1' (Webb Hill-St. George). Cross-section 1-1' (Fig. 2) is the most southerly cross-section of this series, location shown in Fig. 1. Surface geology along the cross-section is modified from Christenson and Deen, [37]. This cross-section was constructed a few miles south of St. George, and extends for about 4.75 miles in a NW-SE direction. The cross-section line is normal to the fold axis of the Bloomington Dome which is situated a few miles south of St. George. The Permian Kaibab Limestone forms the crest of the dome with overlying Triassic Moenkopi Formation on their flank.

The balanced cross-section allows the following structural interpretation: 1) the Bloomington Dome is asymmetrical structure which is characterized by a moderately steep west flank, a flat crest in the younger rocks, and a more gentle and broad east flank, 2) the origin of the structure is a step in a deep detachment thrust in the Precambrian rocks, 3) a flank thrust located on the west flank of the structure visibly repeats the Shinarump Member of the Chinle Formation (Fig. 3).

b. Cross-section 2-2' (Harrisburg Dome-Purgatory). This cross-section 2-2' (Fig. 4) is a few miles north of cross-section 1-1'. It is a few miles south of the town of Hurricane (Fig. 1), passes through the Harrisburg Dome, just south of Purgatory Flats (crossed by Utah Highway 9). It extends for about 4.75 miles in NW-SE direction. There is no geologic map available for this part of the area, so surface geology along the cross-section line was collected by authors. Similar to Bloomington Dome, the Permian Kaibab Limestone is exposed at the surface along the crest of the dome. Both limbs are exposed at the surface.

The balanced cross-section reveals the following: 1) the Harrisburg Dome is asymmetrical structure with steep west flank, a flat crest in the younger rocks, and a gentle east flank, 2) the shape of the fold is due to a basal detachment at the Precambrian-Cambrian boundary that ramps up to the upper Moenkopi Formation, 3) the cross-section shows two structural relationships: i) the flank thrust on the west limb of the anticline which repeats the Shinarump Member of the Chinle Formation is offset by an axial thrust, shown thus because the flank thrust is judged to be older than the axial thrust; ii) the axial thrust, east of and parallel to the fold axis, which repeats the Kaibab formation (Fig. 5) and the lower red member of the Moenkopi Formation is offset by the ramp fault, because at high structural levels the ramp fault is presumed younger than the flank and axial thrusts. Both the flank and axial thrusts can be seen in the field.

c. Cross-section 3-3' (Spring Creek-Kanarraville). This cross-section (Fig. 6) was constructed just north of Spring Creek which is located 0.5 mile southwest of the town Kanarraville (Fig. 1), about 10 miles south of Cedar City. It extends for about 4.5 miles in a NW-SE direction. Surface geology along the cross-section line is modified

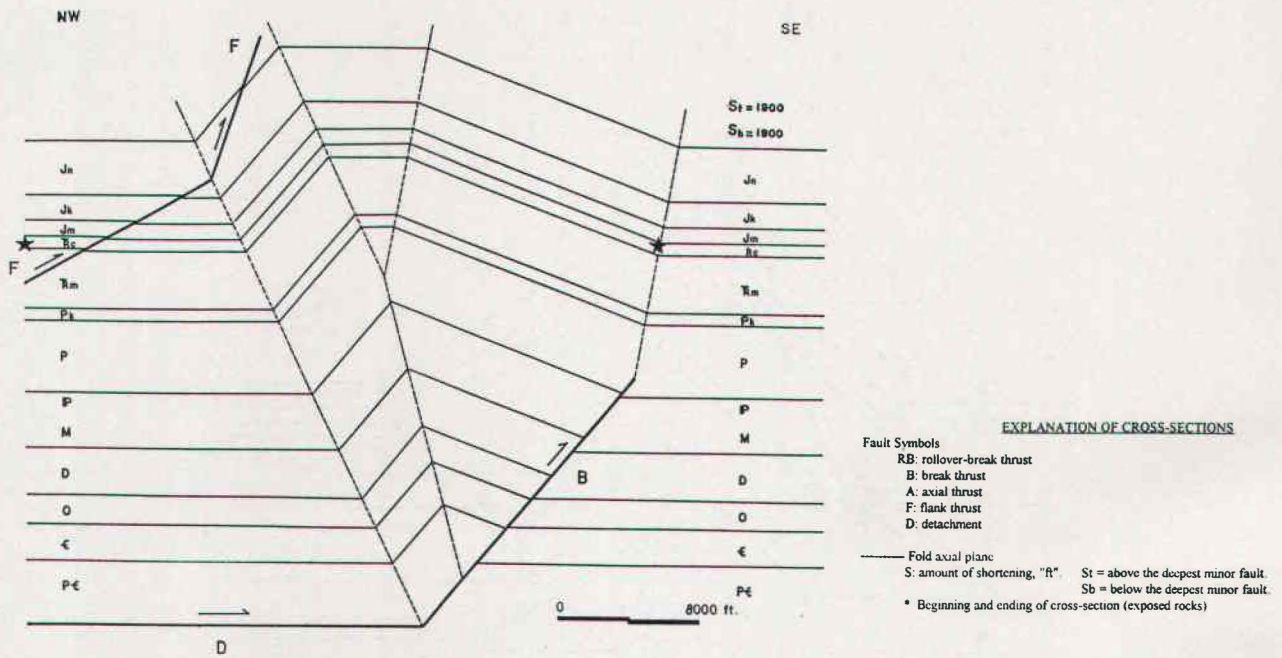


Figure 2. Balanced cross-section 1-1' of the Webb Hill-St. George, deformed state.



Figure 3. A thrust fault (200 ft displacement) on the left in which the left side of the Shinarump Member, TRCs, has moved up and over the right side. Webb Hill-St. George, looking N.

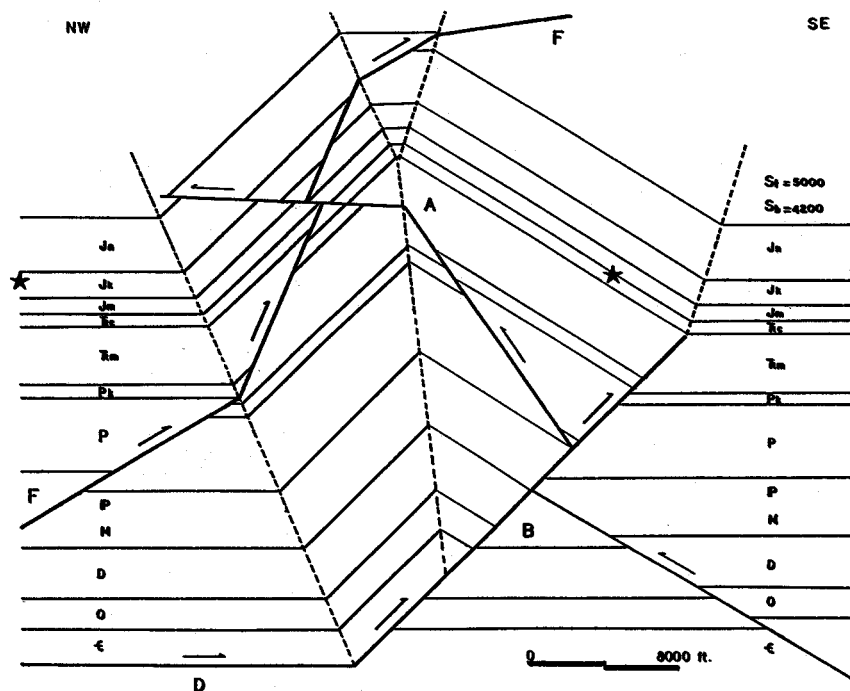


Figure 4. Balanced cross-section 2-2' of the Harrisburg Dome-Purgatory, deformed state. See Figure 2 for symbols.

from Averitt [38]. The overall structure in the canyon is a huge S-shaped fold (looking south) and parts of the canyon are complicated by a number of different types of faults including rollover-break thrust, flank thrust and zig-zag faults. The latter is not shown on the cross-sections, because of its small net slip.

The deformed cross-section shows the following: 1) an asymmetrical anticline characterized by a gentle west flank, a flat crest, and a steep and overturned east flank, 2) a detachment fault located at the lower part of the Permian Kaibab Limestone that ramps up through the entire section is responsible for the fold shape and the structure. The ramp fault shows a double action, normal slip near the ramp base, where the rocks on the hanging wall (i.e. TRc) moved down and a reverse slip near the ramp top, where the rocks on the hanging wall (i.e. JK) moved up, 3) flank thrusts appear on both limbs of the fold. The eastern one can be seen in the field which causes the repetition of the Springdale Member of the Moenave Formation. This flank thrust is shown off-

set by the ramp fault, because the flank thrust is older. The western flank thrust is presumed to exist on the west flank which is hidden from view beneath alluvium, 4) two axial thrusts are shown in the core of the fold, causing the repetition of the Permian Kaibab Formation, 5) the renewed movement of the rocks along the ramp fault resembles that of fault-bend folding, that occurred when the ramp fault propagated to the ground surface, 6) this cross-section representative of the highly deformed part in the area under study.

d. Cross-section 4-4' (Parowan Gap). Cross-section 4-4' (Fig. 7) is the most northerly cross-section of this series and in the area under study; its location is shown in Fig. 1. It extends for about 6.5 miles in an NW-SE direction. Surface geology along the cross-section is modified from Threet, [39]. It is worthy to note that the Jurassic Navajo Sandstone which appears along the west flank of the Parowan Gap horst is the oldest exposed in the area.

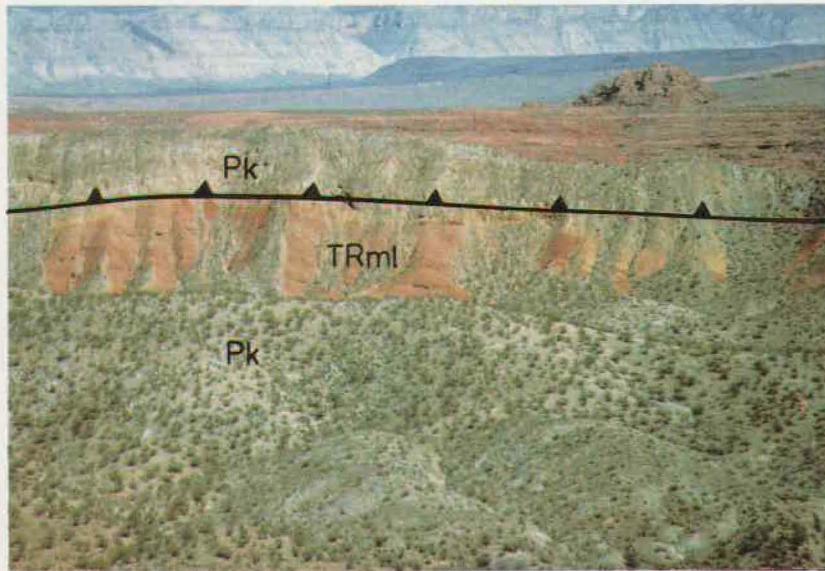


Figure 5. Shows the repetition of the Permian Kaibab Formation, Pk, by an axial thrust fault just east of the axis of the Virgin anticline at Purgatory. The Triassic lower red member TRml, of the Moenkopi Formation lies between the two Kaibabs, and the fault is at the top of the lower red member. Looking E.

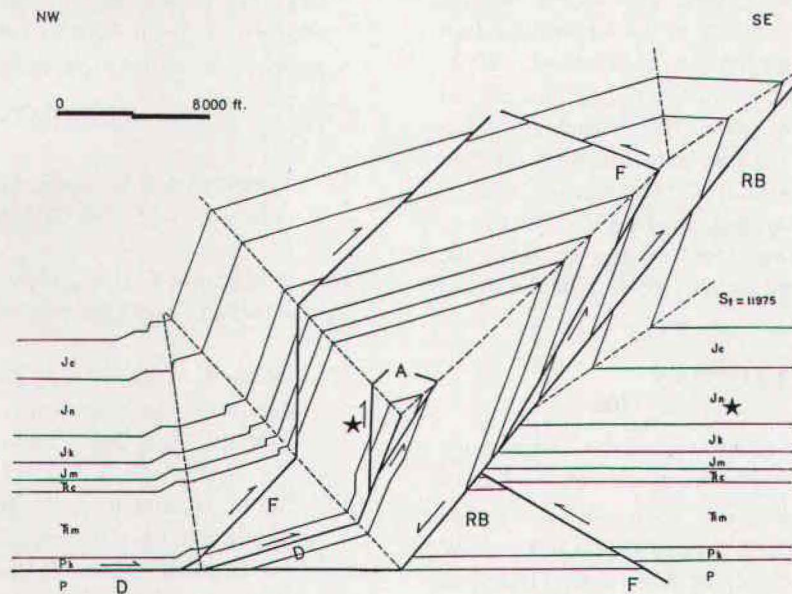


Figure 6. Balanced cross-section 3-3' of the Spring Creek-Kanarraville, deformed state. See Figure 2 for symbols.

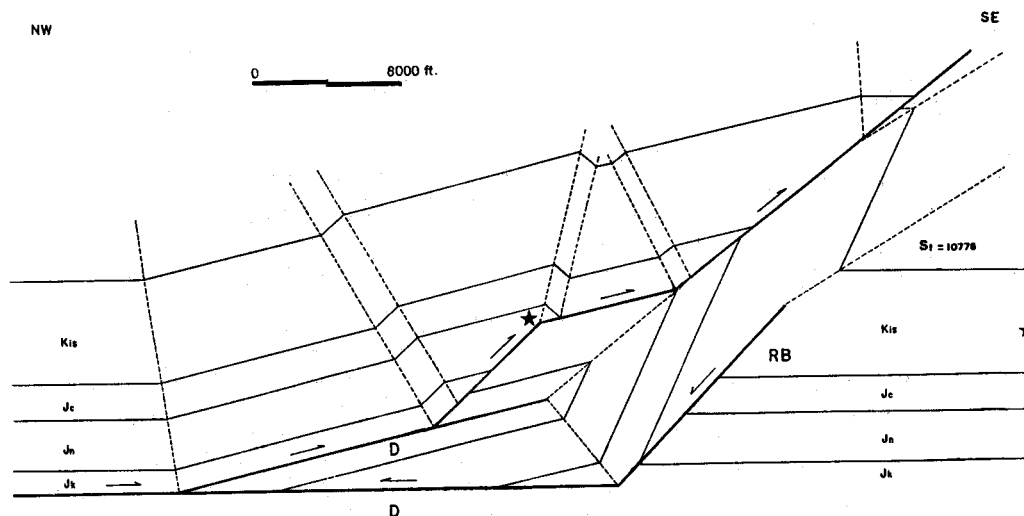


Figure 7. Balanced cross-section 4-4' of Parowan Gap, deformed state. See Figure 2 for symbols.

The deformed cross-section shows the following: 1) an asymmetrical anticline characterized by a gentle west flank, a flat crest, and a steep and overturned east flank, 2) a detachment fault, situated at the lower part of the Jurassic Kayenta Formation, that ramps up to the Cretaceous Iron Springs Formation is responsible for the structure. While the ramp fault propagates up, the hanging wall units moved down parallel to the fault, 3) another fault branching from a detachment in the core of the fold and following the fold axial plane causes the repetition of the Mesozoic formations. This odd fault is required from the fact that east-dipping Jurassic Navajo Sandstone lies too far from the Break thrust, to be explained by only folding of the major structure.

CONCLUSIONS

Analysis of the structural geometries of the leading-edge folds of the OTB is primarily based on the construction of balanced geological cross-sections. As a result of detailed and geometric studies of the overthrust belt (OTB) in SW Utah, our structural interpretation of the structural style that developed strongly suggested the following conclusions:

- 1- The folds have mainly formed by the processes of fault-propagation folding, where thrust faulting and folding are coeval together with fault-bend folding which commonly occurs in fold and thrust belts.
- 2- The shape and amplitude of the folds were controlled by initial form of the basal detachment at depth and the amount of displacement or by the ramp height.

- 3- The magnitude of deformation (shortening) along the major fold, the Virgin-Kanarra anticline, is variable, with stronger activity in the middle (e.g. Spring Creek) and northern portions and less deformation in the southern part. In detail, activity increases and decreases on a wavelength similar to the spacing of the cross-sections.

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Map GQ-694, scale 1: 24,000.

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