ELSEVIER

Journal of Structural Geology 27 (2005) 51–65

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Fold–thrust styles in the Absaroka thrust sheet, Caribou National Forest area, Idaho–Wyoming thrust belt

Subhotosh Banerjee, Shankar Mitra*

School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019-1009, USA

Received 29 August 2003; received in revised form 3 May 2004; accepted 1 July 2004
Available online 27 October 2004

Abstract

The Bear Creek, Big Elk and Black Mountain anticlines are macroscopic structures located in the hanging wall of the Absaroka thrust within the Idaho–Wyoming fold–thrust belt. Structural mapping of the area was conducted by draping existing geologic maps and digital orthophotos over digital elevation models (DEM) to obtain a three-dimensional perspective of the area. The map was further refined by reconnaissance field mapping of selected outcrops. Construction of balanced cross-sections suggests that these structures detach at three stratigraphic levels, within the Cambrian Gros Ventre Formation, Devonian Darby Formation, and Triassic Dinwoody Formation. The folds in the upper stratigraphic package consist of symmetric to asymmetric detachment folds, which show variable vergence along trend. The structures in the lower stratigraphic packages primarily evolved as low-amplitude detachment folds, which were subsequently displaced over fault ramps to form fault–bend folds or duplexes. The duplex geometries in the Cambro–Ordovician units under the Bear Creek and Poker Peak anticlines vary from independent anticlines in the south to completely overlapping stacks in the north. The macroscopic structural patterns of folds proposed in this study will be useful in interpreting subsurface structures in other parts of the Idaho–Wyoming fold–thrust belt.

Keywords: Structural mapping; Fold–thrust belts; Detachment folds; Fault–bend folds

1. Introduction

The Bear Creek, Big Elk, and Black Mountain anticlines are located in the hanging wall of the Absaroka thrust fault in the Caribou National Forest area within the Idaho–Wyoming thrust belt. The area is located approximately 60 miles southeast of Idaho Falls, Idaho and about 18 miles northwest of Alpine, Wyoming, in Bonneville county, eastern Idaho (Fig. 1). The area covers parts of five USGS 7½ minute quadrangles: the Red Ridge, Palisades Dam, Big Elk Mountain, Poker Peak, and Alpine quadrangles.

This paper examines the three-dimensional (3-D) structural styles of the Caribou National Forest area using mapping of surface structures and the extrapolation of these structures to the subsurface. The approach used to interpret the structures included (1) compiling a revised geologic map of the area using a combination of field studies and remote sensing; (2) constructing a series of interpretive cross-sections to study the variation in geometry with depth; and (3) developing a 3-D model using the surface map and cross-sections to study the variation in structural style along trend.

2. Regional stratigraphy and structure

The Idaho–Wyoming fold–thrust belt forms an eastwardly convex thrust belt about 200 miles long and 60 miles wide, extending from the Snake River Plain in Idaho, southward into Utah (Fig. 1). The fold–thrust belt structures formed during the late Jurassic to early Eocene Sevier orogeny (Armstrong and Oriel, 1965). Seismic, aeromagnetic, and surface data indicate that the crystalline basement is not deformed over most of the region and is structurally detached from the sedimentary cover (Royse et al., 1975). The fold–thrust structures are cut by late Eocene–Recent

* Corresponding author. Tel.: +1-405-325-3253; fax: +1-405-325-3140
E-mail address: smitra@ou.edu (S. Mitra).

0191-8141/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2004.07.004

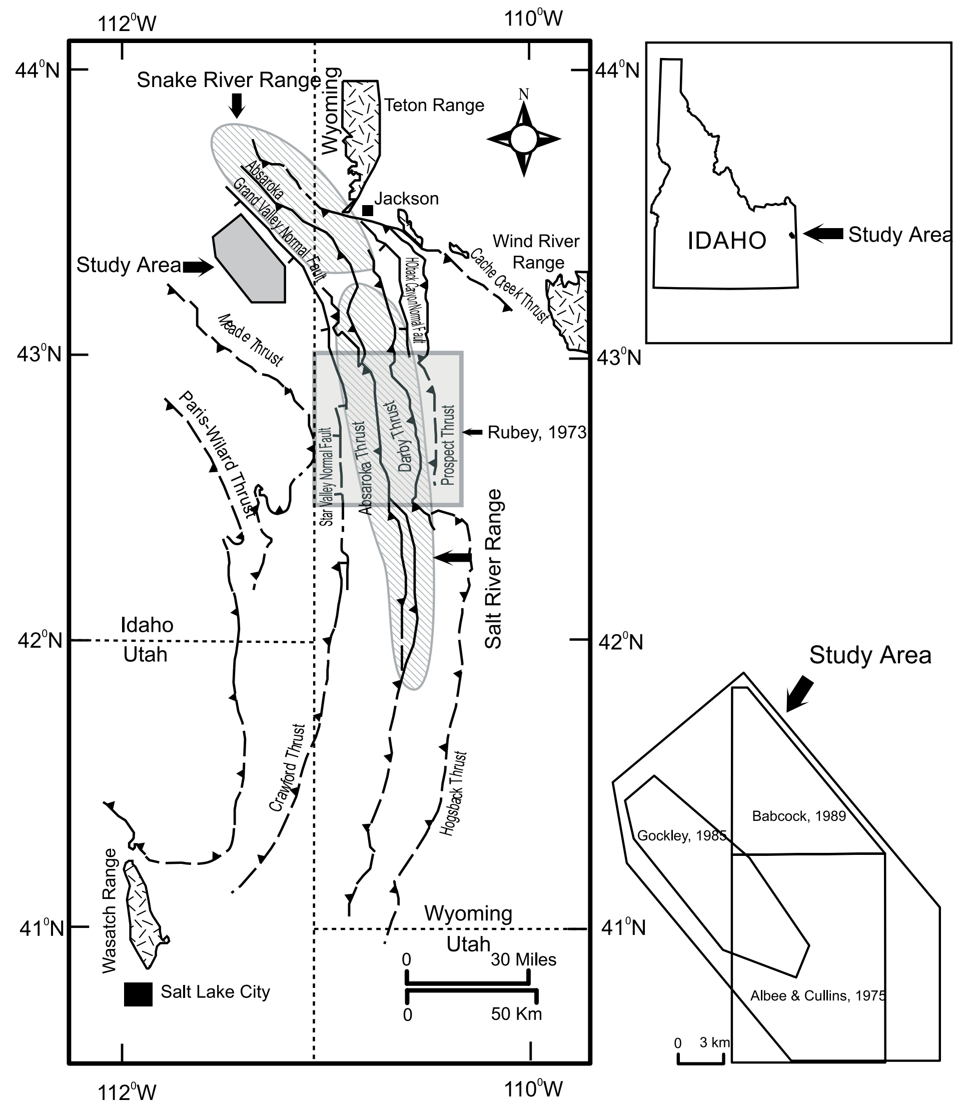


Fig. 1. Map of the Idaho–Wyoming fold–thrust belt (modified from Royse et al. (1975)) showing the location of the study area. Major thrusts and the location of the Snake River Range are also shown. Box shows the location of the Afton–Smoot area mapped by Rubey (1973). Areas with hatchured pattern are major mountain ranges. Inset to the bottom right shows the locations of other studies in the area.

normal faults throughout the area. The major normal faults are the Grand Valley and Snake River normal faults, forming the Snake River graben. This graben marks the boundary between the Caribou National Forest and the Snake River Range.

The structures in the Caribou National Forest area contain units of Cambrian–Upper Cretaceous age (Fig. 2). The detailed stratigraphy of the area and the thicknesses of individual units are shown in Fig. 2 (compiled from Rubey (1973) and Woodward (1986)). The oldest unit exposed in the area is the Pennsylvanian Wells Formation. However, the oldest unit in the hanging wall of the Absaroka thrust is believed to be the middle to upper Cambrian Gros Ventre Formation (Rubey, 1973; Woodward, 1986).

On the basis of mechanical stratigraphy, the units can be divided into three main structural packages. From bottom to top these are: (1) a lower package consisting of Cambrian Gros Ventre shales overlain by Cambro–Ordovician carbonates of the Gallatin formation and the Bighorn group; (2) a middle package consisting of the Devonian Darby, Mississippian Madison, and Pennsylvanian Wells and Permian Phosphoria Formations; and (3) an upper package consisting of interlayered sequence of varying lithologies ranging in age from the Triassic to the Cretaceous, with numerous internal detachments (Fig. 3).

The belt is deformed by six major thrust faults. From west to east, these are: Paris–Willard, Meade, Crawford, Absaroka, Darby and Prospect (Wiltschko and Dorr, 1983) (Fig. 1). Some of these thrust faults are buried under the Snake River Plain, which underwent Cenozoic normal faulting and volcanism (Armstrong and Oriel, 1965).

The surface structural style in the Caribou National Forest area consists of subangular to concentric disharmonic folds with few exposed thrust faults. Units ranging from the

Age	Formation	Group	Thickness (m)	Mechanical Units
Cretaceous	Wayan Formation (Kw)		550	3
Cretaceous	Bear River Formation (Kbr)		300	3
Cretaceous	Upper Gannet Group (Kg)		200	3
Cretaceous	Peterson Limestone (Kp)	Lower Gannet Group	50	3
Cretaceous	Ephraim Conglomerate (Ke)	Lower Gannet Group	200	3
Jurassic	Stump Formation (Js)		350	3
Jurassic	Preuss Formation (Jp)			3
Jurassic	Twin Creek Formation (Jt)		430	3
Jurassic	Nugget Formation (JTRn)		250	3
Triassic	Ankareh Formation (TRa)		150	3
Triassic	Thaynes Formation (TRt)		350	3
Triassic	Woodside Formation (TRw)		140	3
Triassic	Dinwoody Formation (TRd)		190	3
Permian	Phosphoria Formation (Pp)		65	2
Pennsylvanian	Wells Formation (PIPw)		350	2
Pennsylvanian	Amsden Formation	Madison Group (Mm)	600	2
Mississippian	Madison Limestone	Madison Group (Mm)		2
Devonian	Darby Formation (MDd)		200	2
Ordovician	Bighorn Group (Ob)		220	1
Cambrian	Gallatin Formation (Cg)		100	1
Cambrian	Gros Ventre Formation (Cgv)		500	1
Precambrian	Basement			

Fig. 2. Stratigraphic column of the study area (compiled from Rubey (1973) and Woodward (1986)). Mechanical packages are shown to the right.

Pennsylvanian Wells Formation to the Upper Cretaceous Wayan Formation are exposed in this area. In contrast, across the Palisades Reservoir, in the Targhee National Forest of the Snake River Range, there are abundant large thrust faults exposing Cambrian–Mississippian rocks (Oriel and Moore, 1985; Woodward, 1986), suggesting that this area exposes units of a lower structural level than the Caribou National Forest area.

3. Previous studies

Parts of the study area have been mapped at various scales in the past (Fig. 1); however, there are relatively few detailed structural interpretations for the area. Gardner (1961) published a geologic map for the Irwin 30 minute quadrangle in the Caribou National Forest area. His map covers the present study area and adjacent 7½ minute quadrangles. Albee and Cullins (1975) conducted a detailed study of the southeastern quarter of the present study area, which was published as a USGS 7½ minute quadrangle geologic map for the Poker Peak quadrangle. It incorporates one shallow cross-section through the southern part of the Big Elk anticline. Gockley (1985) mapped the Big Elk anticline at 1:24,000 scale in the southwestern part of the area. Babcock (1989) mapped the area around the Bear Creek inlet at 1:24,000 scale and constructed three structural cross-sections through the Bear Creek anticline.

The only published structural cross-sections in the area are those made by Babcock (1989). More regionally, structural geometries in the area can be compared with the structural analysis of Rubey (1973) in the Afton-Smoot area (Fig. 1), regional cross-sections through the Snake River Range (Woodward, 1986), and subsurface cross-sections through the Fossil Basin area (Royse et al., 1975; Lamerson, 1982).

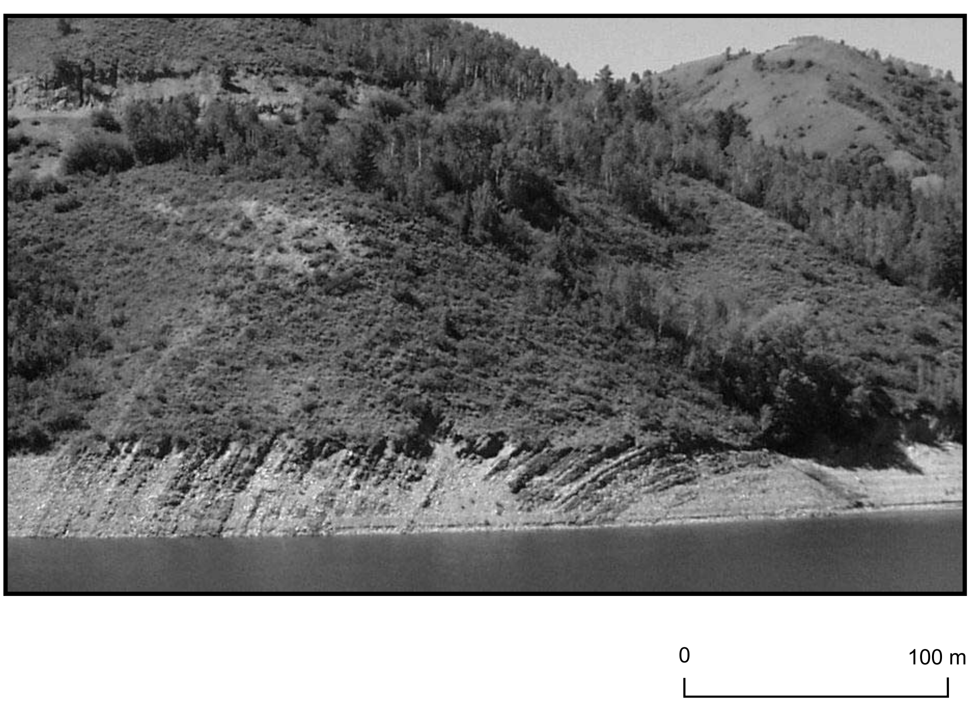


Fig. 3. Field photograph, looking northwest across the Bear Creek Inlet, showing outcrop-scale disharmony between beds within the Triassic Dinwoody Formation.

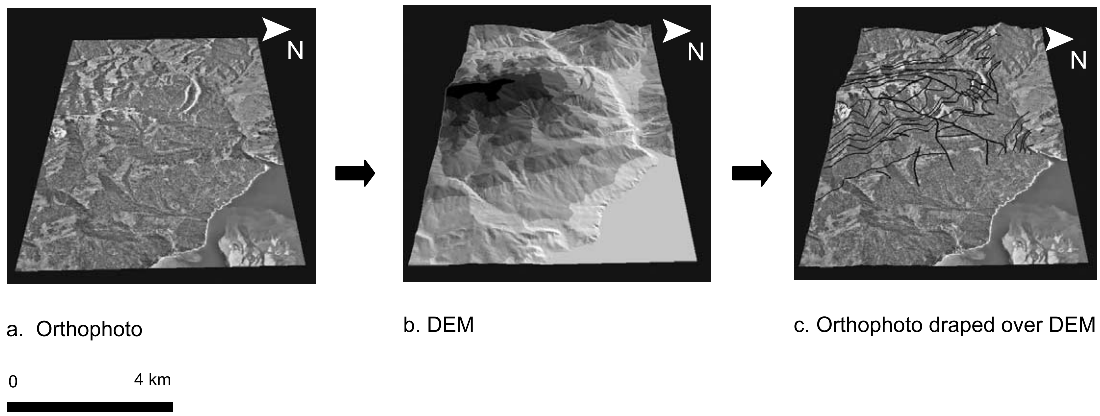


Fig. 4. Method of construction of a 3-D terrain model shown for the Black Mountain area, looking west. (a) Orthophoto. (b) DEM. (c) Orthophoto draped over DEM. Final 3-D terrain model is georectified.

4. Surface structural map

4.1. Methodology

A revised structural map of the area (Fig. 8) was compiled by combining remote sensing approaches involving the integration of digital elevation models, orthophotos, LANDSAT images, existing geologic maps, and field reconnaissance studies.

Parts of the study area were previously mapped by Gardner (1961), Albee and Cullins (1975), Gockley (1985), and Babcock (1989) (Fig. 1). These maps were geo-rectified using ERDAS Imagine 8.4 Image analysis software and normalized to UTM coordinate system Zone 12N using NAD 27 as datum. These raster maps were then imported into a GIS project and all the formational contacts and other geological elements were digitized to create a vector database. The dataset was then draped over 1-m-resolution USGS Digital Orthophoto mosaics and 15-m-resolution Landsat 7 images to check the validity of the contacts. Orthophotos provide better resolution of detailed structures, whereas a Landsat 7 image provides a picture of the regional structure.

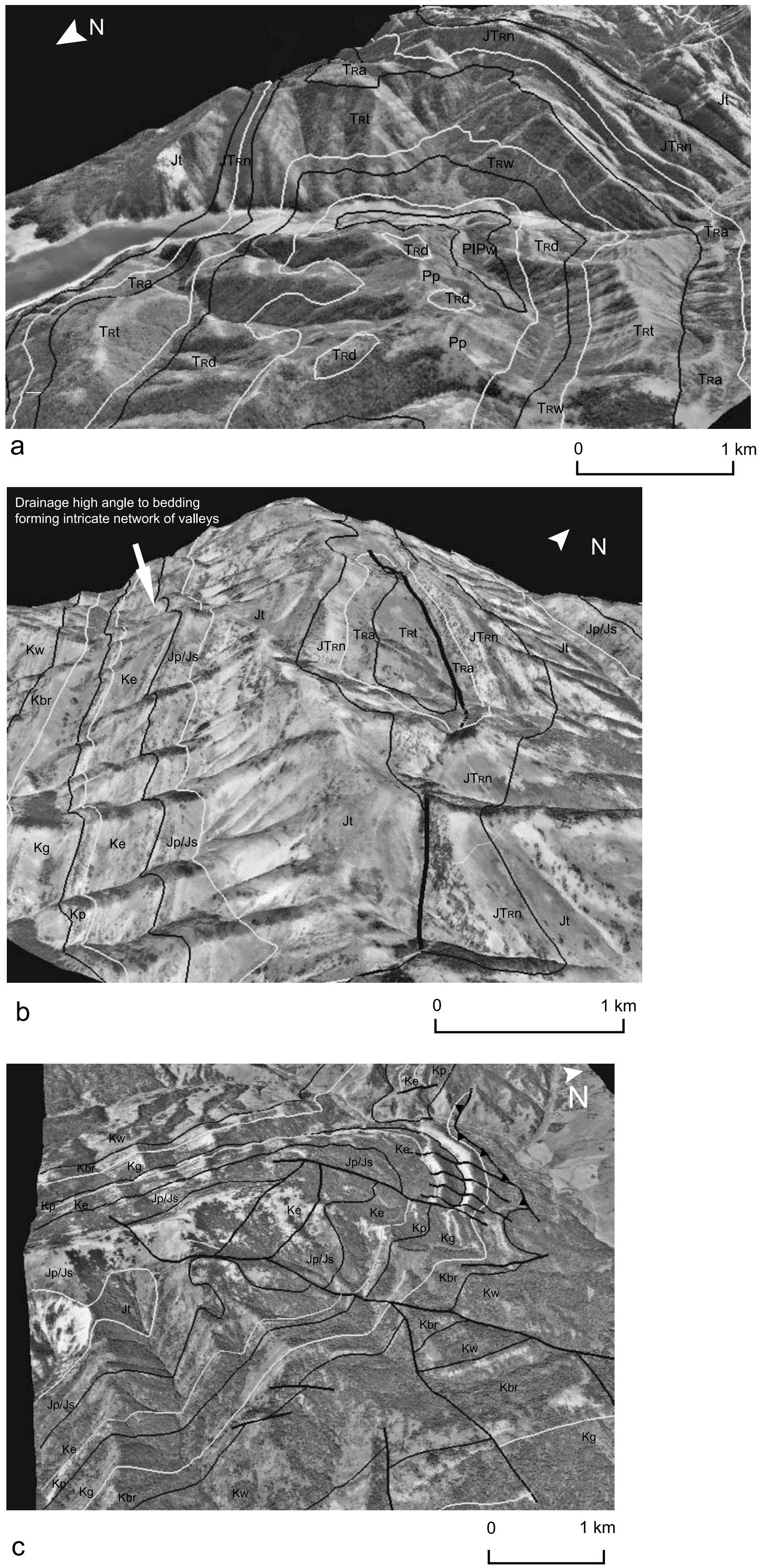
Digital orthophotos are 3.75 minute aerial photographs in which distortions caused by camera orientation and terrain have been removed. Therefore, they combine the image quality of a photograph with the geometric precision of a map. Landsat 7 provides a seven-band image, with three visible bands, three infrared bands and one panchromatic band. Effective resolution of all bands was improved to 15 m by image interpolation within ERDAS Imagine. A false color composite image (bands 4, 3 and 2) was used to study the regional structure and faults, whereas an infrared image (bands 6, 5 and 4) was used for separating key lithologies and to differentiate gravel and alluvium deposits from exposed rock outcrops (Mather, 1999).

For more refined mapping, the digital orthophotos and the composite geologic maps were then draped over USGS Digital Elevation Models (DEM) to generate 3-D terrain models (Fig. 4). The DEMs have a ground resolution of 30 m. Formational contacts were then revised within this 3-D visualization project (Fig. 5). The 3-D terrain models provided better perspective and less distortion than field photographs (Fig. 6), which exhibit some degree of distortion. Published structural data were also incorporated into the database.

Because the area has considerable topographic relief and stream valleys cut the structural trend at high angles, flatirons and dip slopes were used to determine bedding plane orientation through 3-D visualization (Banerjee and Mitra, 2004). For dip slopes, the maximum value of the slope, determined using the average maximum technique (Burrough, 1986) provided a good approximation of the actual dip of the bedding plane (Fig. 7). Similarly the strikes of the beds could be determined from the trends of the outcrop in 3-D. The resolution of the slope mapping was limited by the resolution of the DEM grids. In the study area, dip slopes and flatirons were commonly hundreds of meters long; therefore, measurements of dip could be made. Using these remote sensing approaches, structural data could be generated for a relatively large and inaccessible area within a short period of time.

Both remotely sensed structural data and modified formational contacts were validated during reconnaissance fieldwork. More structural data and ground control points were incorporated during the fieldwork and the final geologic map was constructed (Fig. 8).

Fig. 5. 3-D terrain models of (a) the Bear Creek anticline looking southeast; (b) the Big Elk anticline looking northwest; (c) the Black Mountain anticline looking west. Final mapped formation contacts and maps are shown in each case.


N
JTRn
TRa
TRt
Jt
TRw
TRd
PIPw
Pp
a
0
1 km
Drainage high angle to bedding
forming intricate network of valleys
Jp/Js
Kw
Ke
Kbr
Kg
Kp
b
Kw
Kbr
Kg
Kp
Ke
Jp/Js
Jt
c

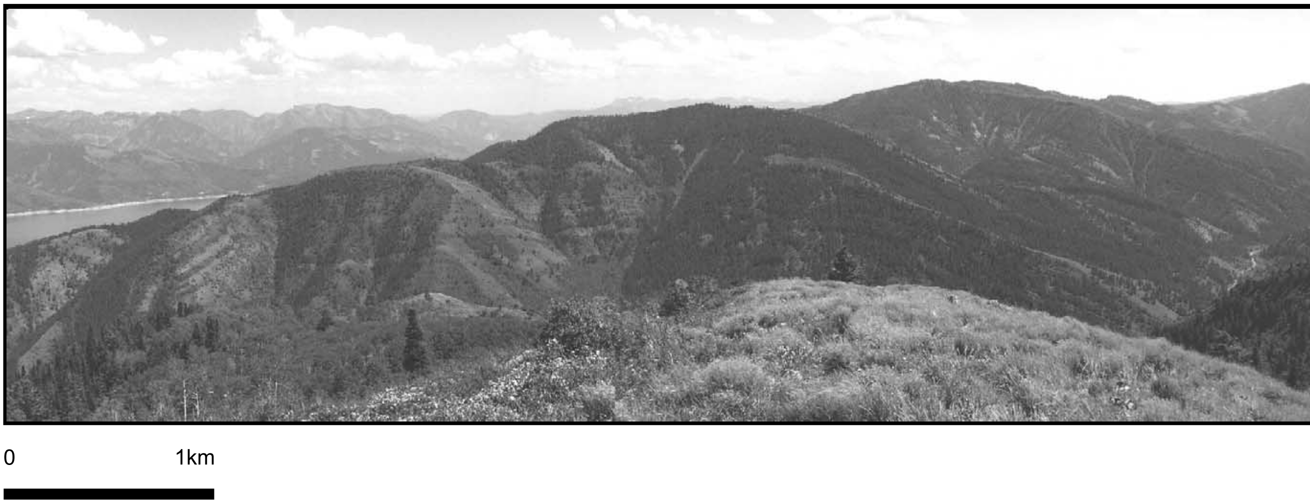


Fig. 6. Field photograph of the Bear Creek anticline looking southeast. The Palisades Reservoir and the Snake River Range are in the background. Compare with the terrain model in Fig. 5a.

4.2. Map pattern

The general trend of structures in the area is NW–SE There are three anticlines in the study area: the Bear Creek anticline in the northeast, the Big Elk anticline in the southwest, and the Black Mountain anticline in the south (Fig. 8).

The Bear Creek anticline is a southeasterly-plunging box fold with an overturned northeastern limb (Fig. 8). The two anticlinal branches of this box fold are the Bear Creek anticline to the northeast and the Poker Peak anticline to the southwest. The Bear Creek axis plunges at a low angle (0–14°) to the southeast and follows the eastern edge of the map area (Fig. 9). The Bear Creek axial plane shows a shallow southwesterly dip near the inlet area, but becomes sub-vertical to almost vertical within less than 4 km to the southeast. The Poker Peak axial trace, on the other hand, plunges towards the south and loses amplitude within a relatively short distance to die out in the structural low of the Jensen Creek syncline. The poles to bedding for the Bear Creek anticline show highly variable orientations, which suggests a disharmonic 3-D geometry (Fig. 9).

The Big Elk anticline is a doubly plunging fold and shows a closed outcrop pattern defined by the Thaynes Formation to Upper Gannet Group (Fig. 8). At the stratigraphic level of the Nugget and Twin Creek

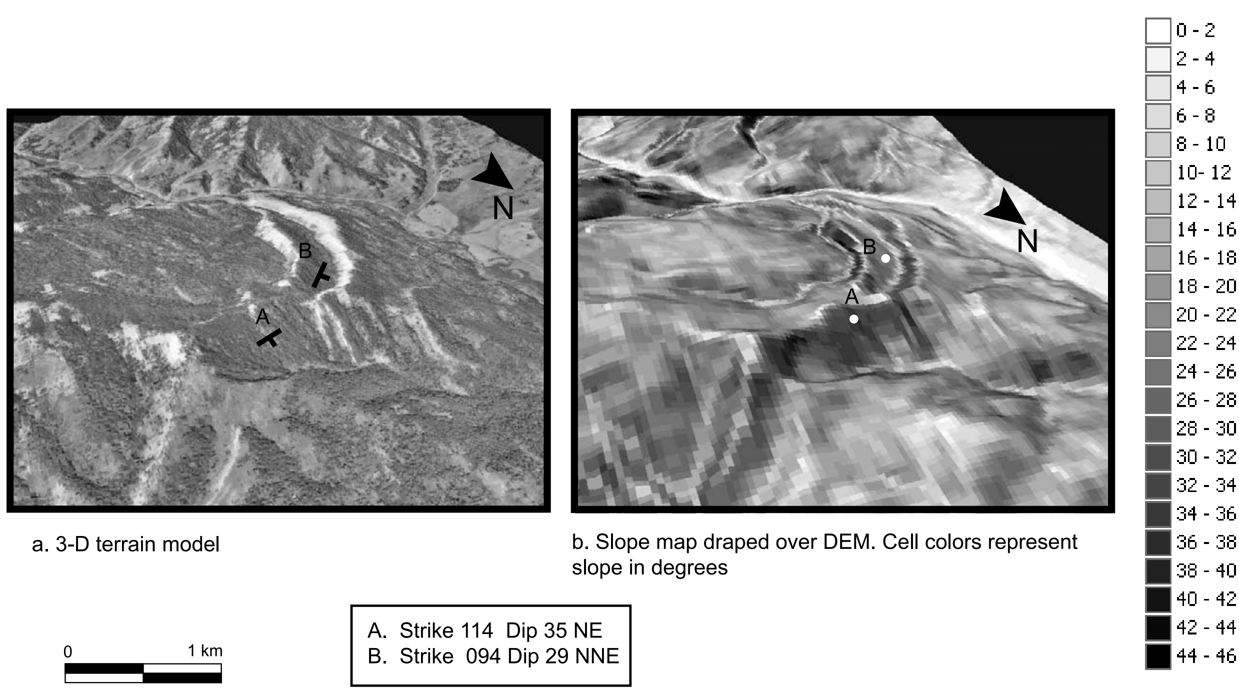


Fig. 7. Extraction of strike and dip values from slope map and 3-D terrain models. Grayscale on slope map shows magnitude of slope in degrees.

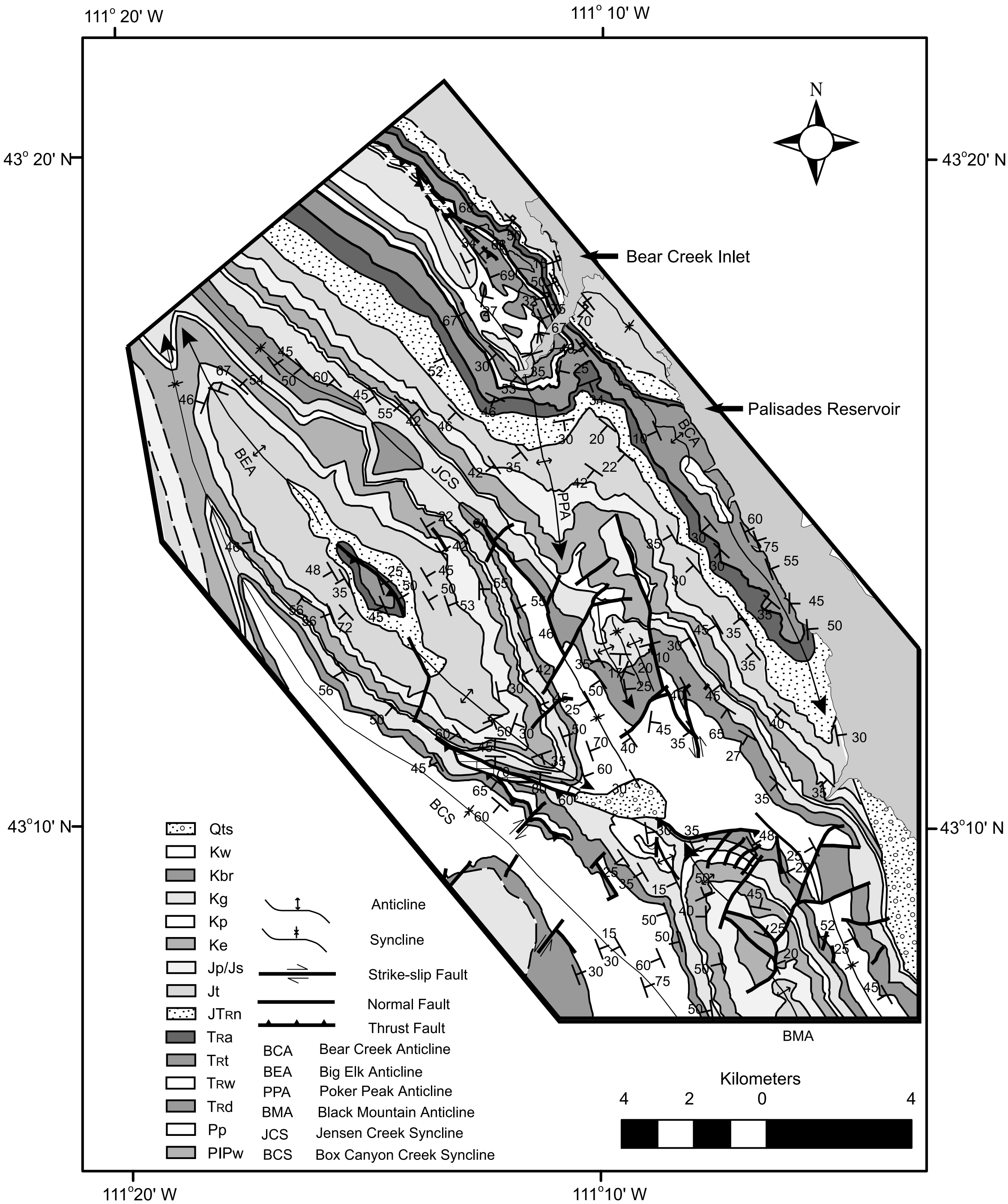


Fig. 8. Completed structural map of the study area showing formation contacts, surface dips and strikes, and major anticlinal and synclinal traces.

formations, the anticline verges to the northeast in the northern part; it is symmetrical in the central part, and verges to the southwest in the southern part. The Big Elk anticline plunges 25° towards 349° in the northern part. In the central part, where it has the highest relief, it is almost horizontal, and it plunges 23° towards 135° in the southern part (Fig. 9).

The Black Mountain anticline is a northwesterly-plunging symmetrical structure, which shows an en-échelon pattern with respect to the Big Elk and Bear Creek anticlines (Fig. 8). It dies out in the structural low of the Jensen Creek syncline that separates Bear Creek and Big Elk anticlines. The Black Mountain anticline has a plunge of 17° towards 329° (Fig. 9).

The general map pattern of the Bear Creek, Big Elk and Black Mountain anticlines shows branching, and relay arrangement of axial traces, suggestive of disharmonic folding. This will be discussed in more detail in the section on 3-D geometry.

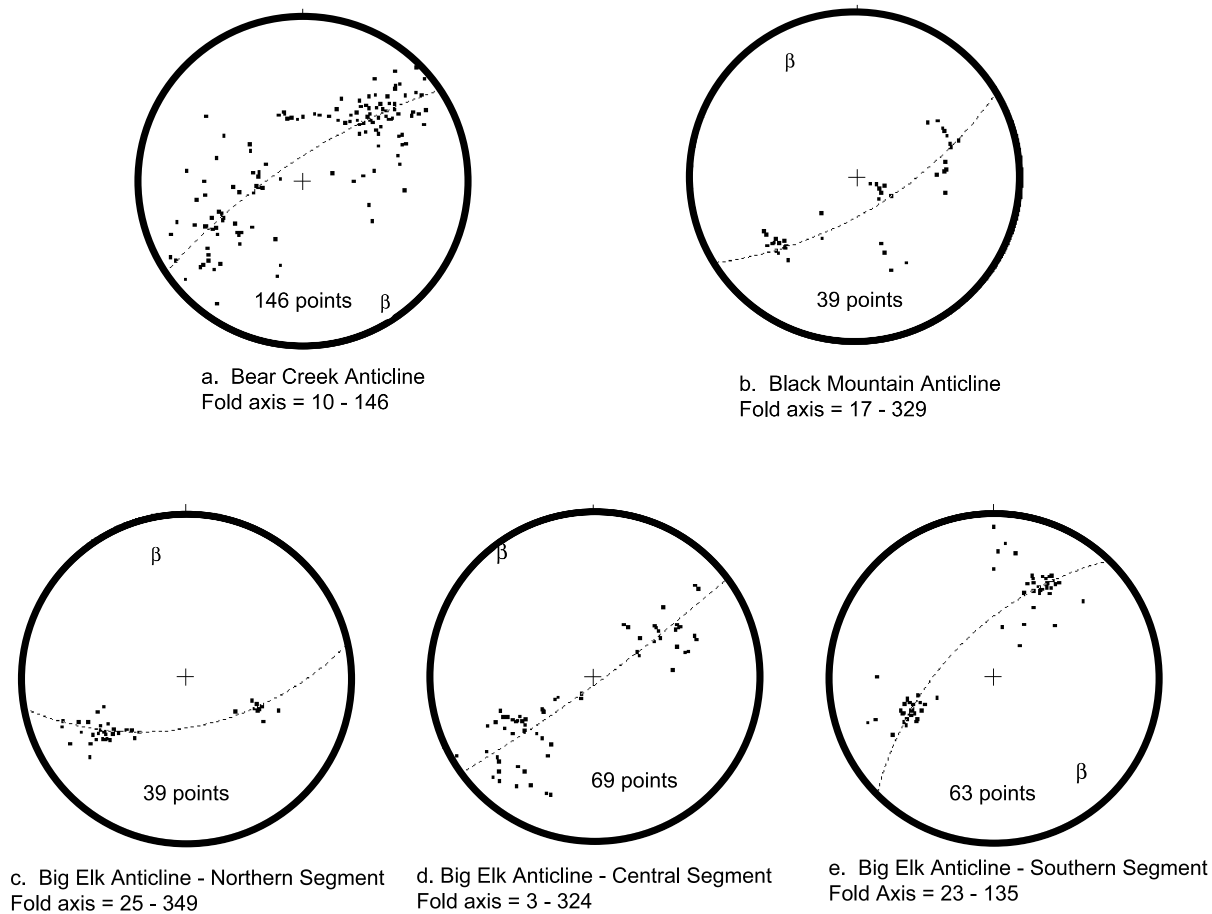


Fig. 9. (a) Poles to bedding planes for the Bear Creek anticline showing low southeasterly plunge. High scattering of data-points suggests the disharmonic nature of the fold. (b) Poles to bedding for the Black Mountain anticline showing northwesterly plunge. (c)–(e) Poles to bedding for the Big Elk anticline for the northern, central and southern segments.

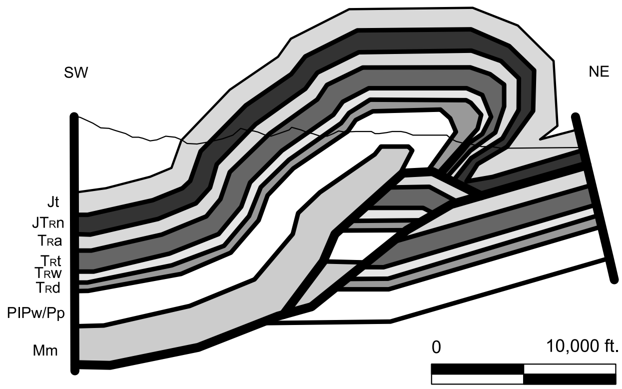


Fig. 10. Structural cross-section through the Bear Creek anticline by Babcock (1989). This section is approximately at the same location as section AA′ in the present study. Babcock interpreted the structure to detach at the base of the Mississippian Madison Group.

The Box Canyon thrust is the only significant exposed thrust fault in the area. It is located on the southwestern limb of the Big Elk anticline, and dies out along strike. It has a small displacement and brings the Upper Cretaceous Draney Limestone against the Upper Cretaceous Bechler Formation. There are some normal faults with small displacements that cut through the fold–thrust structures. These are most likely associated with the formation of the Snake River Graben during Tertiary time (Armstrong and Oriel, 1965).

5. Subsurface structural styles

Babcock (1989) constructed the only subsurface cross-section through the Bear Creek anticline in the Bear Creek Inlet area (Fig. 10). In his interpretation, Babcock (1989) placed the regional detachment for the Bear Creek anticline at the base of the Mississippian Madison Group and interpreted the Bear Creek anticline as a fault-propagation fold uplifted by a deeper fault-bend fold related to a ramp from the base of the Madison Group to the top of the Triassic Ankareh Formation (Fig. 10). The reasons for his choice of the basal detachment level were consistency with a proprietary seismic line and with the regional position of the observed basal detachment in the Snake River Range on the east side of the Grand Valley normal fault. However, he did not cite the specific nature of the seismic evidence that led to this interpretation, or discuss whether his basal detachment could be folded by a deeper structure. Also, his interpretation was based on data from the Inlet area, and did not consider the 3-D geometries of the structures.

The present study offers an alternative interpretation for the structures in the area, based on consideration of the following factors: (1) the locations of major detachment horizons based on the mechanical stratigraphy, and the known stratigraphic positions of detachments in adjacent areas; (2) the projection of surface structures to depth in a series of interpretive cross-sections, using structural styles that are compatible with the mechanical stratigraphy; (3) the along-trend variations of the structures; and (4) the use of structural balancing and restoration to test for admissibility and to choose between alternate solutions.

5.1. Location of major detachments

On a regional scale, the Absaroka thrust carries Cambrian–Cretaceous units in the hanging wall within the hanging wall units, the potential detachment levels determined from the mechanical stratigraphy are within the Cambrian Gros Ventre Formation, the Devonian Darby Formation, and the base of the Triassic Dinwoody Formation.

The Triassic Dinwoody Formation is the location of the uppermost major detachment. Some of the thrust faults exposed at the surface root into this detachment.

The base of the Darby Formation is interpreted to be a second major detachment, above which the units deform by detachment folding. This interpretation is based on the fact that the Darby Formation is an incompetent unit approximately 200 m in thickness made up of interbedded shales and siltstones. Chester (1987) also proposed a detachment within the Darby Formation, based on her studies in the Haystack Peak area in the Snake River Range.

The structures are believed to extend to a deeper level because the basal detachment in both the Snake River Range to the east, and the Afton–Smoot area to the south is located in the Cambrian Gros Ventre Formation. In the Snake River Range, Oriel and Moore (1985) and Woodward (1986) interpreted secondary thrusts in the hanging wall of the Absaroka thrust to involve the Gros Ventre Formation, and also documented surface exposures of this unit. This clearly suggests that the basal detachment for the Absaroka thrust is located in the Gros Ventre Formation. In the Afton–Smoot area (Rubey, 1973), approximately along trend with the study area, the Gros Ventre Formation is interpreted to be folded into the core of a tight lift-off fold, and exposes units as old as the Mississippian Madison Formation (Fig. 11). Furthermore, the Absaroka thrust, where exposed, brings the Gros Ventre Formation to the surface (Rubey, 1973; sections CC′–GG′). Although it is possible that Absaroka thrust climbs section laterally between the Afton–Smoot and Caribou National Forest areas, this results in a major discrepancy in shortening of the lower Paleozoic units. Because the basal detachment is located in the Gros Ventre Formation in both the Snake River Range, and the Afton–Smoot areas, the basal detachment in this study is placed at the base of the Gros Ventre Formation.

5.2. Structural cross-sections

Four widely spaced cross-sections (AA′, BB′, CC′, DD′) were constructed and restored to check for validation (Fig. 12).

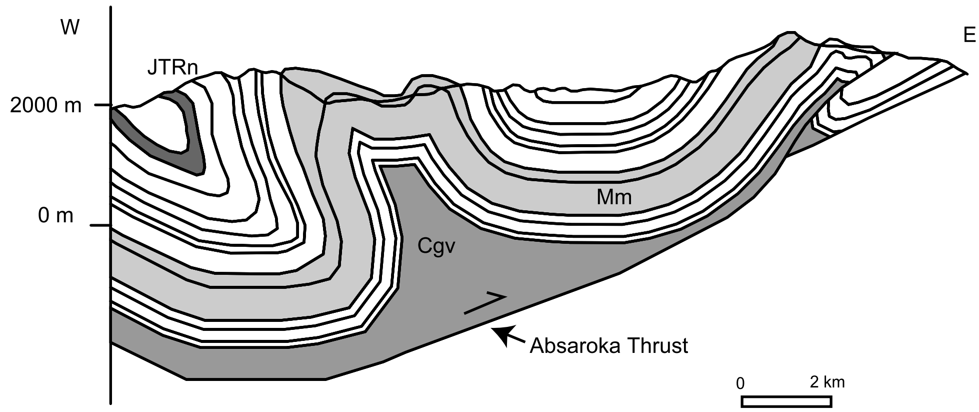


Fig. 11. Outcrop pattern and subsurface interpretation of folds in the hanging wall of the Absaroka thrust in the Afton–Smoot area (from Rubey, 1973). The Cambrian Gros Ventre Formation is involved in the folding. The Absaroka thrust brings the Gros Ventre Formation to the surface in adjacent sections. Cgv = Cambrian Gros Ventre Formation; Mm = Mississippian Madison Formation; JTrn = Jurassic Nugget Formation.

5.2.1. Section AA′

Section AA′ is located to the north of the Bear Creek Inlet (Fig. 13a). The Bear Creek anticline is a box-shaped fold (Boyer, 1986) with a strongly overturned and thinned northeastern forelimb and a moderately dipping backlimb. The Bear Creek anticline shows its highest structural relief in this section, exposing the Pennsylvanian Wells Formation at the hinge of the fold. At the core of the Bear Creek anticline, the deformation style in the Cambro–Ordovician units was interpreted as a duplex structure with complete overlap of two thrust sheets (Mitra, 1986). Vertical stacking of two transported faulted detachment folds (Mitra, 2002b) explains the high structural relief of the Bear Creek anticline. The structure above the Darby detachment is a tight and overturned detachment fold, with a fault in the core of the structure. This fault splays off a ramp from the Darby detachment to the Dinwoody detachment. Along trend, this imbricate fault branches into a number of small-scale thrust faults that are exposed at the northeastern corner of the area.

The back limb of the Bear Creek anticline goes into the broad and slightly asymmetric Jensen Creek syncline and then into the Big Elk anticline. The Big Elk anticline verges slightly to the northeast at the level of the Nugget and Twin Creek Formations. The structure in the upper units (Dinwoody–Twin Creek Formations) is a broad faulted detachment fold formed above a detachment in the Dinwoody Formation. The vergence of the Big Elk anticline changes to the southwest below the Dinwoody detachment. Therefore, the ramps in the Cambro–Ordovician and the Devonian–Triassic units are interpreted to dip in an opposite direction to those under the Bear Creek anticline. This model is supported by well data close to section BB′ discussed below.

5.2.2. Section BB′

Section BB′ transects the high cliffs to the south of the Bear Creek Inlet (Fig. 13b). The Bear Creek anticline has a flat top, and a distinct box-shaped geometry. This geometry is formed due to the divergence of the two axial traces for the Bear Creek and the Poker Peak anticlines. There is a minor syncline at the flat top that becomes more prominent farther south. The northeastern limb of the Bear Creek anticline is sub-vertical to slightly overturned in this section, which suggests that the fold undergoes relatively less shortening in this section compared with section AA′, where this limb is strongly overturned and thinned. Basal Cambro–Ordovician units ride up to the Devonian Darby detachment on a pair of southwesterly-dipping ramps, forming a partially overlapping duplex (Mitra, 1986). A forelimb thrust that splays off the Darby–Dinwoody ramp breaks through the Darby and Madison Group and dies out in the ductile Woodside Formation.

The Big Elk anticline is interpreted as an asymmetric faulted detachment fold, vergent to the northeast at the surface. This is supported by the steeper dips of the northeast limb at the surface and in the Sun–Sinclair No. 1 well (Neighbor, 1953). The front limb of the structure is cut by two forelimb thrusts (Mitra, 2002a), one of which is exposed at the surface. Below the Dinwoody detachment, the vergence of this structure changes to the southwest, suggesting that the ramps through the Cambro–Ordovician and Devonian–Permian units dip to the northeast. The Big Elk anticline shows its maximum structural relief in this section.

5.2.3. Section CC′

Section CC′ is about 4 km to the north of the McCoy Creek drainage (Fig. 13c). In this section, the Bear Creek anticline branches into two independent folds, the Bear Creek and Poker Peak anticlines, separated by a central syncline. The Woodside Formation is the oldest unit exposed at the surface at the core of this structure. The Bear Creek and Poker Peak anticlines are interpreted to have formed above two independent ramps in the Cambro–Ordovician section. The Big Elk anticline is a southwesterly vergent structure at all structural levels formed above

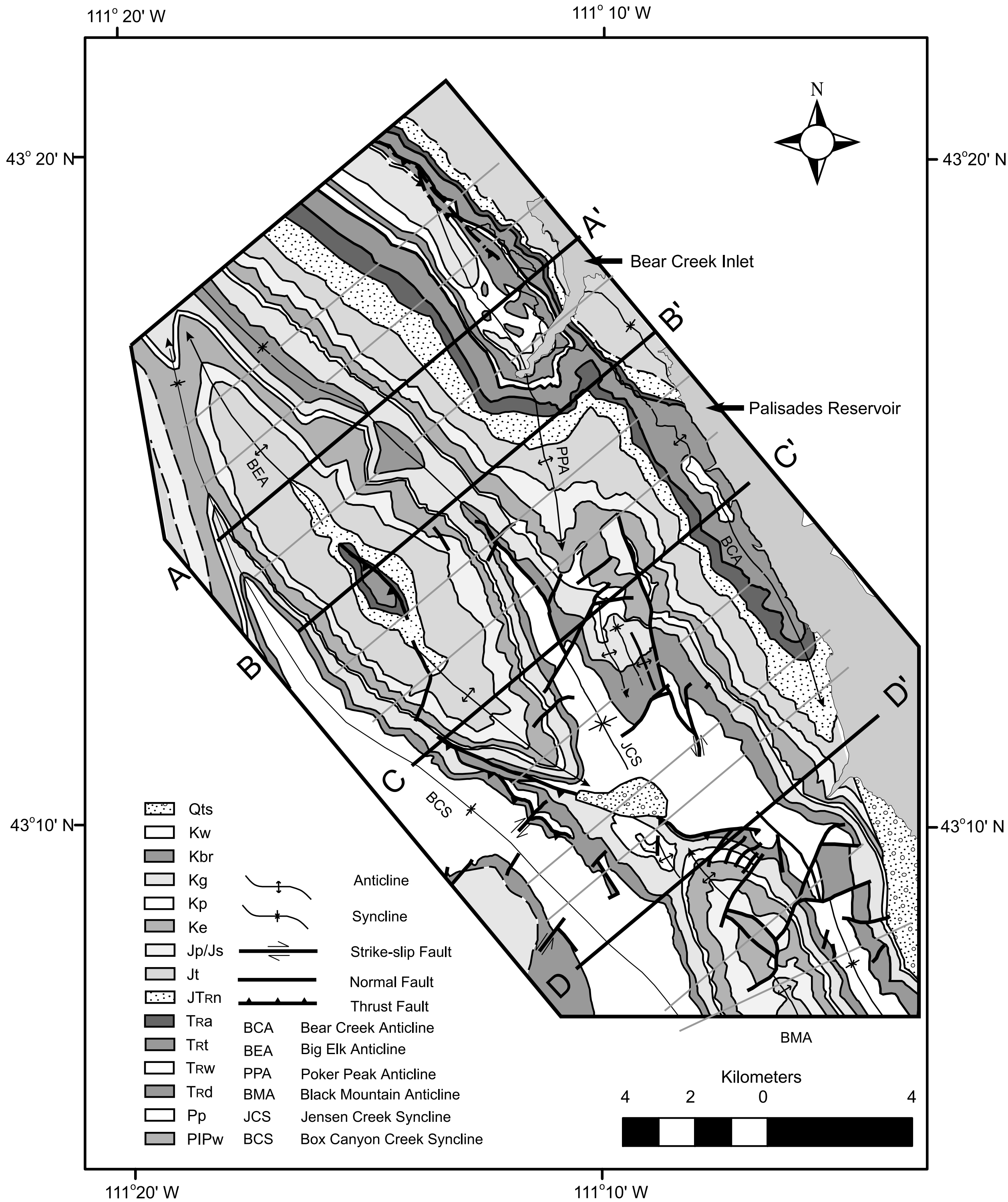


Fig. 12. Geologic map of the study area, showing formation contacts, faults, and major anticlinal and synclinal traces. The locations of cross-sections AA′–DD′, and 10 additional shallow sections used to construct the 3-D model for the structure in the Nugget Formation. Locations of interpretive cross-sections and shallow sections are shown.

northeasterly dipping ramps in the Cambro–Ordovician and Devonian–Triassic units.

5.2.4. Section DD′

Section DD′ follows the drainage of McCoy Creek (Fig. 13d). This section transects the Black Mountain anticline, which is the symmetric anticlinal structure in the central part of the section (Fig. 13d). This is a relatively low amplitude structure compared with both the Bear Creek and the Big Elk anticlines, and the

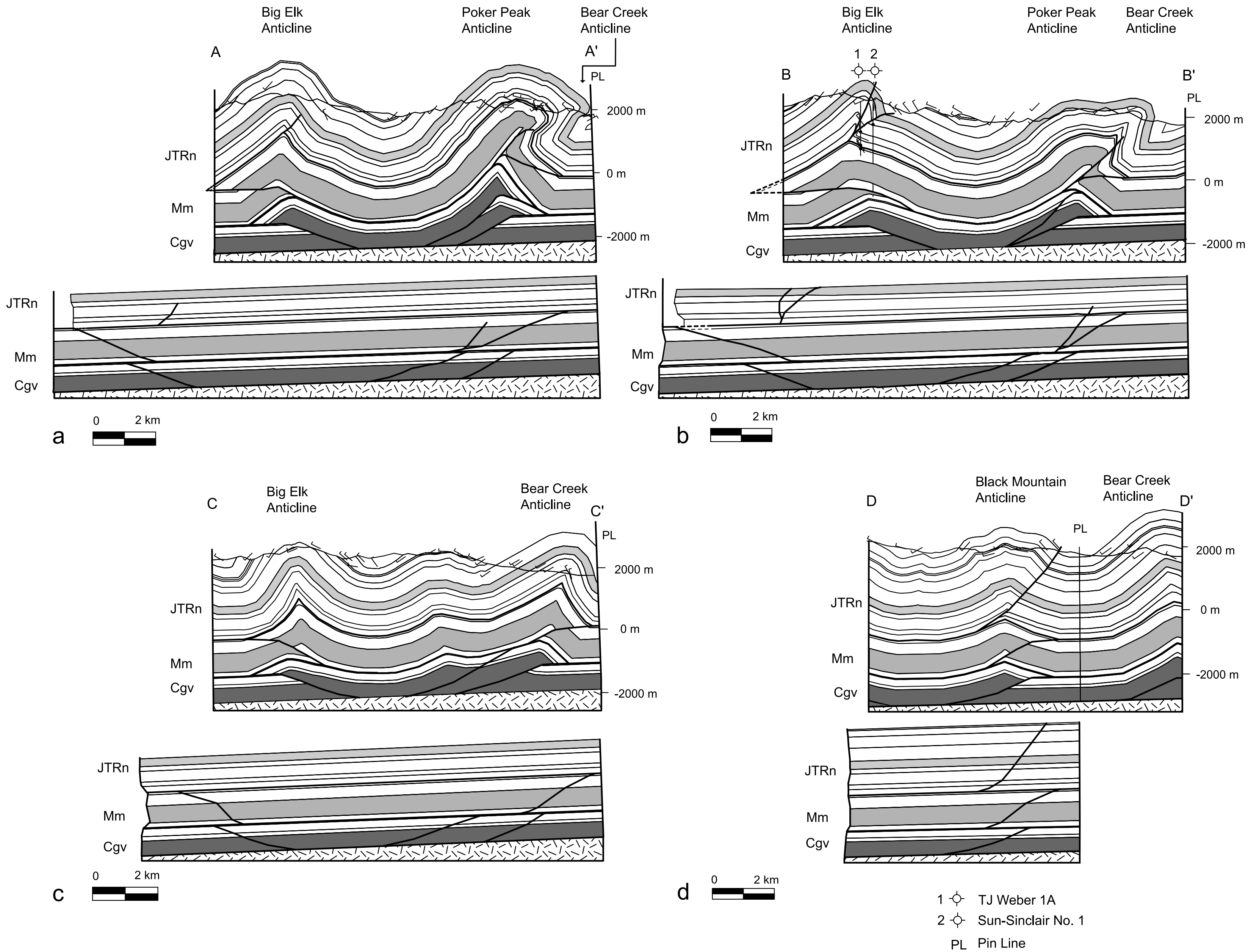


Fig. 13. Structural cross-sections: (a) AA′, (b) BB′, (c) CC′, and (d) DD′ through the Big Elk, Bear Creek, Poker Peak, and Black Mountain anticlines, respectively. Bottom figure shows the restored section for parts of the cross-sections. Cgv = Cambrian Gros Ventre Formation; Mm = Mississippian Madison Formation; JTrn = Jurassic Nugget Formation.

oldest unit exposed at the core of this structure is the Upper Cretaceous Ephraim Conglomerate of the Lower Gannet Group. A small-displacement thrust fault cuts through the forelimb of the anticline. The Black Mountain anticline is interpreted to have been formed above southwesterly-dipping ramps in the Cambro–Ordovician and Devonian–Permian units, with some detachment folding prior to fault breakthrough.

The Bear Creek anticline is almost a symmetrical structure in this section and the Jurassic Twin Creek Formation is exposed at the core of the anticline. The northeastern limb is mostly unexposed and concealed under the Palisades Reservoir.

5.3. Structural restoration and balancing

The four cross-sections described above were restored to their undeformed state (Fig. 13). With the absence of any subsurface data, balancing was one of the main constraints for the construction of these cross-sections. The cross-sections AA′, BB′ and CC′ were pinned at local pin lines in the syncline to northeast of the Bear Creek anticline (Fig. 13).

Units were line-length balanced except for the incompetent basal Gros Ventre Formation, which was area balanced. The Gros Ventre Formation was area-balanced for all the sections. The total deformed area for the Gros Ventre Formation was measured (A). The regional undeformed thickness for the Gros Ventre Formation was then estimated from regional studies (Rubey, 1973; Woodward, 1986), to be 500 m (t). The undeformed average line-length for the Gros Ventre (l) was determined using the relation:

$$l = A/t$$

Although both the Darby shale and the Dinwoody formations behave as incompetent horizons, there is only local thickening. The thickness variations of these units are relatively small; therefore, these were also line-length balanced.

The total shortening for the section between the Cambrain Gros Ventre and the Permian Phosphoria Formations decreases from 5109 m in AA′, to 3803 m in BB′, to 2306 m in CC′. The section above the Dinwoody detachment is slightly shorter in sections AA′ and BB′ in the restored state, suggesting that a small amount of slip (approximately 450–650 m) is transferred out of the section along the Dinwoody detachment.

The Bear Creek anticline undergoes maximum shortening to the north, where it has the highest structural relief, and deformation progressively decreases to the south where the structure dies out within 10 km. The Big Elk anticline shows its maximum relief and shortening in section BB′. The Black Mountain has a shortening of 633 m in section DD′. This shortening value is in agreement with the low structural relief on this anticline.

5.4. 3-D structural geometry

In addition to the four cross-sections described above, 10 more shallow cross-sections were constructed through the area (Fig. 12). In these sections, the surface structural geometry was projected to the top of the Jurassic Nugget Formation, which is exposed or at a relatively shallow depth throughout the area. These cross-sections were integrated to develop a 3-D model for the top of the Nugget Formation, to understand its structural pattern in three dimensions (Fig. 14).

The 3-D structural model (Fig. 14) shows a fairly complex and disharmonic fold style. Two anticlinal branches of the Bear Creek anticline converge and then diverge from north to south. The syncline separating the two anticlines shows branching patterns and dies out to the south. The Poker Peak anticline branches again into two anticlinal traces before losing amplitude into the structural low of the Jensen Creek syncline. The Big Elk anticline shows a slight eastward bend and forms an en-échelon pattern with the Black Mountain anticline. The Black Mountain anticline dies out into the Jensen Creek syncline. This type of fold geometry of the Triassic–Jurassic units represents a strongly disharmonic detachment fold style, and is very similar to the style observed within late Paleozoic units in the Valley and Ridge Province, Pennsylvania (Faill, 1973).

6. Structural evolution

Structure in the Caribou National Forest area initiated as low amplitude detachment folds with major detachments in the Cambrian Gros Ventre Formation, the Devonian Darby Formation, and the base of the Triassic Dinwoody Formation. With progressive shortening, faults broke through the forelimb of the Cambro–Ordovician units to ride up to the detachment within the Darby Formation. This created the faulted detachment fold to fault–bend fold transition presently observed at the Cambro–Ordovician level. Structures with large amounts of shortening, such as the Bear Creek anticline, contain complex fault–bend folds, which interfere to form high-amplitude duplex-type structures. All variations, from separate faulted detachment and fault–bend folds, to overlapping duplexes were formed along trend. The amount of shortening decreased gradually to the south, so the folds were more open southward. The duplex-forming faults diverged and lost slip to the south.

Units between the Darby and Phosphoria Formations were folded with ramps connecting the Darby and Dinwoody detachments. Units above the Dinwoody detachment were primarily folded by disharmonic and lift-off detachment folding. In the very late stages, a few faults broke through the units, such as those observed in the Inlet

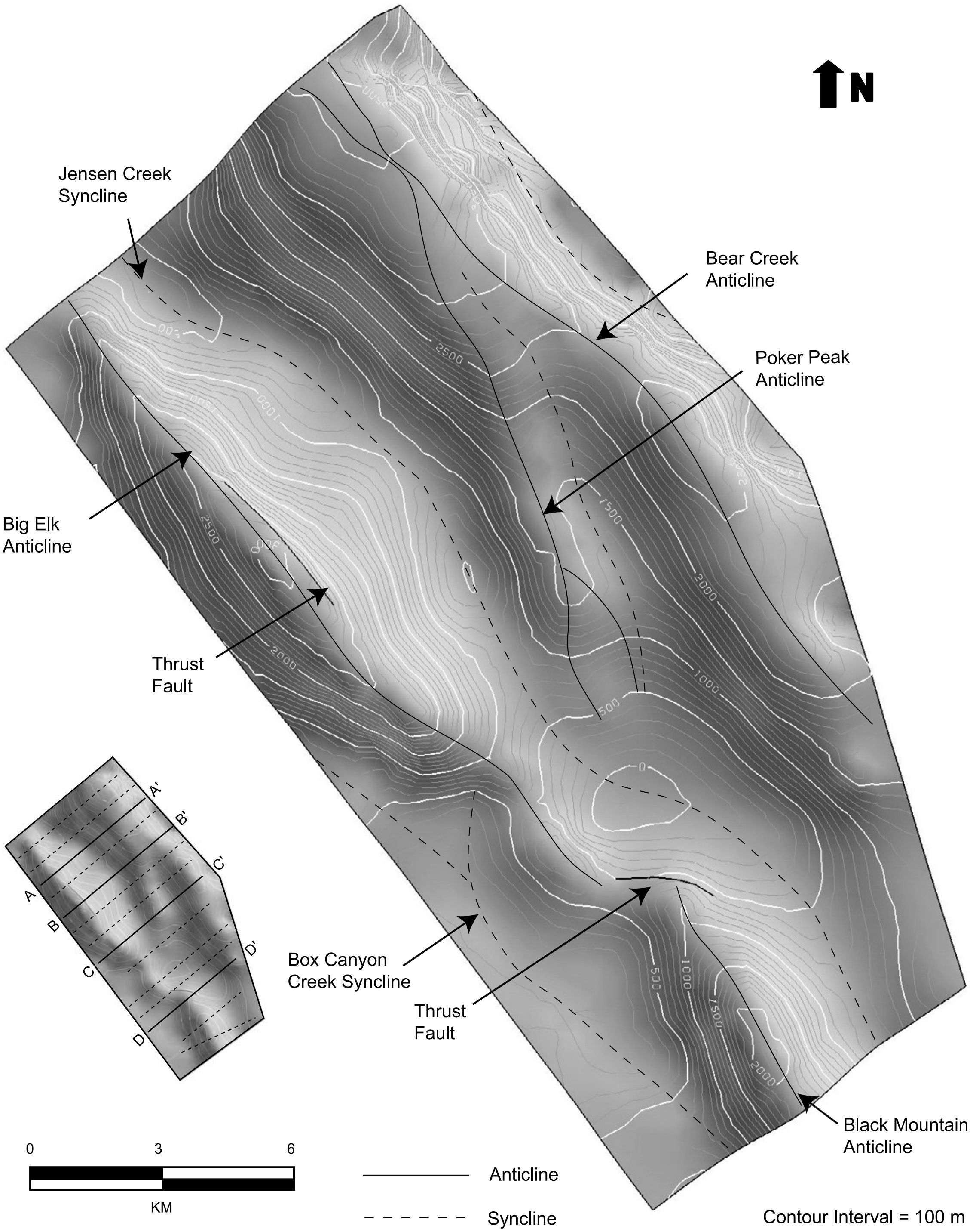


Fig. 14. Top view of a 3-D surface for the top of the Nugget Formation, showing disharmonic fold style. The anticlinal and synclinal traces show branching and en-échelon patterns. Inset shows the location of cross-sections used to develop the 3-D model.

area, and near the crest of the Big Elk anticline. As indicated by the restorations, a small amount of slip was transferred out of the section along the Dinwoody detachment.

7. Conclusions

Superposition of orthophotos and geologic maps on DEMs combined with field reconnaissance provides an effective 3-D mapping tool. It can also be used to obtain quantitative measurements of bedding strike and dip. Application of this method in the Caribou National Forest area of the Idaho fold–thrust belt has resulted in an improved understanding of the structural geometry of the area.

Surface structures within the Triassic to upper

Cretaceous units display en échelon and branching patterns, suggestive of disharmonic folding.

The structures are detached at three main stratigraphic levels, the Cambrian Gros Ventre shales, the Devonian Darby shales, and the Triassic Dinwoody Formation. The structural style in the lower stratigraphic packages consists of detachment folds, which have been subsequently faulted through by ramps connecting the Gros Ventre, Darby, and Dinwoody detachments. Depending on the amount of shortening, the structures vary from independent faulted detachment folds to overlapping duplex-type structures.

The structural style in the upper stratigraphic package consists of disharmonic detachment folds with some late-stage faulting. However, very few faults are exposed at the surface.

Restoration of the structures using line length and area balancing shows that the two lower packages exhibit the same amount of overall shortening in each section. Therefore, no slip is transferred out of the section between the two structural packages. The units above the Dinwoody detachment restore to a shorter length, suggesting that some slip is transferred out of the section along the Dinwoody detachment.

Acknowledgements

Subhotosh Banerjee's thesis was partially funded by a fellowship from Phillips Petroleum. Fieldwork was supported by a student grant from the Geological Society of America. The authors thank Geo-Logic systems for providing us with their LITHOTECT software for the construction of cross-sections, and reviewers Frank Bilotti and Bob Ratliff for their detailed reviews of the manuscript. Steve Boyer suggested the Palisades Reservoir area as a possible study location.

References

Albee, H.F., Cullins, H.L., 1975. Geologic map of the Alpine Quadrangle, Bonneville County, Idaho, and Lincoln County Wyoming. United States Geological Survey Geologic Quadrangle Map GQ-1259, scale 1:24,000.

Armstrong, F.C., Oriel, S., 1965. Tectonic development of the Idaho–Wyoming thrust belt. AAPG Bulletin 49, 1847–1866.

Babcock, W.H., 1989. Kinematic and geometric analysis of the Bear Creek Anticline, Caribou Mountains, Idaho. M.S. thesis, University of Colorado, Boulder, Colorado.

Banerjee, S., Mitra, S., 2004. Remote surface mapping using orthophotos and geologic maps draped over digital elevation models: application to the Sheep Mountain anticline, Wyoming. AAPG Bulletin, in press.

Boyer, S.E., 1986. Styles of folding within thrust sheets: examples from the Appalachian and Rocky Mountains of the U.S.A. and Canada. Journal of Structural Geology 8, 325–339.

Burrough, P.A., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Oxford University Press, New York, p. 50.

Chester, J.S., 1987. Mechanical stratigraphy of the Cambrian through Mississippian section in the Absaroka Thrust Sheet, Haystack Peak Area, Wyoming. Geological Society of America, Abstracts with Programs 19, 618.

Faill, R.T., 1973. Kink-band folding, Valley and Ridge Province, Pennsylvania. Geological Society of America Bulletin 84, 1289–1314.

Gardner, L.S., 1961. Preliminary geologic map of the Irwin quadrangle. United States Geological Survey Open File Report OF 61-53.

Gockley, C., 1985. Structure and strain analysis of the Big Elk Mountain Anticline, Caribou Mountains, Idaho. M.S. thesis, University of Colorado, Boulder, Colorado.

Lamerson, P.R., 1982. The Fossil Basin area and its relationship to the Absaroka thrust fault system, in: Powers, R.B. (Ed.), Geologic Studies of the Cordilleran Thrust Belt. Rocky Mountain Association of Geologists, pp. 279–340.

Mather, P.M., 1999. Computer Processing of Remotely Sensed Data: An Introduction. John-Wiley and Sons, New York, p. 306.

Mitra, S., 1986. Duplex structures and imbricate thrust systems: geometry, structural position, and hydrocarbon potential. AAPG Bulletin 70 (9), 1087–1112.

Mitra, S., 2002a. Fold-accommodation faults. AAPG Bulletin 86 (9), 671–693.

Mitra, S., 2002b. Structural models of faulted detachment folds. AAPG Bulletin 86 (9), 1673–1694.

Neighbor, F., 1953. Big Elk Mountain anticline, Bonneville County, Idaho. Intermountain Association of Petroleum Geologists, Fourth Annual Field Conference, pp. 88–92.

Oriel, S.S., Moore, D.W., 1985. Geologic map of the west and east Palisades roadless areas, Idaho and Wyoming. United States Geological Survey Miscellaneous Field Studies Map, MF-1619-B.

Royse, F.L., Warner, M.A., Reese, D.L., 1975. Thrust belt structural geometry and related stratigraphic problems Wyoming–Idaho–Northern Utah. RMAG Deep Drilling Frontiers in the Central Rocky Mountains, 1975 Symposium, pp. 41–54.

Rubey, W.W., 1973. Geologic map of the Afton quadrangle and part of the Big Piney quadrangle, Lincoln and Sublette Counties, Wyoming. United States Geological Survey Miscellaneous Geological Investigations, Map I-686.

Wiltschko, D.V., Dorr Jr., J.A., 1983. Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah. AAPG Bulletin 67 (8), 1304–1322.

Woodward, N.B., 1986. Thrust fault geometry of the Snake River Range, Idaho and Wyoming. Geological Society of America Bulletin 97, 178–193.