STRUCTURAL ARCHITECTURE OF THE CONFUSION RANGE, WEST-CENTRAL UTAH: A SEVIER FOLD-THRUST BELT AND FRONTIER PETROLEUM PROVINCE

by David C. Green and Donna M. Herring

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by David C. Greene[1] and Donna M. Herring[2]

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Cover photo: *Well-bedded Ely Limestone exposed in the east face of Congor Mountain, showing internal thrust faulting.*

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STRUCTURAL ARCHITECTURE OF THE CONFUSION RANGE, WEST-CENTRAL UTAH: A SEVIER FOLD-THRUST BELT AND FRONTIER PETROLEUM PROVINCE

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EXECUTIVE SUMMARY

The Confusion Range in western Millard County, Utah, exposes Ordovician through Triassic strata in what has previously been described as a broad structural trough or synclinorium with generally minimal overall shortening. Recent work at Denison University indicates that the Confusion Range is more accurately characterized as an east-vergent, fold-thrust belt with significant (~10 km) horizontal shortening during the late Jurassic to Eocene Sevier Orogeny. This newly recognized fold-thrust belt extends for more than 130 km along strike in western Millard County in what has been considered the hinterland of the Sevier Orogeny.

To characterize the structural architecture and style of deformation in this fold-thrust belt, we completed a series of four balanced and restorable cross sections across the Confusion Range and adjacent Tule Valley at a scale of 1:50,000. A fifth strike-parallel cross section ties the strike-perpendicular cross sections together while delineating the lateral and oblique thrust ramps that form a significant complicating factor in the structure of this fold-thrust belt. Together these five cross sections, totaling approximately 290 km in map length, elucidate the structural style of the Confusion Range fold-thrust belt.

The cross sections were constructed at a scale of 1:50,000 and with no vertical exaggeration, using existing geologic mapping at 1:24,000, 1:48,000, and 1:100,000 and our fieldwork. There are few deep drill holes in the Confusion Range, and the only published seismic data covering the Confusion Range is COCORP data collected in the 1980s, optimized for deep reflections and therefore of limited usefulness in interpreting upper crustal structure. However, the well-exposed surface geology plus the requirements of consistent bed length, area balance, and retrodeformability impose significant constraints on possible interpretations. The cross sections as drawn illustrate a set of realistic subsurface structural geometries that are effective in producing the observed surface geology.

Complete balancing is not possible in these sections because (1) they do not cover a large enough cross-strike length to contain sufficient pin lines to fully constrain the deformation, and (2) strata move both into and out of the sections. However, the shortening shown is compatible within and between sections, and, where possible, fold-thrust shortening in the lower Paleozoic section is balanced with shortening via ductile thickening and detachment folding in the overlying Chainman and Ely Formations.

Structures within the Confusion Range are predominantly contractional, and large-offset normal faulting appears mostly restricted to range-bounding faults adjacent to Snake Valley on the west and Tule Valley on the east. Normal faults mapped within the range generally have small displacements and do not significantly offset unit boundaries; these small faults are generally omitted from the cross sections.

The temporal, stratigraphic, and structural correlation of the Confusion Range fold-thrust belt with the Sevier frontal thrust belt in central Utah has significant implications for petroleum potential in western Millard County. Discovery of the Covenant field in Sevier County, Utah—one of the largest new onshore fields discovered in the U.S. in recent years (estimated 100 million barrels of original oil in place)—has proved the petroleum system concept for the Utah salient of the Sevier fold-thrust belt. These cross sections provide basis for seismic interpretation and identification of similar potential plays in the Confusion Range and its southern continuation.

The presented fold-thrust model has a predictive value for finding subsurface structures, based on known surface constraints and several corroborating boreholes. The fold-thrust model includes a mechanism by which the source rocks of the Pilot Shale and Chainman Formation were returned to oil-window depths prior to Basin and Range extension, generating hydrocarbons to fill Sevier-age traps. The cross sections show trapping opportunities in multi-leveled Sevier structures and potential for preserved fold-thrust trap oil fields in the Confusion Range. The cross sections suggest that the east side of Snake Valley is prospective for Basin and Range-age oil generation and extensional traps as well, but this is the least supported of the structural interpretations.

In addition to the five cross sections, this report includes discussion of significant features of the cross sections and their construction, a short discussion of the implications for petro-

leum potential, and an annotated bibliography, especially as it relates to petroleum potential of the study area.

INTRODUCTION

The Confusion Range in western Millard County, Utah (figure 1, plate 1) exposes Ordovician through Triassic strata in what has previously been described as a broad structural trough or synclinorium with generally minimal overall shortening (e.g., Hose, 1977; Hintze and Davis, 2002, 2003). Recent work at Denison University (e.g., Yezerski and Greene, 2009; Matteri and Greene, 2010; Greene et al., 2011), building from fieldwork first initiated in 1998 (Dubé and Greene, 1999), indicates that the Confusion Range is more accurately characterized as an east-vergent, fold-thrust belt with significant (~10 km) horizontal shortening during the Late Jurassic to Eocene Sevier Orogeny. This newly recognized fold-thrust belt extends for more than 130 km along strike in western Millard County in what has been considered the hinterland of the Sevier Orogeny. To characterize the structural architecture and style of deformation in this fold-thrust belt, we completed a series of four balanced and restorable cross sections across the Confusion Range and adjacent Tule Valley at a scale of 1:50,000 (plates 2 to 5). A fifth strike-parallel cross section ties the strike-perpendicular cross sections together while delineating the lateral and oblique thrust ramps that form a significant complicating factor in the structure of this fold-thrust belt (plate 6). Together these five cross sections, totaling approximately 290 km in map length, elucidate the structural style of the Confusion Range fold-thrust belt.

The temporal, stratigraphic, and structural correlation of the Confusion Range fold-thrust belt with the Sevier frontal thrust belt in central Utah has significant implications for petroleum potential of western Millard County. Discovery of the Covenant field in Sevier County, Utah—one of the largest new onshore fields discovered in the U.S. in recent years (estimated 100 million barrels of original oil in place)—has proved the petroleum system concept for the Utah salient of the Sevier fold-thrust belt. These cross sections provide basis for seismic

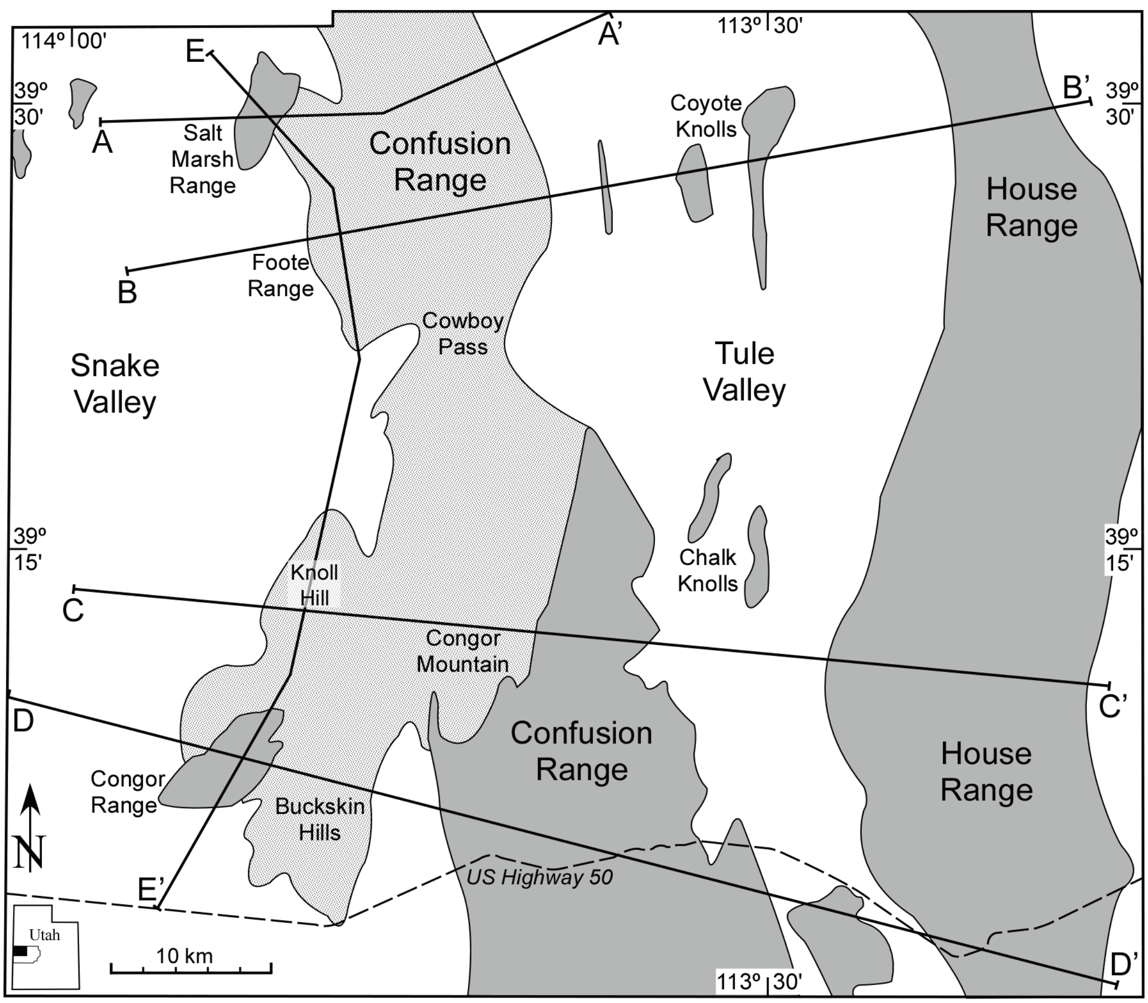

__Figure 1.__ Location map for the Confusion Range showing cross section lines, labeled A through E. Darker shading indicates predominantly lower Paleozoic rocks, lighter shading indicates predominantly upper Paleozoic rocks. See plate 1 for more detail.

interpretation and identification of similar potential plays in the Confusion Range and its southern continuation.

In addition to the five cross sections, this brief report includes discussion of significant features of the cross sections and their construction, a short discussion of the implications for petroleum potential, and an annotated bibliography, especially as it relates to petroleum potential of the study area.

GEOLOGIC HISTORY OF WESTERN MILLARD COUNTY

For a detailed geologic history of the entirety of Millard County, see Hintze and Davis (2003). The brief synopsis below focuses on the western part of the county, drawn in part from Hintze and Davis (2003) and in part from other sources as cited.

The most salient features of western Millard County are related to extension in the Basin and Range Province. The Basin and Range comprises large swaths of the American West from Oregon and Idaho through California and Texas, extending south into Mexico; north-striking basins adjacent to uplifts contain up to 3000 meters of fluvial, alluvial, and lacustrine sediments, and interbedded volcanics. These basins (grabens and half grabens filled with sediments and volcanics) and ranges (uplifts) were formed by extensional faulting, initiated approximately 19 Ma (million years ago) in the Miocene and continuing through the present (Dickinson, 2006). Extensional faults of the Basin and Range significantly complicate the interpretation of older structures.

To begin the discussion of pre-Basin and Range structures, note that a broad, sub-linear shelf edge in the Precambrian and older crystalline rocks of the craton existed in Utah for most of the Paleozoic in a SSW–NNE orientation known as the Cordilleran Hingeline (see especially Allmendinger et al., 1986). East of the Hingeline, Paleozoic sedimentation was thin to nonexistent over a flat plain surface near sea level. West of the Hingeline, sediments accumulated in marine environments on a slowly subsiding, relatively shallow continental shelf from Cambrian through latest Devonian time. The continental edge was farther west in central Nevada, beyond which sediments accumulated very slowly at abyssal depths.

In the latest Devonian, the North American continent began collision with the Antler island arc complex and then other terranes impinging from the west; the Roberts Mountains Thrust (RMT) system was developed at the continental edge in Nevada, and the former shallow shelf was warped downward and began collecting thick foreland basin deposits in front of the thrust system, including organic-rich sediments of the Devonian-Mississippian Pilot Shale and Mississippian Chainman Formation and temporal equivalents. An eastward-migrating low forebulge developed distal to the RMT east of the deepest part of the Antler foreland basin, and locally influenced late Paleozoic sedimentation in western Utah and Millard County (Giles, 1994; Morrow and Sandberg, 2007).

Through the latest Paleozoic and into the earliest Mesozoic, the foreland basin continued to fill with thick Pennsylvanian-Permian carbonate and mixed carbonate-clastic sediments. In the Permo-Triassic, continuing eastward-directed compression emplaced the Golconda allochthon in central Nevada east of the RMT, and fine-grained mainly marine calcareous clastic sequences sourced from the Golconda allochthon were deposited over western Millard County (Triassic Thaynes Formation) above the nearly filled foreland basin (Anna et al., 2007).

By Jurassic time, the continental plate boundary had shifted westward to the west edge of the accreted terranes (Dickinson, 2006). Hintze and Davis (2003) note that Early Jurassic sediments (perhaps as much as 150 m of the Navajo Sandstone) may have been deposited in western Millard County as they were in eastern Millard County, but if so they were later removed by erosion. From the Jurassic until the Eocene, eastern Nevada and western Utah continued to experience compressional tectonics during three overlapping orogenic events: the Nevadan (short-lived, Late Jurassic to Early Cretaceous), the Sevier (long-lived, Late Jurassic to Paleogene), and the Laramide (Late Cretaceous to Eocene), each of which had different strain histories (Yonkee and Weil, 2011).

Pyroclastic volcanism began in the late Eocene and continued through the Oligo-Miocene, accompanied, starting in the Miocene, by the extensional faulting that created the typical Basin and Range topography observed today.

Of the above geologic history of western Millard County, the most important facets in the following discussion are the Sevier Orogeny and the Antler foreland basin. The Confusion Range has previously been interpreted as a synclinorium in the hinterland of the Sevier fold-thrust belt, and is here shown to be a Sevier fold-thrust system. The organic-rich Antler foreland basin deposits are discussed in the context of potential hydrocarbon charge of fold-thrust structures in the Confusion Range thrust system, as well as in their mechanical role in the structural style of the fold-thrust architecture.

STRUCTURAL ARCHITECTURE OF THE CONFUSION RANGE

The Confusion Range is a topographically low mountain range in western Millard County, Utah, (plate 1) that exposes about 5000 m of Paleozoic and Triassic strata comprising the former cover rocks of the Snake Range core complex that is mapped in adjacent White Pine County, Nevada. Previous workers have interpreted the Confusion Range as a broad structural trough or synclinorium, with complex, variable, and by modern standards geometrically unlikely internal deformation, but with little overall shortening (e.g., Hose, 1977; Bartley and Wernicke, 1984; Hintze and Davis, 2002; Rowley et al., 2009). Hintze (in Hintze and Davis, 2003) described the envisioned synclinorium as a structural feature 130 km long, up to 24 km wide, and extending the entire length of western Millard County, with the Confusion Range comprising approximately the northern half.

Published geologic mapping in the Confusion Range includes 1:24,000-scale coverage of most of the range (e.g., Hose, 1963a, 1963b, 1965a, 1965b; Sack, 1994), with additional mapping at scales of 1:48,000 (Hintze, 1974a) and 1:100,000 (Hintze and Davis, 2002). Our fieldwork has concurred nearly completely with units and surface relationships mapped previously. However, the structural interpretations evident in the cross sections accompanying these otherwise accurate maps are incorrect and/or incomplete by modern standards: the cross sections do not balance, the interpreted structures are not compatible with immediately adjacent structures, the cross sections do not extend to any significant depth, and the interpreted structures do not fit the regional trends.

The new, balanced, restorable cross sections presented herein indicate that the Confusion Range is an east-vergent fold-and-thrust belt of Sevier age overprinted by Basin and Range extension. A fold-thrust belt structural style, similar to what we now show in the Confusion Range, is probably present throughout the 130 km length of the originally proposed synclinorium.

General Strengths and Limitations of the Cross Sections

The Confusion Range is well covered by geologic mapping completed in the 1960s and 1970s and confirmed by our local detailed mapping and field reconnaissance. Exposure is generally excellent, bedding orientations are widely available and the stratigraphy is well understood. Within the range, therefore, cross sections are well constrained at the surface, although the regional scale of this work has required generalization and simplification of local detail. In particular, Tertiary normal faults with small displacement have generally been omitted.

There are, however, few deep drill holes in the Confusion Range, and the probability of major structural discontinuities underlying Snake Valley to the west means that data from drill holes in Snake Valley cannot be directly used to interpret structures within the Confusion Range. The only published seismic data covering the Confusion Range is COCORP (Consortium for Continental Reflection Profiling) Nevada Line 5 and Utah Line 1, collected in the 1980s (Allmendinger et al., 1983, 1986, 1987; Hauser et al., 1987). Nevada Line 5 crosses northern Snake Valley and terminates near the Bishop Springs anticline in the northern Confusion Range. Utah Line 1 begins at the Nevada/Utah border and crosses Snake Valley, the Confusion Range at Cowboy Pass, Tule Valley and the House Range. Acquisition of these seismic lines was optimized for deep reflections, and they are therefore of limited usefulness in interpreting upper crustal structure.

Given the general lack of borehole information and useful public seismic data, the subsurface interpretation presented in these cross sections is much less constrained by direct observation than the surface trace of each section. The location and geometry of specific subsurface structures is subject to considerable uncertainty, and the interpretation of deeper structural levels must be considered speculative.

However, the well-exposed surface geology plus the requirements of consistent bed length, area balance, and retrodeformability impose significant constraints on possible interpretations. The cross sections as drawn illustrate a set of realistic subsurface structural geometries that are effective in producing the observed surface geology. These new cross sections, while undoubtedly incorrect in some details, provide a much-improved interpretation that can form the basis for a new understanding of the structural history, petroleum potential, and relation of Sevier contraction to late Tertiary extension in western Millard County.

Methods of Cross Section Construction

There are few named geographic features in the Confusion Range, resulting in few and repetitious names for geologic features. Names used in this discussion generally follow the usage of Hintze and Davis (2003), though we also introduce some informal names.

Stratigraphy

The Confusion Range consists of Cambro-Ordovician through Triassic strata, with predominantly thick-bedded, competent carbonate rocks in the lower Paleozoic section and incompetent shales, sandstone and thin-bedded carbonates in the upper Paleozoic section. Regional stratigraphy is described in detail elsewhere (e.g., Hose et al., 1976; Rodgers, 1984; Peterson, 1994; and Hintze and Davis, 2003). Stratigraphic nomenclature and unit thicknesses used here follow those of Hintze and Davis (2003) for the northern Confusion Range and northern House Range (figure 2), with the exception that as documented by Hose (1974b) the Joana Limestone is absent in the northernmost Confusion Range and adjacent units are thinner than elsewhere.

Mechanical Stratigraphy

In general, the lower Paleozoic carbonate section forms a strong "beam" that deforms primarily by ramp-flat thrust faulting. There are two major detachment horizons in the lower Paleozoic section that are used in constructing these cross sections. A detachment located in the Corset Spring Shale Member of the Cambrian Orr Formation just below the base of the Notch Peak Formation (figure 2) is herein informally referred to as the Orr detachment. In constructing the cross sections, the 56 m thick Sneakover Limestone Member of the uppermost Orr Formation was included with the overlying Notch Peak Formation, so that the illustrated unit boundary coincides with the detachment level.

Figure 2a. *Upper Ordovician to Quaternary composite stratigraphic column and unit thicknesses used in construction of the cross sections, modified from Hintze and Davis (2003). Major detachment levels used in constructing the cross sections are indicated and informally named the Eureka detachment, at the top of the Eureka Quartzite, and the Pilot detachment, at the base of the Pilot Shale. Major zones of detachment due to internal ductile deformation are also present in the Chainman and Arcturus Formations.*

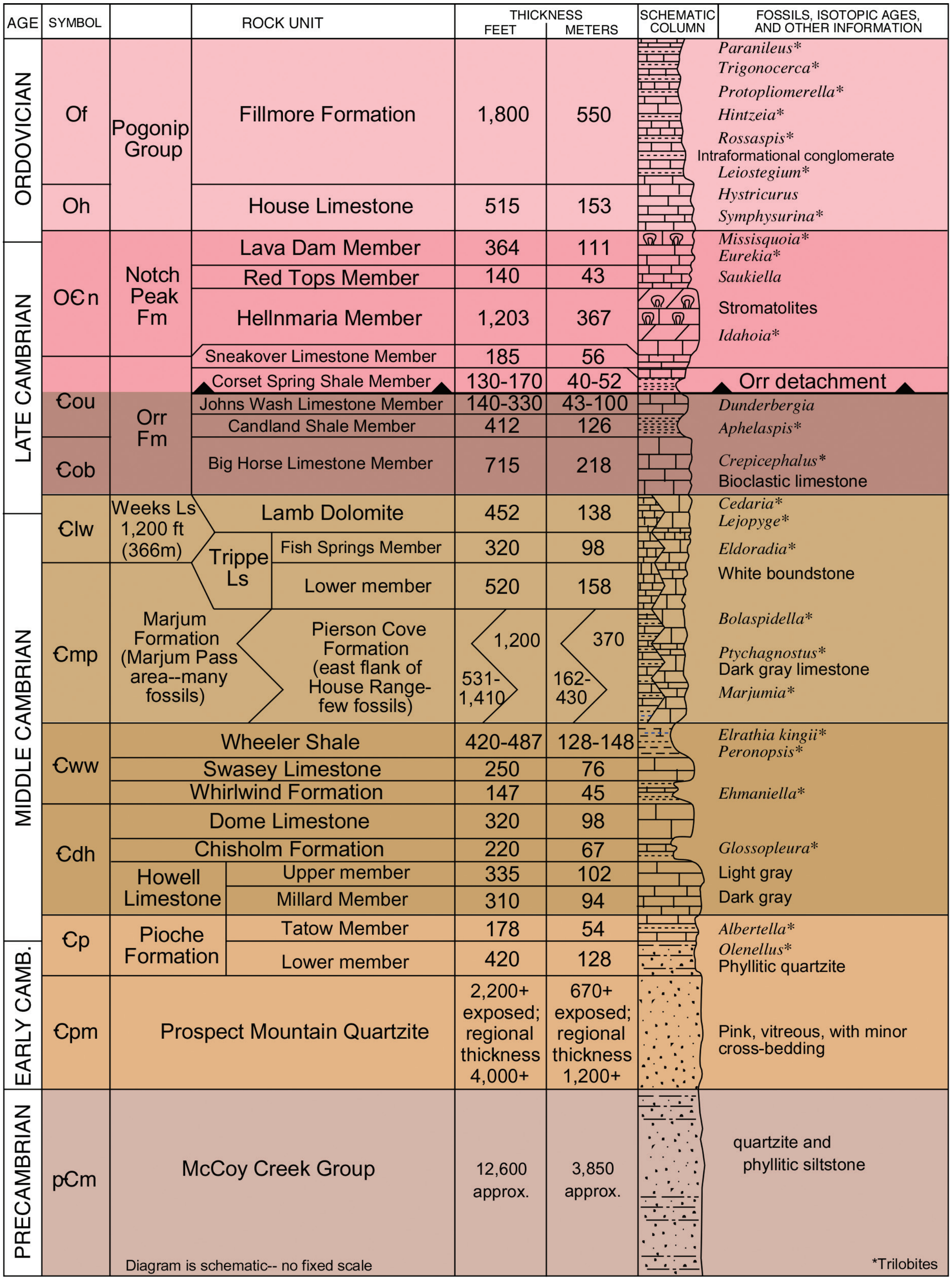

Figure 2b. *Proterozoic to Lower Ordovician composite stratigraphic column and unit thicknesses used in constructing the cross sections, modified from Hintze and Davis (2003), with addition of the McCoy Creek Group (Hose et al., 1976; Rodgers 1984). A major detachment level in the Corset Spring Shale member of the Orr Formation used in constructing the cross sections is indicated and informally named the Orr detachment.*

A detachment at the top of the Ordovician Eureka Quartzite (top of Oew on the cross sections) is herein referred to informally as the Eureka detachment. The Eureka detachment is locally evident in outcrop, especially in the Kings Canyon thrust zone. The Orr detachment is not exposed in the Confusion Range, but is necessary to reconcile geometric relationships in the structures. Other detachment levels that are significant regionally include the Lower to Middle Cambrian Pioche Formation (Miller et al., 1983; McGrew, 1993) and the Neoproterozoic Pocatello Formation (equivalent to the lower part of the McCoy Creek Group) (DeCelles and Coogan, 2006).

The upper Paleozoic section, in contrast, deforms primarily by large-scale detachment folding, with local disharmonic folding and faulting. Thick (>300 m) ductile shales in the Camp Canyon Member of the Chainman Formation (figure 2), and in the Pilot Shale at the top of the Devonian Guilmette Formation, form zones of detachment that separate fold-thrust structures in the underlying lower Paleozoic section from predominantly folding in the less competent upper Paleozoic section. In the cross sections these zones are generalized to a single detachment drawn at the base of the Pilot Shale above the strong carbonates of the Guilmette Formation, and referred to informally as the Pilot detachment.

The Pennsylvanian Ely Limestone in the Confusion Range is a prominent ridge-forming marker unit that outlines major structures in the upper Paleozoic section. Well-bedded and thin- to medium-bedded, the Ely Limestone carbonate package forms a relatively strong layer between two weak, ductily deforming units, the Mississippian Chainman and Permian Arcturus Formations. The Ely Limestone deforms internally primarily by flexural-slip folding and internal accommodation faulting, characteristically forming large detachment folds (e.g., Dahlstrom, 1990; Mitra, 2003) cored by mobile shales of the Chainman Formation, as observed on the west side of the Confusion Range in all four east-west cross sections. The Permian Kaibab Limestone is a relatively thin (~165 m), massive, carbonate unit that deforms in a style similar to the Ely Limestone, forming complex disharmonic detachment folds between the weaker Arcturus Formation and overlying Permian and Triassic units.

Cross Sectional Methods and Assumptions

The cross sections of this study were constructed and are presented at a scale of 1:50,000 and with no vertical exaggeration, utilizing existing geologic mapping at scales of 1:24,000, 1:48,000, and 1:100,000 and our fieldwork; please see the annotated bibliography for a complete listing of the geologic maps covering the area. Our work included local detail mapping, and each of the cross section transects was field-checked before section construction. A regional original average dip of 2° to the west, off the continental platform in central Utah, is assumed.

The cross sections were constructed to have consistent bed lengths and areas, and to be retrodeformable. Complete balancing is not possible in these sections because (1) they do not cover a large enough cross-strike length to contain sufficient pin lines to fully constrain the deformation, and (2) strata move both into and out of the sections. However, the shortening shown is compatible within and between sections, and where possible, fold-thrust shortening in the lower Paleozoic section is balanced with shortening via ductile thickening and detachment folding in the overlying Chainman Formation and Ely Limestone. Upper Paleozoic units above the Ely Limestone are not formally balanced due to insufficient exposure and the common occurrence of additional internal structural complexities where they are exposed (discussed further below).

Structures within the Confusion Range are predominantly contractional, and large-offset normal faulting appears mostly restricted to range-bounding faults adjacent to Snake Valley on the west and Tule Valley on the east. Normal faults mapped within the range generally have small displacements and do not significantly offset unit boundaries. In particular, the Ely and Kaibab Limestones as mapped by Hose (e.g., Hose and Repenning, 1964; Hose, 1965a, 1965b) have a chaotic, "shattered glass" pattern of pervasive small faults that accommodate distributed brittle deformation relative to the ductily deforming units above and below them. These small faults are generally omitted from the cross sections.

Exposures of Oligocene lacustrine limestone with interbedded conglomerate and rhyolitic tuff (Greene and Herring, 1998) are present at scattered locations in the Confusion Range; e.g., Toms Knoll (Hose, 1965b) and Little Mile and a Half Canyon (Hintze, 1974a). Layering in these units can be highly variable, often with steep dips and no consistent relationship to the orientation of underlying strata. In places (e.g., Little Mile and a Half Canyon) layering in the limestones can be demonstrated to be concentric and nodular, related to precipitation on an irregular substrate rather than reflecting an original paleohorizontal. For these reasons, Paleozoic bedding orientations have not been corrected for the tilt of locally overlying Tertiary units, although further study may indicate that this is justified at some locations.

The focus of this study and the emphasis of the cross sections is on understanding contractional deformation in the Confusion Range. The House Range to the east was not a focus of this work, and no new fieldwork was done there. Three of these cross sections do, however include the House Range in order to (a) illustrate the dramatic change in structural level between upper Paleozoic strata in the eastern Confusion Range and Lower Cambrian strata in the adjacent House Range, and (b) provide a direct connection to the work of DeCelles and Coogan (2006), who presented a balanced cross section that extends eastward from the House Range to the Canyon Range and the Sevier frontal thrust zone.

The cross sections presented here begin in Snake Valley just west of the Confusion Range, and structures implied by the structural architecture in the range are continued on the cross sections into the subsurface beneath Snake Valley some distance. There is, however, a major structural and stratigraphic contrast between little-extended Paleozoic strata in the Confusion Range and highly extended, predominantly Cambrian and Precambrian rocks in the northern Snake Range on the west side of Snake Valley (e.g., Gans et al., 1999a, 1999b), suggesting the presence of a major structural discontinuity in the subsurface beneath Snake Valley.

One proposal for this major discontinuity is that the northern Snake Range decollement, with up to 60 km of extensional displacement, continues from exposures on the east side of the Snake Range into the subsurface beneath Snake Valley and the Confusion Range with a dip of 15–25º to the east (e.g., Allmendinger et al., 1983; Bartley and Wernicke, 1984; Lewis et al., 1999; Miller et al., 1999). A reflector that could represent such a structure was imaged by the seismic line COCORP Utah Line 1 (Allmendinger et al., 1983). This proposal is controversial, however (e.g., Smith et al., 1991; Hintze and Davis, 2003), and in fact COCORP Nevada Line 5 in the northern Snake Valley did not image such a reflector (Hauser et al., 1987). Borehole drilling results in Snake Valley west of the current study area do not appear to intersect any juxtapositions that would confirm the decollement. Boreholes farther south do penetrate attenuated lower Paleozoic section, and extending this study farther south could possibly shed some light on the controversy.

Because of the abovementioned lack of data and controversy, structures projected from the Confusion Range into the subsurface beneath Snake Valley are shown grayed out on the cross sections, and no attempt has been made in this work to correlate units or structures across Snake Valley. The constant-dip trajectory proposed by some workers for the Snake Range decollement is shown diagrammatically on the west edge of the sections to emphasize the potential conflict between the deep structure illustrated here and a major low-angle extensional fault at shallow depth beneath the Confusion Range.

Discussion of Structural Style and Major Structures

The apparently synclinal aspect of the Confusion Range results from separate thrust structures that uplift and expose lower Paleozoic strata on the flanks of the range. Contractional structures post-date the Lower Triassic Thaynes Formation, which is involved in the folding, and predate late Eocene and Oligocene volcanic rocks and sediments that are deposited unconformably on deformed upper Paleozoic strata. Tertiary high-angle normal faults of probable Miocene age bound the range and also cut previously deformed Paleozoic strata.

The primary influence on structural architecture of the Confusion Range is a series of frontal and lateral ramps that formed in lower Paleozoic strata in the subsurface on the west side of the range. Ramp anticlines and anticlinal duplexes resulted in uplift of Ordovician through Pennsylvanian strata in the present west edge of the Confusion Range, defined by the minor topographic expressions of the Salt Marsh Range, Foote Range, Knoll Hill, and Congor Range.

A major anticlinal detachment fold, defined primarily by Ely Limestone, developed in the upper Paleozoic section above and east of frontal ramp anticlines. North of Cowboy Pass in the northern Confusion Range, this fold is characterized by a tight, east-vergent, overturned anticline-syncline pair. Steeply west-dipping Ely Limestone in the overturned limb of this fold forms the prominent topographic features of Cockscomb Ridge and Chevron Ridge, and equivalent structures in the Kaibab Limestone form Plympton Ridge to the east.

In the southern Confusion Range south of Cowboy Pass, the correlative detachment fold is upright, tear-drop shaped, bordered by oppositely vergent synclines, and cut by the late Browns Wash thrust fault (informally named by Anderson [1983]). Ridges of oppositely-dipping Ely Limestone that define this fold form part of the prominently striped Buckskin Hills on the southwest side of the Confusion Range.

In the northern Confusion Range, a broad zone of gently dipping upper Paleozoic and Triassic rocks is exposed east of the detachment folds. These relatively weak units are internally deformed but no large through-going structures are apparent. West-dipping lower Paleozoic units ramp to the surface under Tule Valley, and flat-lying Cambrian strata are exposed in the House Range.

In the southern Confusion Range, a second thrust ramp formed east of the Buckskin Hills detachment fold, resulting in uplift and exposure of lower Paleozoic rocks on the east side of the range. The Congor Springs anticline and Congor Mountain syncline that formed above the thrust ramp plunge gently northward, indicating a gently north-dipping lateral ramp that terminates at Cowboy Pass. The thrust underlying these structures is exposed on the east side of the Confusion Range as a continuous series of structures that includes the Kings Canyon thrust, the Payson Canyon thrust, and the Cattlemans Valley anticline.

On the east side of the Confusion Range and in the subsurface of Tule Valley, lower Paleozoic strata ramp upward in a west-dipping monocline that brings Cambrian strata to the surface in the House Range. A series of westward-dipping reflectors underlying the House Range at a depth of 10–15 km are imaged on the COCORP Utah Line 1 seismic line and have been interpreted to indicate Mesozoic thrust ramps that imbricate crystalline basement (e.g., Allmendinger et al., 1983, 1986). This basement duplex was referred to as the Sevier Culmination by DeCelles et al. (1995) and was incorporated into the cross sections of DeCelles and Coogan (2006). Displacement of the hanging wall above these thrust ramps probably resulted in the uplift and westward tilting now observed in Tule Valley and the House Range.

Description of the Cross Sections

Please see plate 1 for locations of the cross sections. The following descriptions start on the west side of each section and proceed east. Previous interpretations of other workers are noted and discussed, especially where they are in disagreement with the fold-thrust model. Each description concludes with discussion of the subsurface fault and fold sequences, area balancing, and shortening along the line of section.

Northern Confusion Range, A–A'

Cross section A–A' (plate 2) crosses the northern Confusion Range at approximately the latitude of Gandy. It extends from northern Snake Valley east across the Salt Marsh Range and Cockscomb Ridge, then continues northeast across the Disappointment Hills to Tule Valley, terminating near the base of the Middle Range at the northern border of Millard County. The area is covered by 1:24,000-scale geologic maps of the Trout Creek SE (Hose, 1974a), Gandy NE (Hose and Ziony, 1963), and Granite Mountain SW (Hose, 1974b) quadrangles, as well as the 1:100,000-scale geologic map of the Tule Valley 30' x 60' quadrangle of Hintze and Davis (2002). These maps and our new fieldwork form the basis for the cross section presented here. Previous cross sections and structural interpretations were presented with the above geologic maps, and in Hose (1977).

In northern Snake Valley, gravity data (Hintze and Davis, 2003; Mankinen and McKee, 2009) and well logs (Herring et al., 1998) indicate a moderately deep subsurface basin containing Tertiary and Quaternary sediments underlying the valley. This basin is here interpreted to be bounded by a west-down normal fault under alluvium on the west edge of the Salt Marsh Range.

The Salt Marsh Range forms a large topographic outlier on the west edge of the northern Confusion Range. This outlier exposes gently west-dipping Devonian carbonates of the Sevy, Simonson, and Guilmette Formations, faulted against upper Paleozoic Chainman Formation and Ely Limestone in the valley to the east, with a stratigraphic offset of more than 1800 m. This fault on the east side of the Salt Marsh Range was initially interpreted as an east-dipping normal fault by Hose and Ziony (1963), but subsequent workers have considered it a west-dipping thrust fault (Herring et al., 1998; Nichols et al., 2002). The Salt Marsh fault is here interpreted as a late out-of-sequence thrust fault that cuts a previously formed thrust duplex.

Eastward from the Salt Marsh thrust, in the valley between the Salt Marsh Range and Cockscomb Ridge, a faulted anticline-syncline pair involves Ely Limestone and Chainman Formation. These structures are a northward extension of the Bishop Springs anticline, exposed to the south and illustrated in cross section B-B'. The prominent, linear Cockscomb Ridge is formed by overturned, west-dipping Ely Limestone in a tight, overturned, east-vergent detachment fold.

East of Cockscomb Ridge, the Desolation anticline is a broad anticline exposed in low hills of Arcturus Formation. A drill hole (Standard Oil of California No.1 Desolation Anticline, Hintze and Davis [2003] reference no. 52-2) located near the crest of this anticline and 3.5 km along strike to the north of the cross section line encountered a normal stratigraphy of Arcturus to Guilmette Formations. The hole terminated at a total depth of 6,200 ft (1,890 m) in Guilmette. The lithologic log on file for the cuttings indicates a thick "sheared" interval through 1000 ft (305 m) of the lower Chainman Formation shales and upper Pilot Shale, including a 3-m-thick Joana Limestone section.

East of the Desolation Anticline, previous work (Hose, 1974b) and our field studies indicate that the Plympton fault is a shallowly east-dipping fault that emplaces Kaibab Limestone and Plympton Formation over Arcturus Formation. This is a younger-on-older stratigraphic juxtaposition, and Hose (1974b, 1977) considered the Plympton fault to be a top-to-the-east low-angle normal fault, part of his "higher decollement" interpreted to be a horizon of eastward gravity sliding into the axis of a structural trough. However, exposures of the fault zone east of Plympton Ridge show slickenlines and kinematic indicators suggesting top-to-the-west displacement. We interpret this fault to be a low-angle, west-vergent thrust fault that cuts previously folded upper Paleozoic rocks and probably formed due to the mechanical contrast between ductily deforming Arcturus Formation and stiffer overlying units. The fault is interpreted to root locally in the Arcturus Formation and to have less than 1 km of displacement.

The Disappointment Hills to the east are underlain by moderately folded Plympton Formation and Gerster Limestone, and cut by northwest-striking normal faults that form a graben in which Triassic Thaynes Formation and Tertiary volcanic rocks are locally preserved.

Quaternary alluvium in Tule Valley obscures Paleozoic rocks immediately to the east, but exposures in the Middle Range to the north of the line of section, and the Coyote Knolls to the south of the line of section, indicate that west-dipping lower Paleozoic strata ramp upward toward the surface and underlie this northwestern corner of Tule Valley. Joana Limestone is not present in the Middle Range to the northeast, and Guilmette Formation is thinner than elsewhere. Thus, Pilot Shale and Chainman Formation in the cross section are merged under Tule Valley.

Interpreted subsurface structure in this cross section consists of a stacked duplex developed above a lower detachment in the Corset Spring Shale Member of the uppermost Orr Formation ("Orr detachment"), just below the base of the Notch Peak Formation.

Three major thrust faults that offset the Cambro-Ordovician section (OCn to Oew) are indicated on the cross section: the Salt Marsh thrust, labeled "c", and two additional faults to the east labeled "a" and "b" (plate 2). The middle thrust "a" is interpreted to have developed first, forming an anticline in the Guilmette Formation, and initiating detachment folding in the overlying Chainman Formation and Ely Limestone. This was followed by development of the easternmost thrust fault "b" and ramp anticline in a break-forward pattern, back-rotating the now piggybacked first-formed plate. Weak strata in the upper Paleozoic section (Arcturus Formation and overlying units) to the east were uplifted and passively folded to form the Desolation anticline. Finally, the Salt Marsh thrust formed as a late, out-of-sequence, break-back structure that cut the first-formed structural plate and uplifted lower Paleozoic strata (Devonian Sevy and Simonson Dolomites) that are now exposed at the surface. Tertiary extension on the east edge of Snake Valley is interpreted to have reactivated the lower part of the Salt Marsh thrust as a west-down normal fault.

Westward tilting of strata under Tule Valley probably occurred late in the contractional deformation history, either before or after formation of the Salt Marsh thrust, and is interpreted to result from passive uplift of the Paleozoic section during formation of a thrust duplex in underlying Precambrian crystalline basement, as suggested by Allmendinger et al. (1983, 1986), DeCelles and others (1995), and DeCelles and Coogan (2006) based on interpretation of the COCORP Utah Line 1 seismic line.

Cross section A–A' shows a total of 12 km of horizontal shortening of the lower Paleozoic section. Line length balancing indicates that shortening on two thrust duplexes in the Cambro-Ordovician section (OCn to Oew) is balanced by folding and thrust imbrication in the Devonian section, except for 4 km of displacement which is interpreted to be transferred eastward on a bedding-parallel detachment at the top of the Eureka Quartzite ("Eureka detachment"). The upper Paleozoic section is decoupled from the strong Guilmette Formation, and deforms primarily by folding, with compensation by ductile flow of shales in the Chainman Formation and internal disharmonic folding in the Arcturus Formation. Line length and area balancing indicate that shortening in the upper Paleozoic section is roughly equivalent to that in the Devonian section.

North-Central Confusion Range, B–B'

Cross section B–B' (plate 3) extends from Snake Valley east-northeast across the Foote Range, Chevron Ridge, Big Horseshoe valley, and Plympton Ridge to the Disappointment Hills. It continues across the Coyote Knolls, Tule Valley, and the House Range, terminating on the east flank of the House Range. The area is covered by geologic maps of the Gandy NE (Hose and Ziony, 1963), Cowboy Pass NW (Hose and Repenning, 1963), Coyote Knolls (Sack, 1994a), Swasey Peak NW (Sack, 1994b), and Swasey Peak (Hintze, 1981) quadrangles at a scale of 1:24,000, and the geologic map of the Tule Valley 30' x 60' quadrangle at a scale of 1:100,000 (Hintze and Davis, 2002). These maps and our new fieldwork form the basis for the cross section presented here. Previous cross sections and structural interpretations were presented with the above geologic maps, and in Hose (1977) and Matteri and Greene (2010). In particular, the new cross section presented here follows the same line as cross section A–A' of Hintze and Davis (2002).

In Snake Valley, a pronounced gravity low indicates the presence of a deep basin filled by low-density Tertiary and Quaternary sediments (Hintze and Davis, 2003; Mankinen and McKee, 2009). Bishop Springs, on the east edge of Snake Valley, is here interpreted to indicate the location of a subsurface, west-down normal fault that bounds this basin. East of Bishop Springs, the Foote Range is underlain by a broad, gently west-dipping block of Ely Limestone and bounded on the east by a high-angle, east-up fault that places Ely Limestone against Pilot Shale with 500 m of stratigraphic offset, cutting out the Chainman Formation. This fault, informally named the Foote Range fault, was considered to be an east-dipping reverse fault by Hintze and Davis (2002), following Hose and Repenning (1963). However, exposures in the fault zone on the southeast side of the Foote Range are steeply west-dipping with down-dip slickenlines, and we here interpret the fault as a west-dipping normal fault that roots locally in Pilot Shale on the west-dipping limb of the Bishop Springs anticline.

The Bishop Springs anticline is a north-trending, doubly plunging fold, cored at the surface by Pilot Shale and Joana Limestone. The fold is one of a series of aligned north- to northwest-trending anticlines exposed in the valley between the Foote Range and Chevron Ridge. A petroleum exploration hole (Gulf Oil/Tiger Oil No.1 Bishop Springs Anticline, reference no. 52-3 of Hintze and Davis, 2003) drilled on the crest of the Bishop Springs anticline 200 m north of the line of section encountered a highly faulted lower Paleozoic section consisting of repeated thrust slices of Guilmette Formation carbonates and underlying Simonson, Sevy, and Laketown Formations, underlain by a relatively intact Ordovician section. This borehole terminated in the Cambro-Ordovician Notch Peak Formation at a total depth of 4894 m (16,058 ft).

The Bishop Springs anticline is here interpreted as a complexly faulted anticlinal duplex formed primarily in the Guilmette Formation and underlying Devonian and Silurian units. The duplex is underlain by a large ramp anticline that repeats the Ordovician section. The complexity in the interpretation of the thrust stacking here is required by the drilled sequence, and exhibits the kind of subsidiary structures likely to be found elsewhere in the subsurface of the Confusion Range but that have not been drawn into the cross sections because direct evidence is lacking.

East of the Bishop Springs anticline, Chevron Ridge consists of overturned, steeply west-dipping Ely Limestone that forms the east limb of a tight detachment fold, cored by ductile shales of the Chainman Formation. This is a southward continuation of the similar structure forming Cockscomb Ridge to the north.

East of Chevron Ridge across Big Horseshoe valley, Plympton Ridge is formed by tight fold repetitions of resistant Kaibab Limestone overlying ductile Arcturus Formation. The Kaibab Limestone, like the Ely Limestone, is a relatively stiff and resistant unit sandwiched between the weak and poorly indurated Arcturus Formation below and Plympton Formation and Gerster Limestone above. Complex detachment folds, as seen here, characteristically develop in the Kaibab Limestone between the ductily deforming units that enclose it (e.g., Hose, 1974a).

East of Plympton Ridge, the Disappointment Hills are underlain by a predominantly east-dipping section of Plympton, Gerster, and Thaynes Formations. The section is cut by numerous west-dipping normal faults that are here interpreted to be relatively shallow listric faults rooting in the underlying Arcturus Formation.

East of the Disappointment Hills, alluvial cover in Tule Valley obscures outcrop except for three north-striking ridges. The first, 3.5 km to the east, is a narrow ridge formed by a tight anticlinal crest at the top of the Guilmette Limestone. This structure is on trend with the Cattlemans Valley anticline, Payson Canyon thrust, Kings Canyon thrust, and associated shortening structures exposed to the south along the east side of the Confusion Range. The Coyote Knolls form the two farther east north-striking ridges; the western knoll is underlain by Laketown Dolomite and the eastern knoll by Notch Peak Formation. The westward dip, spacing, and stratigraphic position of these exposed ridges is consistent with a uniformly west-dipping lower Paleozoic stratigraphic section underlying the western half of Tule Valley. Anomalously thin Sevy Dolomite on the west side of the western knoll is attributed to local attenuation faulting (e.g., Hintze, 1978; Nutt et al., 1996).

A gravity low between the Coyote Knolls and the House Range (Mankinen and McKee, 2009) is interpreted to indicate the presence of steeply dipping, valley-down normal faults in the subsurface. A prominent topographic scarp on the west side of the House Range exposes gently east-dipping Lower Cambrian strata that are cut by high-angle normal faults and a predominantly left-lateral, strike-slip fault interpreted by Hintze (1981) to be a tear fault related to Mesozoic thrusting.

The primary subsurface structure in cross section B–B' is a large ramp anticline that repeats the Cambro-Ordovician section (OCn to Oew). The thrust ramp is placed west of the Foote Range, underlying the east side of Snake Valley, rising from the basal Orr detachment below the Notch Peak Formation to the Eureka detachment at the top of the Eureka Quartzite. Doubling of the Ordovician section is required by the contrast in structural level between the Notch Peak Formation at the bottom of the Bishop Springs well and its projected stratigraphic position under the Disappointment Hills.

Above this simple ramp anticline the Siluro-Devonian carbonate section (Oes to Dg) is highly faulted, with numerous small thrusts and thrust repetitions interpreted from electric and lithologic logs of the Bishop Springs anticline petroleum exploration well. Displacement is transferred eastward on the Eureka detachment, which is interpreted to intersect the ground surface at Coyote Knolls. A splay from this detachment forms a tight fault-propagation anticline in the Guilmette Formation, the crest of which is exposed as a narrow ridge on the west side of Tule Valley.

The COCORP seismic line Utah Line 1 that crossed Tule Valley 20 km to the south imaged a prominent west-dipping reflector at a depth of about 7 km that appears to merge with the House Range normal fault on the east side of Tule Valley. This reflector is inferred to be a horizontal segment of the Canyon Range thrust, reactivated in extension by the Tertiary House Range normal fault (e.g., Allmendinger et al., 1983; Bartley and Wernicke, 1984; DeCelles and Coogan, 2006). That interpretation is followed here, and the high-angle normal faults bounding Tule Valley are drawn intersecting and reactivating a west-dipping detachment tentatively correlated with the Canyon Range thrust of DeCelles and Coogan (2006).

Westward tilting of strata under Tule Valley probably occurred late in the contractional deformation history, and is interpreted to result from passive uplift of the Paleozoic section during formation of a thrust duplex in underlying Precambrian crystalline basement, as suggested by Allmendinger et al. (1983) and DeCelles and Coogan (2006) based on interpretation of the COCORP Utah Line 1 seismic line.

Cross section B–B' shows a total of 9 km of horizontal shortening of the Cambro-Ordovician section in the large ramp anticline, relative to the Cambrian units below. There is 2 km total shortening of the overlying Siluro-Devonian section in the Bishop Springs anticline, and 1 km in the anticline on the west side of Tule Valley. Thus, this interpretation implies that about 6 km of displacement is transferred eastward on the Eureka detachment, as indicated diagrammatically by a hypothetical ramp in Guilmette Formation in the eroded stratigraphy above Tule Valley. Total shortening indicated by the bed length of folded Ely Limestone matches the Guilmette Formation, as does area balancing of the ductile Chainman Formation.

In this interpretation contractional deformation began with eastward displacement above the Eureka detachment (top of Oew), propagating into the section from the west. This drove initial folding and thrust faulting in the Devonian section, and initiated detachment folding in the overlying Ely Limestone.

In the next phase of deformation, displacement shifted to the lower Orr detachment (top of Cou) with eastward displacement stepping upward to the Eureka detachment. The major ramp anticline began to form at this time, driving uplift and tightening of the overlying anticlines in the Guilmette Formation and Ely Limestone. Subsequent eastward transport of Ordovician units in the hanging wall of the ramp anticline was probably accommodated by eastward displacement on the Eureka detachment. The tight anticline in Guilmette Formation on the edge of Tule Valley may have formed during this phase, as a fault propagation fold driven by a splay off the underlying detachment. This structure and surrounding strata underlying Tule Valley were subsequently rotated to steeper westward dips by uplift on proposed thrust duplexes in crystalline basement underlying the House Range.

South-Central Confusion Range, C–C'

Cross section C–C' (plate 4) extends from Snake Valley east across Knoll Hill, Browns Wash, Congor Mountain, and Little Mile and a Half Canyon in the Confusion Range, continuing across Tule Valley to the House Range, and across Pine Peak and Candland Canyon to terminate on the east flank of the House Range.

Geologic map coverage includes the Congor Range NE quadrangle at 1:24,000 scale (Hose, 1965b), the Congor Mountain and Notch Peak quadrangles at 1:48,000 scale (Hintze, 1974a, 1974b), and the geologic map of the Tule Valley 30' x 60' quadrangle at 1:100,000 scale (Hintze and Davis, 2002). These maps and our new fieldwork form the basis for the cross section presented here. Previous cross sections and structural interpretations were presented with the above geologic maps, and in Hose (1977). In particular, the interpretation presented in this cross section may be compared with that of Line B–B' of Hintze and Davis (2002) that begins 4 km north of this section line, and Line A–A' of Hintze (1974a). The COCORP Utah Line 1 seismic line begins in Snake Valley near the same location as this cross section, diverging to the northeast to cross the Confusion Range at Cowboy Pass.

In eastern Snake Valley on the west end of this cross section, gravity data (Hintze and Davis, 2003; Mankinen and McKee, 2009) indicate bedrock at relatively shallow levels in the subsurface, suggesting a transfer zone between deeper basins to the north and south. East of Snake Valley the section crosses Knoll Hill, a broad doubly plunging anticline of Ely Limestone here interpreted to be formed by a ramp anticline in underlying Guilmette Formation.

To the east of Knoll Hill an overturned, west-vergent syncline is cored by Arcturus Formation, and bounded to the east by a ridge of Ely Limestone that forms a faulted anticline cut by the Browns Wash thrust (informal). East of the Browns Wash thrust the west side of Congor Mountain is an east-vergent overturned syncline of Ely Limestone cored by Arcturus Formation.

This pair of oppositely vergent overturned synclines, also seen to the south in cross section D–D', is one of the most enigmatic structures in the Confusion Range, and has given rise to a variety of interpretations (Hose, 1965a, 1965b, 1977; Anderson, 1983; Hintze and Davis, 2002; Nichols et al., 2002; Silberling and Nichols, written communication, 2009; Yezerski and Greene, 2009; Greene et al., 2011). Based on map relations and our current field investigations, we regard this structure as fundamentally an anticlinal detachment fold in Ely Limestone, cored by mobile shales of the underlying Chainman Formation and with oppositely vergent synclines in overlying relatively ductile Arcturas Formation on either side.

While unusual in shape compared to the symmetrical folds common in strata with more uniform bed-parallel strength, detachment folds are well known in areas where a relatively thin strong layer overlies or is enclosed in more mobile layers (e.g., Dahlstrom, 1990; Mitra, 2003; Scharer et al., 2004). In this case, the relatively strong Ely Limestone is enclosed in highly mobile Chainman Formation shales below and the thick but relatively weak fine-grained clastic strata of the Arcturus Formation above.

The detachment fold seen here is cut by a fault in Browns Wash that we interpret as an east-vergent thrust that offsets the east limb of the fold and more closely juxtaposes the bounding synclines. Hose (1965b) originally mapped a fault in this location that he interpreted as a steeply west-dipping reverse fault. Anderson (1983) informally named it the Browns Wash fault and considered it to have been active in Oligocene time. Silberling and Nichols (written communication, 2009) recognized it as a major structure but interpreted it as an east-down normal fault. However, on the basis of sparse outcrop data and geometric considerations we consider the Browns Wash fault to be most likely a west-dipping thrust fault. The Browns Wash fault, detachment fold, and adjacent synclines can be traced to the south along the east side of the Congor Range, with an eastward, left-lateral offset across a tear fault north of Toms Knoll Pass.

East of Browns Wash the line of section crosses Congor Spring anticline, a narrow north-plunging fold on the west side of Congor Mountain, and the Congor Mountain syncline, a broad, open fold with a gently north-plunging axis. The spectacular south-facing cliffs and high plateau that form the summit of Congor Mountain are underlain by resistant Ely Limestone in the axis of the Congor Mountain syncline. East of Congor Mountain, prominent west-dipping strike ridges of Joana Limestone and Guilmette Formation define the east edge of the syncline.

On the east edge of the Confusion Range a complex zone of imbricate thrust faults and structural attenuation involves the Laketown, Sevy, Simonson, and Guilmette Formations. These faults are part of a system of thrust faults and subsidiary folds exposed along the east edge of the Confusion Range that includes the Payson Canyon and Kings Canyon thrusts to the south, and the Cattlemans Valley anticline to the north, and may continue in the subsurface to include the anticline in Guilmette Formation east of the Disappointment Hills that is illustrated in cross section B–B' (plate 3).

East of the Confusion Range, Quaternary alluvium in Tule Valley obscures outcrop, but gravity data (Hintze and Davis, 2003; Mankinen and McKee, 2009) and projection of units southward from the Chalk Knolls indicate that western Tule Valley is underlain by shallow bedrock consisting of uniformly west-dipping Ordovician and Cambrian units, cut by two Tertiary high-angle normal faults. A prominent gravity low in eastern Tule Valley indicates a deeper fault-bounded basin adjacent to the House Range. The House Range in this cross section consists of gently east-dipping Middle and Lower Cambrian units, intruded by quartz monzonite of the Jurassic Notch Peak pluton.

Total shortening in this section is estimated at 6 km, 3 to 6 km less than shortening to the north and south. The moderate amplitude of the Knoll Hill anticline suggests relatively small displacement on an underlying ramp anticline that repeats the Guilmette Formation. Eastward displacement of 2.5 km is interpreted to ramp upward from the Orr detachment below the Notch Peak Formation to a flat in Sevy Dolomite, and then upward again to the Pilot detachment level at the top of the Guilmette Formation. An alternative interpretation is that this increment of displacement enters the cross section from the west at the Eureka detachment level. The detachment fold in Ely Limestone began to form at this time in front of the advancing hanging wall. Continued displacement resulted in the thrust tip cutting upward through the detachment fold, intersecting the ground surface as the Browns Wash thrust.

A second phase of shortening is interpreted to propagate eastward on the Orr detachment and ramp upward beneath Congor Mountain to be exposed on the east side of the Confusion Range as the Kings Canyon-Payson Canyon thrust system (Hintze and Davis, 2003). The Congor Springs anticline is here interpreted as a tight fold formed by local faulting and buckling at the top of the Guilmette Formation, associated with the thrust ramp under Congor Mountain.

Displacement of 3.5 km on the Orr detachment is distributed eastward into two faults, the Kings Canyon thrust with 1.5 km of displacement, and the Eureka detachment. The Kings Canyon thrust is interpreted as a low-angle thrust with a hanging-wall ramp-on-footwall ramp relationship, including local imbrication and attenuation of units.

The structures illustrated form a simple break-forward thrust system, with primary displacement on the basal Orr detachment ramping upward first under Snake Valley to form the Knoll Hill anticline and Browns Wash thrust, and then propagating eastward to ramp up under Congor Mountain and form the Kings Canyon thrust, and with farther eastward propagation of displacement on the Eureka detachment.

Southern Confusion Range, D–D'

Cross section D–D' (plate 5) extends from the Nevada/Utah state boundary east-southeast across Snake Valley, the Congor Range, Okelberry Pass, the Buckskin Hills, and Little Valley, crossing US Highway 50 east of Kings Canyon. The section line continues south of Highway 50 across Cat Canyon, King Cove and the east-facing scarp of the Confusion Range, the southern end of Tule Valley, and the Black Hills south of Skull Rock Pass, and terminates west of Sevier Lake.

Geologic map coverage includes the Congor Range NE and Congor Range SE quadrangles at 1:24,000 scale (Hose 1965a, 1965b), the Congor Mountain and Notch Peak quadrangles at 1:48,000 scale (Hintze, 1974a; 1974b), and the geologic map of the Tule Valley 30' x 60' quadrangle at 1:100,000 scale (Hintze and Davis, 2002). These maps and our new fieldwork form the basis for the cross section presented here. Previous cross sections and structural interpretations were presented with the above geologic maps, and in Hose (1977), Anderson (1983), Dubé and Greene (1999), Nichols et al. (2002), and Silberling and Nichols (written communication, 2009). In particular, the interpretation presented here may be compared with that of Line C–C' of Hintze and Davis (2002) that approximately parallels this section line 1 to 3 km to the north.

In Snake Valley, on the west end of the cross section, gravity data (Hintze and Davis, 2003; Mankinen and McKee, 2009) indicate bedrock at relatively shallow levels in the subsurface, suggesting a transfer zone between deeper basins to the north and south. This is supported by low pediment outcrops of Ely Limestone and other upper Paleozoic units showing through valley-fill alluvium up to 6 km west of the Congor Range frontal scarp.

The upper Paleozoic units west of the range front are poorly exposed and structurally complex, with steep dips and numerous juxtapositions of noncontiguous units. These seemingly chaotic blocks are interpreted to be extensional fault blocks in the hanging wall of the Congor Range fault that were previously deformed by Mesozoic folding and thrust faulting. At the Congor Range front Permian Kaibab Limestone is juxtaposed against Silurian Laketown Dolomite to the southeast with a minimum stratigraphic offset of 3800 m.

The Congor Range fault in this area is a northwest-dipping normal fault that bounds a structurally and topographically high block of lower Paleozoic carbonate rocks at the southwest corner of the Congor Range. This block is similar to the Salt Marsh Range in that it is an isolated, anomalously high block of older Silurian and Devonian rocks faulted against younger upper Paleozoic units on the west edge of the Confusion Range.

As illustrated in this cross section, the northwest-trending portion of the Congor Range fault as presently exposed is a normal fault with about 7 km of west-down displacement. This normal fault is interpreted to intersect and reactivate the ramp and lower flat segments of a previous thrust fault that emplaced the lower Paleozoic Congor Range block as a hanging-wall ramp anticline above a detachment in Pilot Shale (Dubé and Greene, 1999). Thus the Congor Range is interpreted as the truncated, east-dipping forelimb of a ramp anticline that formed in the lower Paleozoic carbonate section, rising from a basal detachment below the Notch Peak Formation to an upper detachment in the Pilot Shale.

In this interpretation, west-down normal displacement at the range front had a significant component of horizontal extension due to reactivation of and west-directed displacement on the lower detachment. This resulted in antithetic faulting and hanging-wall collapse, producing the complex structure observed in the upper Paleozoic rocks.

In the Okelberry Pass area, steeply west-dipping, down-to-the-west faults that formed in Joana Limestone and the underlying Pilot Shale have previously been interpreted as normal faults (Hose, 1965b; Hintze and Davis, 2002), but are here considered overturned west-vergent thrust faults that imbricated the Joana Limestone and were subsequently rotated to steep west dips during eastward advance of the hanging-wall block.

In front of the advancing hanging wall, a detachment fold formed in the overlying Ely Limestone, cored by mobile shales of the Chainman Formation and with oppositely vergent synclines in Arcturus Formation on either side. The detachment fold was tightened and then cut by the Browns Wash thrust, closely juxtaposing the east- and west-vergent synclines. This detachment fold is a continuation of the fold illustrated in C–C', but here with tighter limbs and exposed at a somewhat deeper structural level.

East of the Congor Range, alluvium in Little Valley obscures the trace of the Congor Springs anticline, but the Congor Mountain syncline is visible as a broad shallow north-plunging structure exposed in low outcrops of Guilmette Formation.

Gently west-dipping lower Paleozoic carbonates (Simonson, Sevy and Laketown Dolomites) on the west side of the Confusion Range are cut by the Kings Canyon Thrust, which in this line of section places Ordovician Ely Springs Dolomite on Devonian Sevy Dolomite with an interpreted thrust displacement of 2.5 km.

A series of northeast-dipping normal faults form the southern end of Tule Valley, where southwest-dipping Sevy Dolomite is repeated in a series of down-dropped fault blocks. The steeply southwest-dipping House Range normal fault forms the east side of Tule Valley, with gently southwest-dipping Ordovician carbonates exposed to the east.

In this interpretation the first phase of deformation involved eastward displacement on the Orr detachment, propagating in from the west and ramping upward through the entire Paleozoic carbonate section to an upper detachment zone in the Chainman Formation. Thrust imbrication and detachment folding in the Ely Limestone preceded and accompanied this shortening in the lower Paleozoic section.

A detachment fold developed in the Ely Limestone in front of the advancing hanging-wall block. Continued advance of the hanging-wall block first tightened the detachment fold, and then resulted in propagation of the thrust tip upward, cutting and displacing the east limb of the fold. Total shortening of the lower Paleozoic section during this phase was approximately 9.5 km.

Subsequently, displacement on the basal Orr detachment propagated eastward and ramped upward to the upper Eureka detachment, presently exposed on the east side of the Confusion Range as the Kings Canyon thrust with an additional 2.5 km of displacement. Thus total shortening across the Confusion Range along this cross section line is about 12 km.

Finally, uplift resulting from thrust duplexes in the crystalline basement below tilted the entire lower Paleozoic section, including the Kings Canyon thrust, to dip more steeply westward. The structural succession described here follows a break-forward pattern, with successive thrusts progressing eastward and up-section.

Strike-Parallel Cross Section of the Confusion Range, E–E'

Cross section E–E' (plate 6) illustrates the structure in a strike-parallel transect along the west side of the Confusion Range. The section extends from northern Snake Valley in the northwest to US Highway 50 in the Ferguson Desert on the southwest, crossing the Salt Marsh Range, the Foote Range, the western approaches to Cowboy Pass, Knoll Hill, and the Congor Range.

Geologic map coverage includes the Trout Creek SE (Hose, 1974a), Gandy NE (Hose and Ziony, 1963), Gandy SE (Hose and Ziony, 1964), Congor Range NE (Hose, 1965b), and Congor Range SE (Hose 1965a) quadrangles at 1:24,000 scale and the geologic map of the Tule Valley 30' x 60' quadrangle at 1:100,000 scale (Hintze and Davis, 2002).

This cross section ties together the four transverse cross sections (A–A', B–B', C–C', and D–D') while emphasizing the location of lateral ramps that form an important component of the regional structure. The section is drawn approximately perpendicular to transport direction, with displacement predominantly top-to-the-east, into the plane of the section. Thus, this section cannot be balanced.

The structures illustrated are predominantly bedding-parallel detachments with hanging-wall flat on footwall flat relationships that developed as eastward-transported thrust sheets climbed up a series of footwall ramps underlying the west edge of the Confusion Range. Lateral changes in the number of thrust slices or the location and height of the frontal ramp control the stratigraphic level exposed at the surface.

At the northwestern end of the cross section a range-bounding normal fault with 2000 m of west-down displacement is interpreted on the west edge of the Salt Marsh Range, based on gravity data (Hintze and Davis, 2003; Mankinen and McKee, 2009) and well data (Balcron No. 12-36 Cobra-State; Herring et al., 1998) in Snake Valley.

The section obliquely cuts the Salt Marsh thrust and underlying duplex that are responsible for uplift and exposure of older Devonian rocks in the Salt Marsh Range, as illustrated in more detail on cross section A–A' (plate 2). Southeast of the Salt Marsh Range the section follows the strike of the Foote Range, a gently west-dipping ridge of Ely Limestone.

The Foote Range, as illustrated in B–B' (plate 3), is located just east of a footwall ramp that steps displacement upward from the lower Orr detachment below the Notch Peak Formation to the Eureka detachment at the top of the Eureka Quartzite. The resultant repetition of Ordovician carbonate strata on the ramp anticline is seen in this strike-parallel cross section. This thrust sheet thins to the south under Cowboy Pass.

Knoll Hill also exposes Ely Limestone, in a ramp anticline resulting from repetition of Devonian Guilmette Formation with a hanging-wall-ramp-on-footwall-flat relationship.

West of the line of section, displacement steps upward from the Orr detachment (seen at the base of this cross section) to an upper detachment at the top of the Guilmette Formation. A north-dipping lateral ramp underlying Cowboy Pass results from stepping downward of this upper detachment.

South of Knoll Hill, lower Paleozoic rocks in the Congor Range are exposed in a ramp anticline above a westward protruding footwall ramp, as illustrated in section D–D' (plate 5). Lateral ramps bound the Congor Range on the north and south. A major normal fault bounding the north and northwest sides of the Congor Range reactivates the pre-existing lateral and frontal ramps (Dubé and Greene, 1999; Yezerski and Greene, 2009).

The east-striking lateral ramp on the north side of the Congor Range forms a significant transverse structural break that continues eastward to offset Ely Limestone in the Buckskin Hills with an apparent left-lateral sense.

IMPLICATIONS FOR PETROLEUM POTENTIAL

The recent Hingeline discoveries of Covenant (100 million barrels of oil in place; Chidsey and Sprinkel, 2009) and Providence (11 million barrels of oil in place; Chidsey et al., 2011) fields after 50 years of sparse drilling in the play has revived interest in other frontier areas of Utah. Similar to the Hingeline, the Confusion Range and adjacent valleys have also been sporadically drilled for petroleum since the 1950s; six deeper dry holes have tested the area, with eight more in or near the continuation of the fold-thrust belt to the south. Individual, mapped, long-axis folds identified as within the "synclinorium," and mainly small-displacement thrusts have been drill targets, as well as anomalies on (generally poor) seismic lines.

Comparison both to Nevada oil fields and to the Utah Hingeline production will be useful to exploration in the Confusion Range. The Nevada fields in Railroad and Pine valleys are traps with almost entirely extensional origin, and the Hingeline field traps are dominantly compressional in origin. However, the Railroad Valley fields' extension overprints a fold structure that contributes to entrapment (French, 1998), and the Hingeline thrusts are in part relaxed (reactivated by extension) and in part dissected by normal faults (Chidsey and Sprinkel, 2009; Chidsey et al., 2011). The Confusion Range play is expected to more nearly resemble the Hingeline, with major thrusts that are dissected in part.

The balanced, restorable cross sections of this report present a more plausible regional geologic model of the Confusion Range and western Millard County than previously available. The picture will certainly prove more complex than the current cross sections can show (for reasons of resolution and lack of certain data noted above), but, as in the sustained search for hydrocarbons in the Hingeline, a better model should in the end be successful.

The most critical task in finding currently reservoired petroleum in western Millard County is discerning the relative timing of structural events and the associated formation and re-formation of hydrocarbon "kitchen" conditions for the source rocks. Below are brief descriptions of the source rocks, potential reservoirs, traps and seals, followed by a section on the relative timing of structures and hydrocarbon generation, and a summary of hydrocarbon potential of the Confusion Range fold-thrust belt.

Source Rocks in the Confusion Range Area

Anna et al. (2007) calculated the mean total organic carbon (TOC) of the Chainman Formation to be about 1.5% in the Confusion Range area, where it averages 580 m thick. The Pilot Shale in the northern and central Confusion Range includes 91 m of organic-rich shale with an average 2.2% TOC for the section (Poole and Claypool, 1984). Organic matter in the organic-rich portions of the Chainman Formation and Pilot Shale consists mainly of marine sapropelic, type II kerogen (Poole and Claypool, 1984) with a RockEval S1/S2 ratio indicating it is mainly marine in origin and oil-prone (Anna et al., 2007).

Anna et al. (2007) modeled regional hydrocarbon generation from the Chainman to have begun after burial was sufficiently deep from sedimentary overburden, in the Permian. Erosion later removed enough overburden that generation ceased by mid-Triassic time; generation conditions were renewed locally by thrust loading in the Mesozoic and by deep burial in extensional basins more recently (see further discussion below). Anna et al. (2007) indicate a current depth to the oil-generating window in the Basin and Range (absent a local heat source) of about 2500–2650 m, based on heat flow mapping.

Potential Hydrocarbon Reservoirs in the Stratigraphic Section

Reservoir rocks in the Hingeline oil fields include sandstones of the eolian, Jurassic Navajo Sandstone. Producing reservoirs in the Nevada oil fields include Paleozoic shelf-edge carbonates, Cretaceous lacustrine rocks, Oligocene volcanics, and Tertiary slide blocks of Paleozoic lithologies in older valley fill. Common to the Hingeline and Nevada fields are ubiquitous fractures that are responsible for most permeability within the reservoirs.

In Nevada, porosities of the producing intervals are typically low, regardless of rock type. For instance, matrix porosity of dolomite producing in the Grant Canyon field is less than 5%, though production testing indicated an absolute open flow potential of 20,800 barrels of oil per day for the No.4 Grant Canyon.

In the Utah Hingeline, average porosity of the Navajo Sandstone at Covenant field is 12% (Chidsey et al., 2011), and the discovery well had an initial potential (IP) of 708 barrels of oil per day. Average porosity at Providence field is 11% for the First Navajo (IP per day of 220 barrels of oil plus 2320 MCF of gas and 15 barrels of water) and 6% for the Second Navajo (IP per day of 500 barrels of oil plus 1000 MCF of gas and no water). Note that the lower porosity reservoir had the highest IP. In short, any lithology competent enough to fracture is a reasonable reservoir target in the eastern Great Basin and therefore in the Confusion Range area.

Potential Petroleum Traps

Structural traps in overthrust plays include four-way closure folds associated with thrusts, and fault confinement traps. Both of these types are likely to occur in the Confusion Range; however, some of the folds evident at the surface will not be prospective at depth because of the structural decoupling of the upper and lower Paleozoic section.

An example of structural decoupling occurs in one of the earliest petroleum tests drilled in western Millard County, the Gulf No.1 Bishop Springs, on the mapped Bishop Springs anticline (shown in cross section B–B', plate 3) that has four-way closure at the surface. In 1952, this hole spudded in Pilot Shale and penetrated multiple small-displacement reverse faults with sparse minor shows of dead oil, "carbonaceous material" (possibly bitumen) in fractures, and fetid gas odor in Devonian carbonates and the Pilot Shale. The hole was reentered and deepened by Tiger Oil in 1980, with a final TD of 16,058' in Cambro-Ordovician Lava Dam Member. The results of the No.1 Bishop Springs suggest that oil passed through the Devonian rocks, but the shows are too minor and sparse to indicate a former significant accumulation that has been breached. Cross section B–B' shows the apex of rollover in the Guilmette to be east of the surface fold axis in the Pilot Shale, and anticlinal closure in the Guilmette may not be four-way.

Structural traps related to extension that have produced in the Basin and Range to date include faulted gravity slide blocks and tilted fault blocks, both of which occur in the subsurface of valleys. The Confusion Range itself is not prospective for these types of traps, but the valleys on either side of the range can be expected to contain both types. Like Railroad Valley, Snake Valley has source rocks in the subsurface and should have extensional traps. The current cross sections do not predict any preserved source rocks in Tule Valley, however, so any accumulations in extensional traps in Tule Valley would be remigrated hydrocarbons from a pre-Basin and Range generation episode.

One possible stratigraphic trap type expected in western Millard County is unconformity related, though it would undoubtedly occur in combination with structural entrapment. Anna et al. (2007) note that most carbonate intervals drilled in the eastern Great Basin have a sonic log porosity of less than 8%, but that the tops of the carbonate sequences on outcrop commonly have porosities that range from 10% to 40% in shoaling-upward packages that may have been diagenetically altered at or near sea level. In particular, Cook and Corboy (2004) noted that the upper part of the Silurian Laketown Dolomite near the Utah-Nevada border is karsted. Anna et al. (2007) indicate that the Joana, Guilmette, Sevy, and Simonson Formations have potential for similar early diagenetic porosity enhancement. Cook and Corboy (2004) state that the Guilmette Formation in the Confusion Range has no evidence of karsting; however, Hintze and Davis (2003) describe a thick section of the lowermost Guilmette as a “basal massive solution breccia.”

Potential Reservoir Seals

The Chainman Formation and Pilot Shale are known aquitards and confining beds in the Snake Valley area just west of the Confusion Range (Rowley et al., 2009). Either of these shaly units in contact, stratigraphically or structurally, with more permeable or porous intervals would likely form a competent seal for hydrocarbon entrapment. The Triassic Thaynes Formation is also a known aquitard (Rowley et al., 2009), of similar lithology to the Arapien Shale in the Hingeline area that seals in the Providence and Covenant fields.

In the Nevada oil fields, Tertiary valley fill and weathered volcanics are proven seals. As noted by Anna et al. (2007), though there are commonly shows in valley fill above the reservoirs, "the sealing capacity of the valley fill at Grant Canyon field must be efficient, considering the large volume of oil in place, the large oil column, and the strong water drive."

As summarized by Gabrielson (2010), any well-developed fault gouge zone typically occludes cross-fault fluid migration, but the damage zones on either side of the gouge zone include fracture systems that may easily transmit fluids. A fault without a well-developed gouge may admit significant cross-fault migration as well. Faults in the Nevada oil fields appear to seal best when they juxtapose Chainman or Pilot shales, valley fill, or non-welded volcanics against the reservoir rocks. The Hingeline accumulation with a fault seal, the Second Navajo at Providence field, also juxtaposes impermeable rocks across the fault.

Relative Timing of Structures and Hydrocarbon Migration

Burial history modeling of the Chainman Formation in central Nevada indicates the beginning of oil generation in the Middle Permian, reaching peak generation in the Early Jurassic (Anna et al., 2007, who incorporate prior workers' burial history results into their analysis). However, expulsion was far from complete, because mid-Mesozoic erosion and resultant cooling interrupted the process (Anna et al., 2007).

Anna et al. (2007) suggest that Chainman oil generated and expelled during the Permo-Triassic in central Nevada migrated to 1) lower Paleozoic rocks or Pennsylvanian-Permian carbonate rock reservoirs, 2) central Utah through regional rock conduits (presumably to updip pinchouts at the Hingeline), 3) the surface, or 4) some combination of these. Any Permo-Triassic generated Chainman oil trapped in western Utah is likely to have re-migrated during the Sevier orogeny, into thrust-related structural traps.

Blumstein et al. (2004) found that the Chainman Formation in western Millard County has a pre-folding chemical remanent magnetization Triassic-Jurassic event, indicating the beginning of oil migration. The Chainman at the surface in the Confusion Range also exhibits a post-folding chemical remanent magnetization overlapping the oil window, acquired in the Late Cretaceous to early Tertiary. Thrust loading is likely the origin of re-entry of the Chainman into the oil window in Late Cretaceous to Tertiary time in western Utah. The concurrent remanent magnetization event means that oil was migrating during and after formation of the Sevier fold-thrust traps and before Basin and Range extension. The cross sections suggest that the east side of the northern Confusion Range includes Chainman Formation that is still buried deeply enough by thrust loading to be in the generation window.

In Nevada, the late Tertiary reburial of the Chainman in some Neogene valleys has been deep enough to generate and expel remaining hydrocarbons (Anna et al., 2007). In western Millard County, the Pilot Shale and Chainman Formation are likely to have returned to the oil window by reburial in parts of the east side of Snake Valley, as suggested in cross sections A–A', B–B', and D–D'. However, these cross sections do not purport to resolve the controversy regarding the relationship of the Snake Range decollement to the subsurface of Snake Valley, and the locations of rock units beneath the valley is still conjectural.

Summary of Implications for Hydrocarbon Prospectivity

The presented fold-thrust model has a predictive value for finding subsurface structures, based on known surface constraints and several corroborating boreholes. The fold-thrust model includes a mechanism by which the source rocks of the Pilot Shale and Chainman Formation were returned to oil-window depths prior to Basin and Range extension, generating hydrocarbons to fill Sevier-age traps. The cross sections show trapping opportunities in multi-leveled Sevier structures and therefore potential for preserved fold-thrust trap oil fields in the Confusion Range. The cross sections suggest that the east side of Snake Valley is prospective for Basin and Range-age oil generation and extensional traps as well, but this is the least supported of the structural interpretations.

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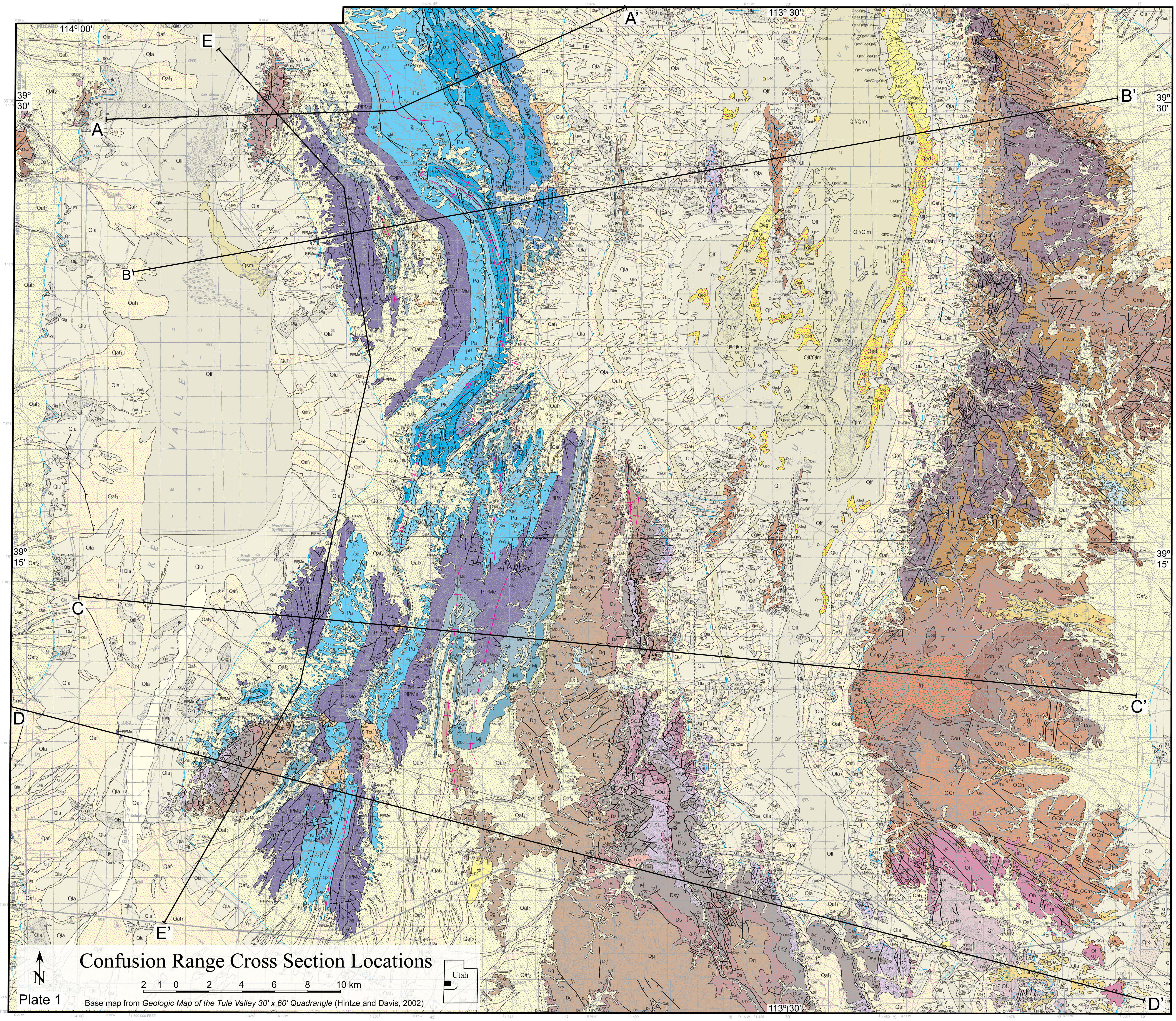
Confusion Range Cross Section Locations
Plate 1
Base map from Geologic Map of the Tule Valley 30' x 60' Quadrangle (Hintze and Davis, 2002)
Utah
N
2 1 0 2 4 6 8 10 km
114°00'
113°30'
39° 30'
39° 15'
A
A'
B
B'
C
C'
D
D'
E
E'

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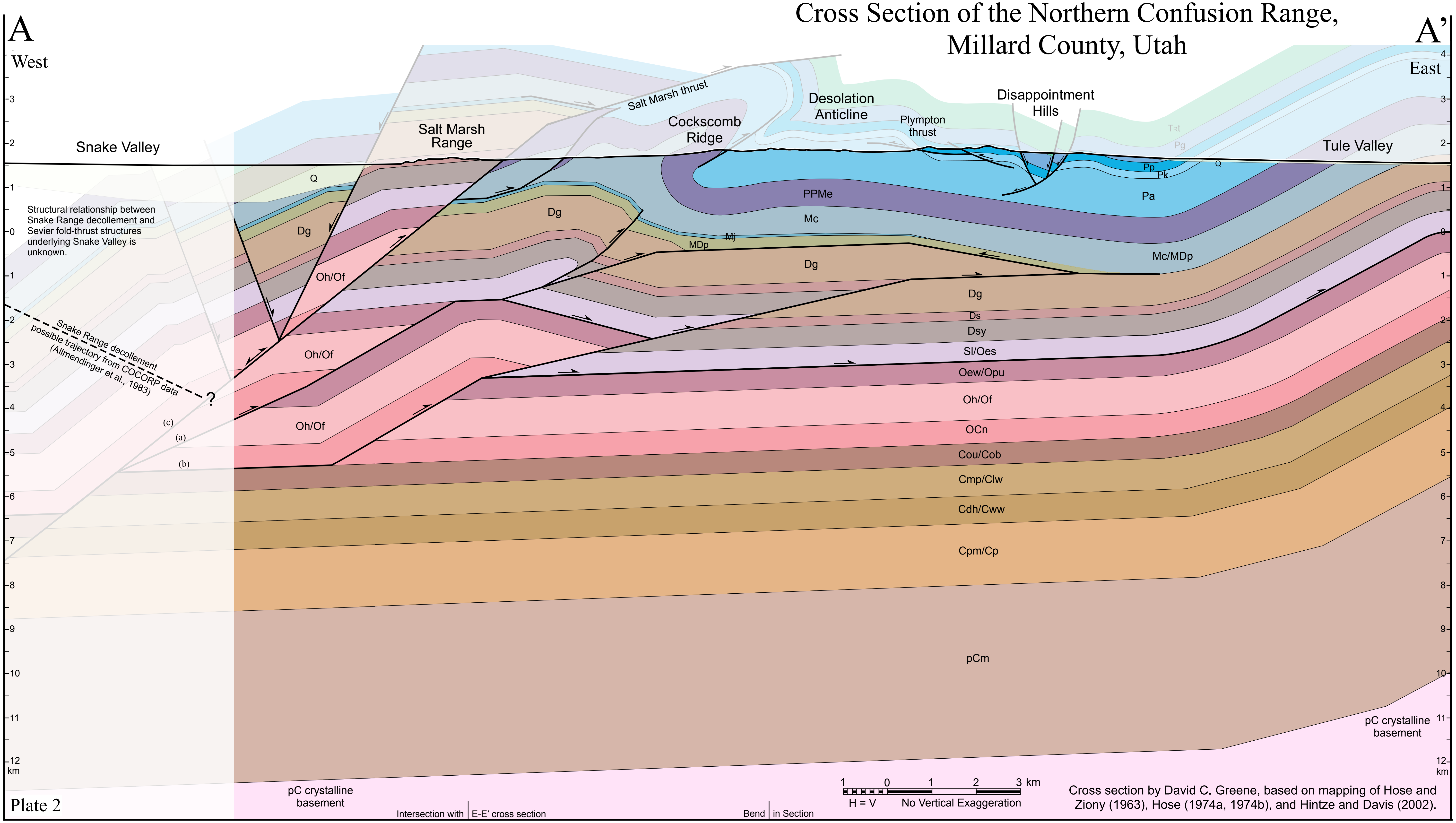
Cross Section of the Northern Confusion Range, Millard County, Utah



Cross section by David C. Greene, based on mapping of Hose and Ziony (1963), Hose (1974a, 1974b), and Hintze and Davis (2002).

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Cross Section of the North Central Confusion Range, Millard County, Utah

Cross Section of the South Central Confusion Range, Millard County, Utah

Cross section by David C. Greene, based in part on Yezerski and Greene (2009), and on mapping of Hose (1965b), Hintze (1974a, 1974b), and Hintze and Davis (2002). Subsurface structure under the House Range and Tule Valley after DeCelles and Coogan (2006).

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Cross Section of the Southern Confusion Range, Millard County, Utah

Cross section by David C. Greene, based in part on Yezerski and Greene (2009), and on mapping of Hose (1965a, 1965b), Hintze (1974), and Hintze and Davis (2002). Subsurface structure under the House Range and Tule Valley after DeCelles and Coogan (2006).

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Strike-Parallel Cross Section of the Western Confusion Range, Millard County, Utah

Cross section by David C. Greene, based on mapping of Hose (1965a, 1965b, 1974a), Hose and Ziony (1963, 1964), and Hintze and Davis (2002).