

# Folded and Faulted Salt Lake Formation Above the Miocene to Pliocene New Canyon and Clifton Detachment Faults, Malad and Bannock Ranges, Idaho: Field Trip Guide to the Deep Creek Half Graben and Environs

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## ABSTRACT

Previous studies identified a major detachment terrane in southeast Idaho in the Oxford Ridge area of the Bannock Range. This study shows that these top-to-the-WSW detachment faults are late Cenozoic in age, not Mesozoic to early Tertiary as previously inferred. Provenance and facies patterns in the Miocene-Pliocene Salt Lake Formation in the Deep Creek supradetachment basin show that deposition was syntectonic to slip on the detachment faults. The highly extended Bannock detachment terrane likely persists north to the Snake River Plain and south into Utah. The breakaway for this system lies in the Portneuf Range to the east. At least one and possibly three generations of normal faults postdate the large-magnitude extension along the Bannock detachment system. Extensional folds, including folds with vertical limbs, are plentiful within the hanging wall of the detachments and formed in association with each generation of normal faults. The modern Basin-and-Range extension in this area initiated in latest Cenozoic time.

## Regional tectonic Setting

Detachment faults (low-angle normal faults of regional extent) are important structural elements of the Basin-and-Range province because they accommodate large amounts of horizontal extension and have been active in the region since Cretaceous time (Wernicke, 1992; Hodges and Walker, 1992). In southern Idaho and northern Utah, detachment faults are early to mid-Tertiary in age, and bound metamorphic core complexes and adjacent areas of the Basin-and-Range province (Axen et al., 1993; Wernicke, 1992; Constenius, 1996; Stewart, 1998). Late Miocene to Recent detachment faults (10 Ma to present) are rare in the western United States and have been reported only in the greater

Death Valley area (Holm et al., 1992; Burchfiel et al., 1987), adjacent to the Gulf of California (Axen and Fletcher, 1998), the Sevier Desert region (Allmendinger et al., 1983; Coogan and DeCelles, 1996), the Walker Lane, and in the Raft River Range of northwest Utah (Covington, 1983; Compton, 1983; Todd, 1983; Stewart, 1998).

The apparent change from large magnitude extension along early to mid Tertiary detachment faults to lower magnitude extension accommodated by spaced, moderately dipping, planar to listric "Basin-and-Range" normal faults has long been interpreted as a fundamental tectonic transition in the western United States, and has motivated many two-phase models of extension in the Basin-and-Range province (Axen et al., 1993; Wernicke, 1992; Constenius, 1996; Stewart, 1998). The specifics of the time-space patterns of this transition, and therefore its ultimate cause, have been controversial, but no workers have argued for large magnitude extension in southeast Idaho after 27 Ma.

Stewart (1998) analyzed the entire Basin-and-Range province including large parts of Mexico and southern Canada, and found that both large-magnitude and younger Basin-and-Range extension youngs generally WSW-ward over time. Constenius (1996) studied two rift basins within the Sevier fold and thrust belt, in a setting similar to that of our present study area, and found evidence for major backsliding along thrust faults beginning after the end of Sevier contraction in Eocene time. He inferred that the same pattern characterized the rest of the province. The presence in the Oxford Ridge area of the Bannock Range, southeast Idaho, of late Miocene to Pliocene detachment faults is not predicted by any existing tectonic model and significantly expands the area affected by large magnitude extension in the late Cenozoic. If, as we show here, large magnitude extension along detachment faults continued into the late Cenozoic in the northeastern Basin-and-

Range province, then the timing and cause of this tectonic transition must be reconsidered.

In this field trip we will visit the deformed basin-fill deposits in the hanging wall of the Bannock detachment, explore the stratigraphic and structural evidence for a late Cenozoic age of the large-magnitude extension, and review evidence for a very recent (possibly <5 Ma) transition to modern Basin-and-Range extension. The field trip guide is written to accommodate a visit during the summer months when side roads are dry and passable.

## INTRODUCTION TO THE GREATER CACHE VALLEY AREA

This field guide begins in the northern end of Cache Valley, southeast Idaho, and then examines relationships within the Oxford Ridge segment of the Bannock Range and the Malad Range along the northwest flank of Cache Valley. The northernmost segments of the Wasatch normal faults bound the study area on the west, along the west flank of the Malad Range (Fig. 1). Marsh Valley, a Basin-and-Range rift basin, lies north of the study area, and the southern end of the Portneuf Range bounds the area on the east. The Bear River Range comprises most of the eastern margin of Cache Valley (Fig. 1). Highlands on the west side of Cache Valley are discontinuous and consist of several mountain ranges separated by passes and intermontane valleys (Fig. 1).

Previous mapping (Prammani, 1957; Murdock, 1961; Axtell, 1967; Wach, 1967; Raymond, 1971; Willard, 1972; Burton, 1973; Gray, 1975; Shearer, 1975; Mayer, 1979; Oriel and Platt, 1980; Danzl, 1982; Link, 1982a and b; Sacks and Platt, 1985; Green, 1986; Platt and Royse, 1989; Brummer, 1991; Brummer and McCalpin, 1995; Oaks and Runnells, 1991; Dover, 1995; Evans and Oaks, 1996; Smith, 1997; S. S. Oriel, unpublished mapping) in the greater Cache Valley region and our ongoing field studies show that several generations ( $\geq 2$ ) of normal faults extended the Cache Valley region during the Cenozoic. The presently active range-bounding normal faults (Fig. 1) are here termed "active Basin-and-Range normal faults." The majority of the active Basin-and-Range faults strike north to north-northwest and dip west or east, but other strike directions are also present. Figure 1 also shows some WSW-dipping normal faults on the northeast side of Cache Valley that probably formed as Miocene-Pliocene normal faults but might be active Basin-and-Range faults. At present we lump all the older normal faults into a single group of "Miocene-Pliocene normal faults" even though these clearly include more than one generation of normal faults (cf., Link, 1982a and b, and stop 3). WSW-dipping detachment faults are the primary Miocene-Pliocene structures. The details of the relative and absolute timing of major movement on each geometric set of normal faults are the subject of ongoing research, and this paper summarizes our findings following two years of field studies.

The paper first describes the neotectonics and general geology of the northern end of Cache Valley. Our focus then shifts to our primary interest; the Miocene-Pliocene normal faults that were partially exhumed by the active Basin-and-Range extension. We will discuss the overall geometry of the Miocene-Pliocene detachment faults, the new evidence for a late Cenozoic age, and then visit exposures of Miocene to Pliocene basin-fill deposits in the hanging wall of the detachment faults to examine folds and

faults associated with this episode of extension. Facies patterns in the basin-fill deposits and provenance data relate the Salt Lake Formation to the normal faults.

## STRUCTURAL GEOLOGY

### Physiography and Neotectonics of Cache Valley

Cache Valley is 110 km long north-south and 35 km wide at its widest, and has the shape, in plan view, of a very elongate, distorted north-south trending diamond (Fig. 1). The present physiography of Cache Valley is the result of both active Basin-and-Range normal faulting and the Miocene-Pliocene extension. The valley lies within the seismic and topographic parabola that is centered on the Yellowstone hotspot and east of the Wasatch normal fault (Anders et al., 1989; Piety et al., 1992) (Fig. 1).

The Cache Valley rift basin changes symmetry from a dominantly east-tilted half graben in the south to a dominantly west-tilted half graben in the north. Reflection seismic data and geologic mapping show that the listric East Cache fault is the dominant structure in the southern portion of Cache Valley, south of Hyrum, Utah (Evans and Oaks, 1996; Smith, 1997). Northward the West Cache fault zone becomes an increasingly important structure within the valley. In northernmost Cache Valley (around stop 1) the Oxford-Dayton normal fault on the west side of the valley is clearly the master fault of the active Basin-and-Range fault system. The change in symmetry of Cache Valley from an east-tilted to a west-tilted half graben occurs over a broad north-south zone centered roughly on the Utah-Idaho border (Fig. 1) (Peterson and Oriel, 1970; Evans and Oaks, 1996). The Oxford-Dayton normal fault forms a right en echelon step with the Clarkston Mountain segment of the West Cache fault zone at its southern end (Fig. 1) and has been included in (Link, 1982a and b), and excluded from (Solomon, 1997; Black, 1998), the West Cache fault zone by various researchers.

Neotectonic studies of the range-bounding normal faults in Utah show that Cache Valley has been the site of several large ( $M > 6$ ) earthquakes during the Holocene (Oviatt, 1986a and b; McCalpin, 1994; McCalpin and Forman, 1991; Evans and Oaks, 1996; Black, 1998; Black et al., 1998). The paleoseismic histories of the along-strike portions of these faults in Idaho are poorly known. The most recent surface rupture on the East Cache fault along its most active central segment near Logan, Utah occurred about 4 ka (McCalpin, 1994). The West Cache fault zone, at the base of the Wellsville Mountains, east of the low-lying Junction Hills, and east of Clarkston Mountain, was also active in the Holocene after the withdrawal of Lake Bonneville from Cache Valley. Trenching and natural exposures of the three faults of the West Cache fault zone show surface ruptures at  $4.6 \pm 0.2$  ka,  $8.45 \pm 0.2$  ka, and  $3.8 \pm 0.2$  ka, from south to north (Black, 1998; Black et al., 1998). The morphology of the northern half of the Oxford-Dayton normal fault, on the west flank of Cache Valley, is suggestive of Holocene or latest Pleistocene surface ruptures, but neotectonic studies are needed to test this hypothesis.

The northeast margin of Cache Valley is marked by a series of low rolling foothills at the southern end of the Portneuf Range and the western edge of the Bear River Range. These foothills consist of generally east- to northeast-dipping Miocene-Pliocene Salt Lake Formation overlying Cambrian to Ordovician carbon-

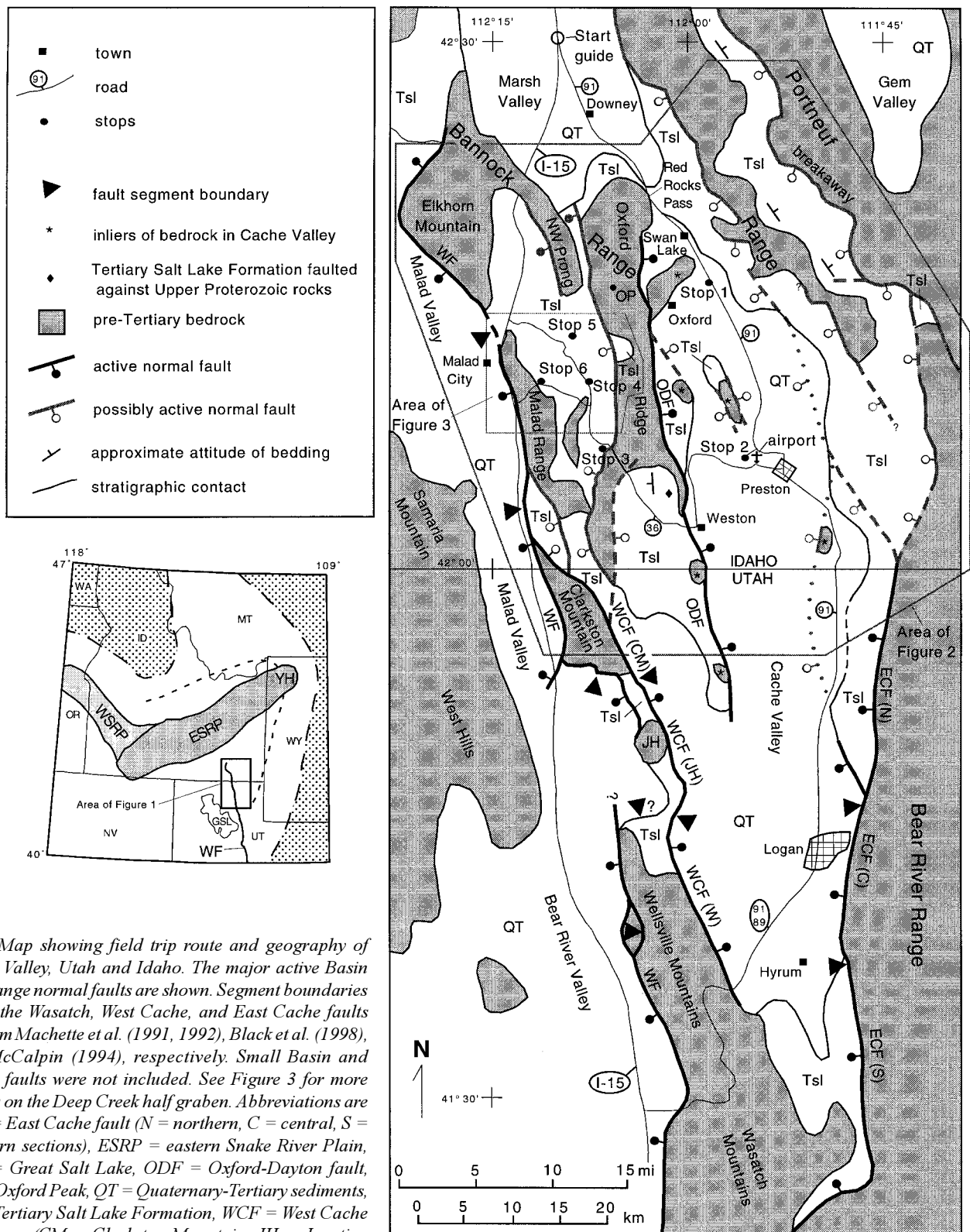


Figure 1. Map showing field trip route and geography of Cache Valley, Utah and Idaho. The major active Basin and Range normal faults are shown. Segment boundaries along the Wasatch, West Cache, and East Cache faults are from Machette et al. (1991, 1992), Black et al. (1998), and McCalpin (1994), respectively. Small Basin and Range faults were not included. See Figure 3 for more details on the Deep Creek half graben. Abbreviations are ECF = East Cache fault (N = northern, C = central, S = southern sections), ESRP = eastern Snake River Plain, GSL = Great Salt Lake, ODF = Oxford-Dayton fault, OP = Oxford Peak, QT = Quaternary-Tertiary sediments, Tsl = Tertiary Salt Lake Formation, WCF = West Cache fault zone (CM = Clarkston Mountain, JH = Junction Hills, W = Wellsville faults), WF = Wasatch fault, WSRP = western Snake River Plain, YH = current location of the Yellowstone Hotspot. Stippled areas on regional map denote regions outside of the Basin and Range province.

ate rocks that are faulted on Neoproterozoic to Cambrian quartzite of the Brigham Group along west- to southwest-dipping normal faults (Willard, 1972; Oriel and Platt, 1980; Danzl, 1982; Sacks and Platt, 1985). The subdued topographic expression of these faults, and growth strata within the Salt Lake Formation, suggest that the faults are inactive Miocene-Pliocene normal faults that flatten at a shallow depth (Sacks and Platt, 1985). Because Oriel and Platt (1980) show these faults as continuous with the East Cache fault zone to the south, they might also be part of the Basin-and-Range fault system. Extensional folds, including a large roll-over anticline northeast of Preston, Idaho (Willard, 1972; Oriel and Platt, 1968; S.U. Janecke, unpublished mapping), and ENE-plunging synclines and anticlines, deform the Miocene-Pliocene Salt Lake Formation and complicate the east-tilted half graben along the northeast flank of Cache Valley (Sacks and Platt, 1985).

### Older Structures

The active Basin-and-Range normal faults are superimposed on an older system of generally WSW-dipping detachment faults here named the Bannock detachment system for the mountain range in which the faults are best developed (Fig. 2). Cross-cutting relationships between the two systems of normal faults are best developed at Oxford Ridge (stop 1). Portions of the detachment faults in the Oxford Ridge area of the southern Bannock Range were first mapped by Raymond (1971), Shearer (1975), and Mayer (1979) as younger-on-older thrust faults. Unpublished and incomplete mapping of these detachment faults in the Clifton 7.5 minute quadrangle by Steven Oriel provided the first detailed map of the southern half of the detachment system and reaffirmed the contractional origin of these structures (Oriel and Platt, 1979; Allmendinger et al., 1979). Link (1982a and b) was the first to interpret the "thrusts" as low-angle normal faults, based on extensive new mapping in the northern Oxford Ridge area, north of our present study area, but inferred an early Tertiary to Mesozoic age because he mapped the Miocene-Pliocene Salt Lake Formation as lapping across the faults. Our current understanding of these detachment faults builds upon this previous work, especially the mapping by Link (1982a) and the unpublished mapping by Steven Oriel in the Clifton and Malad City East quadrangles.

New mapping and analysis of the Tertiary deposits of the Deep Creek half graben in the hanging wall of the Bannock detachment system (Figs. 3 and 4), regional compilation and synthesis of existing geologic maps, extensive aerial photographic mapping, and reconnaissance around the region show that the Bannock detachment system accommodated large amounts of top-to-the-WSW extension during late Cenozoic time. Two detachment faults, the New Canyon and underlying Clifton detachment faults, are the main faults within this system (Link, 1982a and b), but structurally higher low-angle normal faults that place the Miocene-Pliocene Salt Lake Formation on older rocks also form part of this fault system (Fig. 3).

The New Canyon fault places Ordovician and Cambrian carbonate rocks on quartzites of the Neoproterozoic to Cambrian Brigham Group, whereas the Clifton fault places the Brigham Group on metasedimentary and metavolcanic rocks of the Neoproterozoic Pocatello Formation (Fig. 3) (Raymond, 1971; Shearer, 1975; Mayer, 1979; Oriel and Platt, 1979; Link, 1982a

and b). Locally, the New Canyon detachment fault cuts out the underlying Clifton detachment fault, and places lower Paleozoic carbonate rocks directly on the metamorphic rocks of the Pocatello Formation (Oriel and Platt, 1979; Link, 1982a and b). The detachment faults dip gently WSW in most of the area, but the pattern is quite complex in detail and includes folded segments along the east side of the Deep Creek half graben (Fig. 4b).

The detachment faults are major structures that eliminate up to 2700 m of stratigraphic section, crop out over tens of kilometers, and coincide with a major metamorphic discontinuity (Raymond, 1971; Oriel and Platt, 1979; Link, 1982a and b). The Pocatello Formation in the footwall of the Clifton detachment fault is sheared, lineated, and metamorphosed to lower greenschist grade (Fig. 5) (Oriel and Platt, 1979; Link, 1982a and b; S.U. Janecke, unpublished data). It is not clear whether the shearing and deformation is due to Mesozoic to early Tertiary contraction and/or to the late Cenozoic extension. The persistent east-northeast trend of the stretching and mineral lineation within an area east of Oxford Peak is consistent with either interpretation (Fig. 5).

Our new mapping shows that the Clifton and New Canyon detachments cut the Miocene-Pliocene Salt Lake Formation, and are therefore anomalously young structures for this part of the Basin-and-Range province (Figs. 1 and 3). We have identified several areas where the Clifton or New Canyon detachment faults cut the Salt Lake Formation, including the east side of Clifton basin (Clifton detachment fault), in the upper reaches of Fivemile Canyon (Clifton and New Canyon detachment faults), along the north side of Mine Hollow on the east side of the Deep Creek half graben (Clifton and New Canyon detachment faults), and along the crest of Oxford Ridge (Clifton and New Canyon detachment faults) (Figs. 1 and 3). We could not confirm previous mapping that showed the Salt Lake Formation as depositional on the Pocatello Formation (Link, 1982a & b; Oriel and Platt, 1980), and find instead that the Salt Lake Formation overlies Cambrian to Silurian carbonate rocks throughout most of this region. The only major exception to this rule may be in the incompletely mapped southern part of Oxford Ridge, where the little known Weston Canyon thrust of Murdock (1961) places Neoproterozoic to Cambrian Brigham Group rocks over Cambrian carbonate rocks (see stop 3). There, the Salt Lake Formation locally lies in depositional contact on the Brigham Group (S.S. Oriel, S.U. Janecke, unpublished mapping). Additional field checking is needed to fully test our working hypothesis that the basal units of the Salt Lake Formation were deposited on lower Paleozoic rocks prior to any significant extension of the region.

The Bannock detachment system is coeval to younger than the Salt Lake Formation, and older than the superimposed Basin-and-Range normal faults. A new  $^{40}\text{Ar}/^{39}\text{Ar}$  age determination within the Deep Creek basin constrains the age of the Salt Lake Formation in the hanging wall of the Bannock detachment system. Single crystal laser fusion data on sanidine from a biotite-bearing rhyolite tuff near the base of the Cache Valley member of the Salt Lake Formation yielded an age of  $10.27 \pm 0.07$  Ma (Table 1, Fig. 6). This age confirms our lithologic correlation of the biotite-bearing rhyolite tuff with the 10.2 to 10.3 Ma tuff of Arbon Valley (Kellogg et al., 1994), and provides a valuable chronostratigraphic marker in the west-central part of the basin.

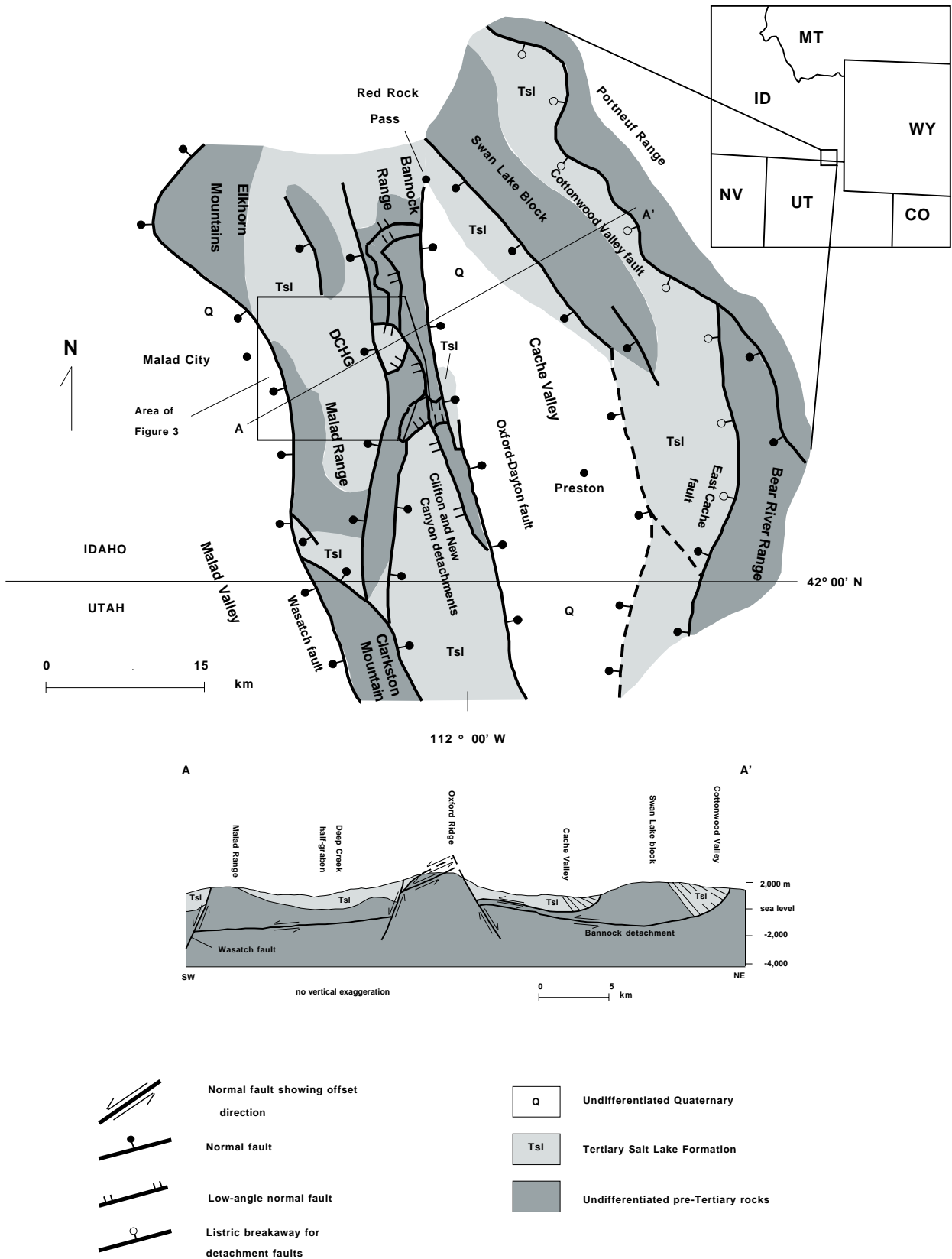


Figure 2. Simplified map showing the generalized geology and cross-section of the northern Cache Valley region. The cross-section illustrates the working hypothesis of this research. DCHG = Deep Creek half graben.

**Table 1.**  $^{40}\text{Ar}/^{39}\text{Ar}$  analytical data from single-crystal laser-fusion of sanidine crystals.

ID	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ ( $\times 10^{-3}$ )	$^{39}\text{ArK}$ ( $\times 10^{-15}$ mol)	K/Ca	% $^{40}\text{Ar}^*$	Age (Ma)	$\pm 2s$ (Ma)
<b>98-207, <math>J=0.000794852\pm 0.10\%</math>, Irradiation NM-92, Lab#=9401</b>								
13	7.095	0.0109	0.0532	3.02	46.8	99.8	10.12	0.14
08	7.205	0.0089	0.4056	3.42	57.4	98.3	10.13	0.11
11	7.208	0.0101	0.3489	3.67	50.7	98.6	10.16	0.11
05	7.204	0.0107	0.1620	4.09	47.5	99.3	10.23	0.10
01	7.219	0.0124	0.1953	7.75	41.0	99.2	10.24	0.07
14	7.208	0.0110	0.1406	2.23	46.3	99.4	10.25	0.20
04	7.254	0.0104	0.1951	4.98	49.0	99.2	10.29	0.09
03	7.346	0.0102	0.4727	4.59	50.0	98.1	10.31	0.10
12	7.358	0.0068	0.3429	1.64	75.0	98.6	10.38	0.26
15	7.399	0.0120	0.4450	5.44	42.5	98.2	10.39	0.10
09	7.434	0.0107	0.4962	3.77	47.5	98.0	10.42	0.11
02	7.414	0.0066	0.2009	1.30	77.3	99.2	10.52	0.33
<b>weighted mean</b>			n=12		52.6 $\pm$ 11.7		10.27	0.07

**Notes:** Each data line represents a laser-fusion analysis of a single sanidine crystal. Measured isotopic ratios are corrected for blank, radioactive decay, and mass discrimination, but not corrected for interfering reactions.  $^{39}\text{ArK}$  = number of moles of  $^{39}\text{Ar}$  produced from neutron irradiation of K. % $^{40}\text{Ar}^*$  = percentage of radiogenically derived  $^{40}\text{Ar}$  (non-atmospheric). K/Ca = molar ratio calculated from  $^{39}\text{ArK}$  and  $^{37}\text{ArCa}$ . Age errors for individual analyses show analytical error only. Weighted mean line shows n = number of individual crystal analyses used in mean, mean K/Ca value  $\pm 2s$ , and weighted mean age  $\pm 2s$ , calculated by inverse variance weighting (Samson and Alexander, 1987). Mean age errors include errors in J and irradiation parameters. Decay constant and isotopic abundances after Steiger and Jaeger (1977).

**Sample preparation and irradiation:** Sanidine separated by crushing, LST heavy liquid, Franz, HF, then irradiated in machined Al discs for 7 hours in the D-3 position, Nuclear Science Center, College Station, TX. Neutron flux monitored by interlaboratory standard Fish Canyon Tuff sanidine FC-1 with an assigned age of 27.84 Ma (Deino and Potts, 1990), relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987).

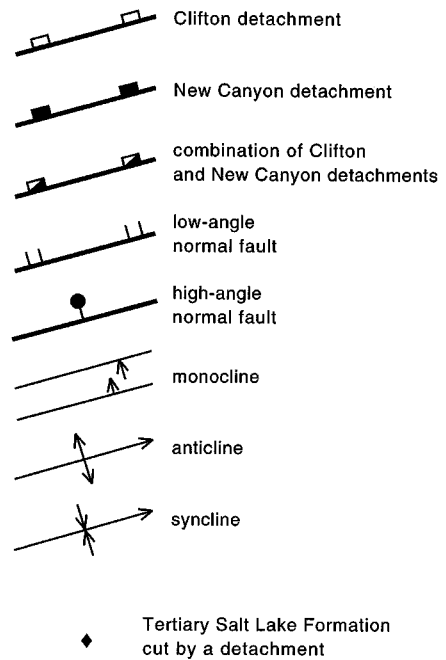
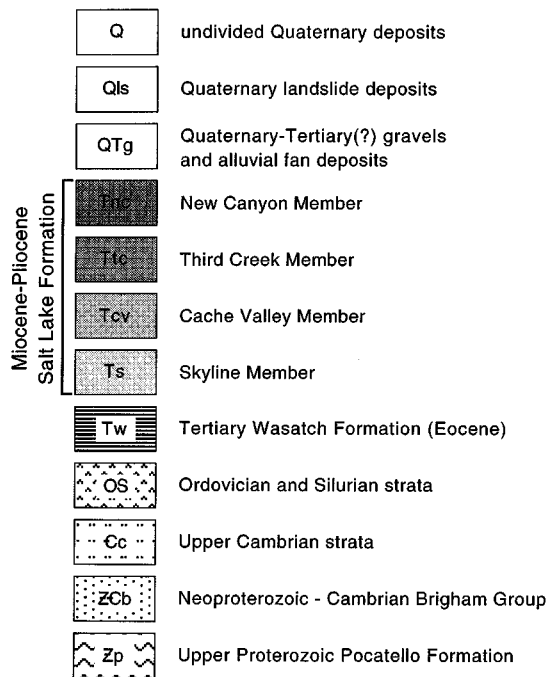
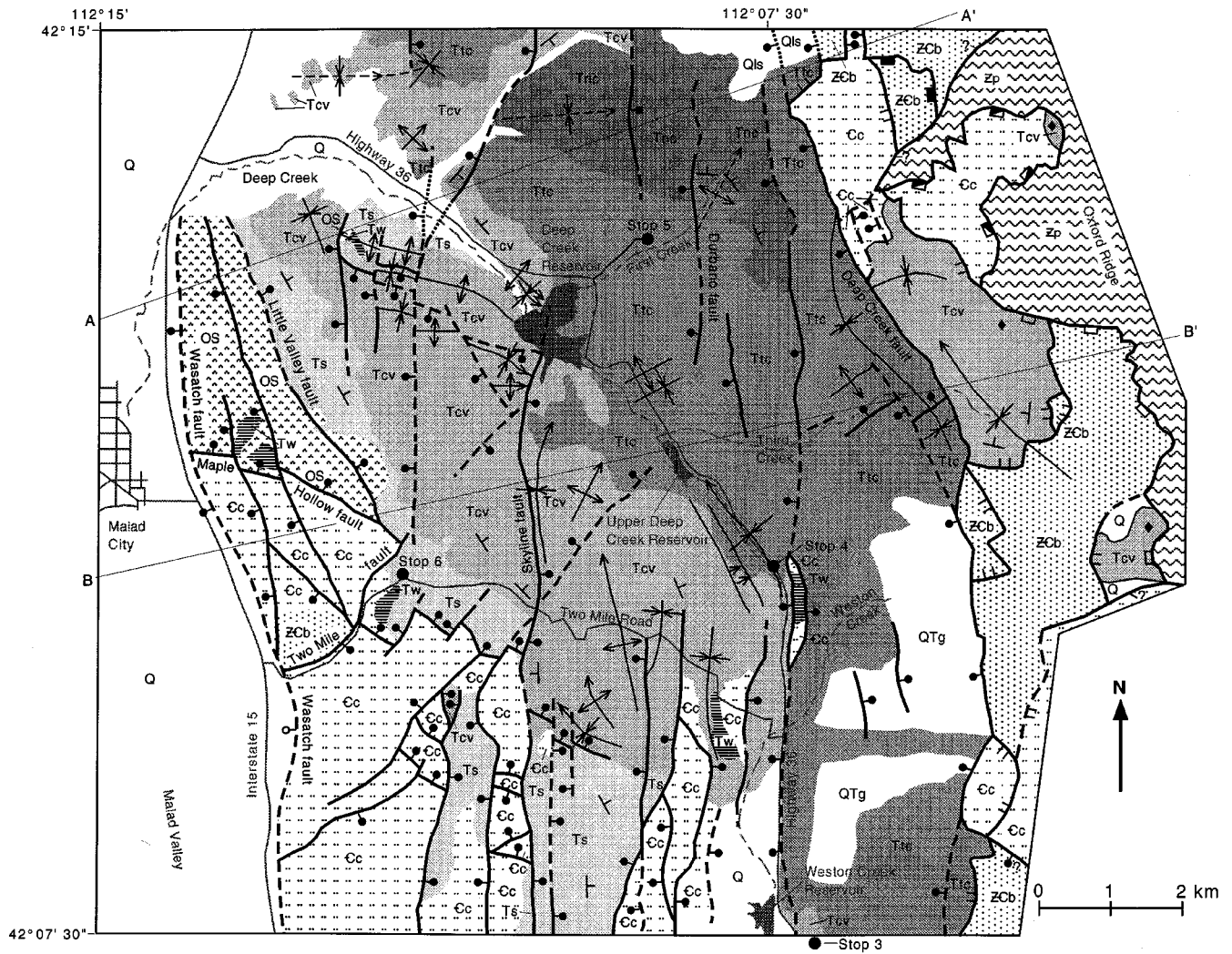
**Instrumentation:** Mass Analyzer Products 215-50 mass spectrometer on line with automated, all-metal extraction system at New Mexico Geochronology Research Laboratory, Socorro. Individual sanidine crystals were fused in vacuo by a 10W continuous  $\text{CO}_2$  laser. Reactive gasses removed for 1 to 2 minutes by SAES GP-50 getters operated at  $20^\circ\text{C}$  and  $\sim 450^\circ\text{C}$ .

**Analytical parameters:** Electron multiplier sensitivity =  $6 \times 10^{-17}$  moles/pA; average system blanks = 300, 3, 0.6,  $1.2, 1.2 \times 10^{-18}$  moles at masses 40, 39, 38, 37, 36 respectively. J-factors determined to a precision of  $\pm 0.2\%$  by  $\text{CO}_2$  laser-fusion of 4 to 6 single crystals from each of 4 radial positions around irradiation vessel. Correction factors for interfering nuclear reactions, determined using K-glass and  $\text{CaF}_2$ , ( $^{40}\text{Ar}/^{39}\text{Ar}$ )K =  $0.00020 \pm 0.0003$ ; ( $^{36}\text{Ar}/^{37}\text{Ar}$ )Ca =  $0.00026 \pm 0.00002$ ; and ( $^{39}\text{Ar}/^{37}\text{Ar}$ )Ca =  $0.00070 \pm 0.00005$ .

A 10.27 Ma age from the lower part of the Salt Lake Formation (Late Miocene) is consistent with recent studies of lithologically similar units of the Salt Lake Formation 35-80 km to the south. There, dozens of tephra correlations show that the Salt Lake Formation has an age span from about 11-12 Ma to 5 Ma and younger (Smith and Nash, 1976; Smith, 1997; Smith et al., 1997a and b; Perkins, et al., 1998; Goessel, in press). The oldest and youngest parts of the Salt Lake Formation are undated. If the age of the Salt Lake Formation in the greater Oxford Ridge area is similar, then detachment faulting continued into the Pliocene, and active Basin-and-Range normal faults are only a few million years old. Chemical fingerprinting of tephras collected throughout the Salt Lake Formation in the Deep Creek half graben is



Figure 3. Simplified geologic map of the Deep Creek study area showing the field trip route and location of major faults, folds, and distribution of members of the Salt Lake Formation. Compiled from unpublished mapping by J.C. Evans, S.S. Oriel, and S.U. Janecke.



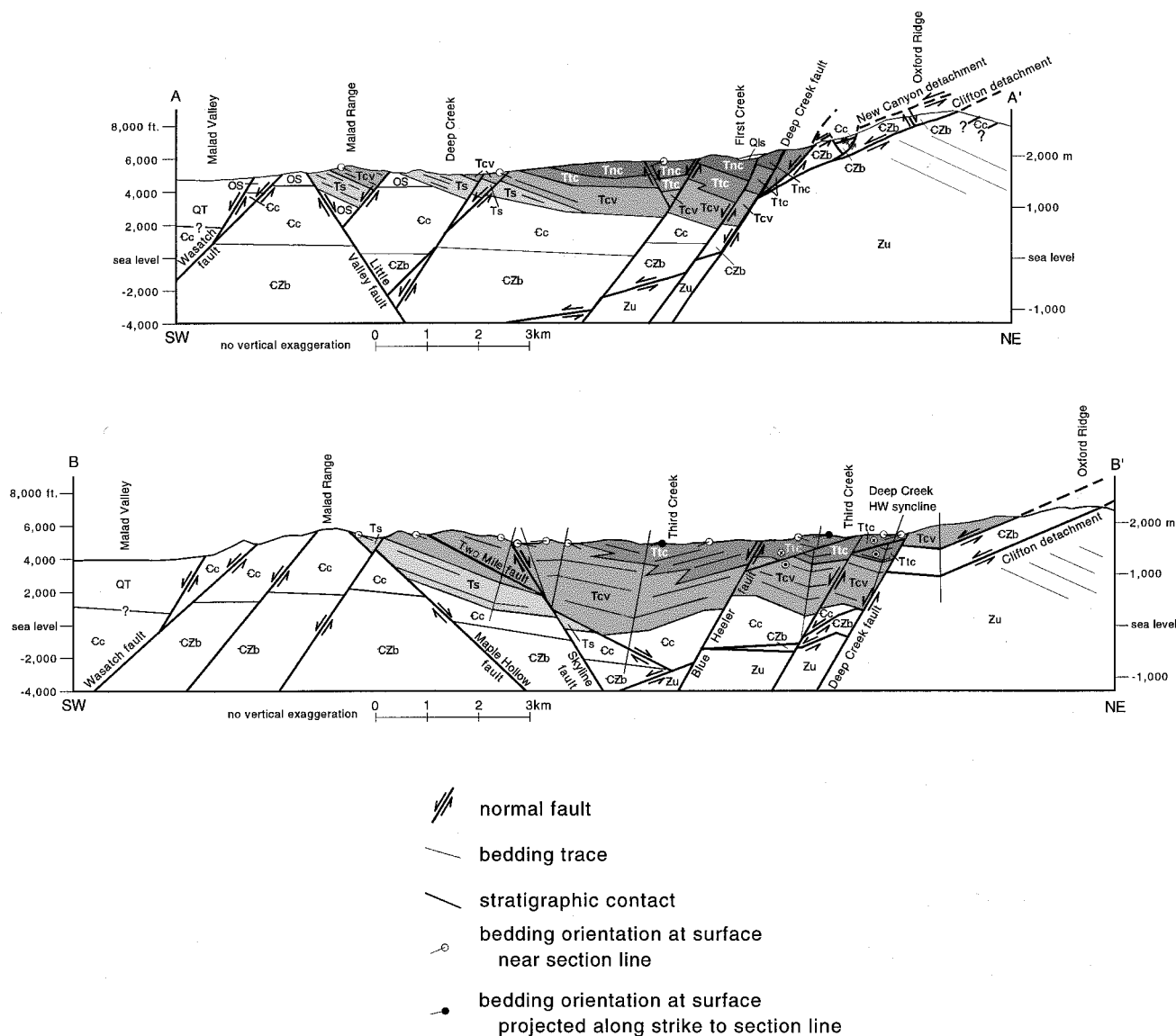


Figure 4. Simplified cross-sections through the Deep Creek study area. Lines of section are shown on Figure 3.

planned and should clarify the age of the deformation.

The Bannock detachment system is exposed over a north-south distance of >30 km in the Oxford Ridge area (Raymond, 1971; Murdock, 1961; Link, 1982a and b; S.S. Oriel and S.U. Janecke, unpublished mapping) but probably underlies most of northern Cache Valley, continues south in the footwall of the Oxford-Dayton fault at least to the Utah-Idaho border, and as far east as the southern Portneuf Range and foothills of the Bear River Range (Fig. 2). The shallow depth of bedrock within the northern part of Cache Valley inferred from gravity data (Peterson and Oriel, 1970; Zoback, 1983), and the numerous horst blocks of pre-Tertiary rocks within the northern part of Cache Valley, are consistent with the detachment fault system underlying the northern two-thirds of the region in Fig. 1.

The Bannock detachment system can be traced discontinuously north all the way to the eastern Snake River Plain where gently west-dipping normal fault(s) disrupt the Putnam thrust sheet and have steeply east-dipping Miocene to Pliocene volcanic and sedimentary rocks of the Starlight Formation in their hanging wall

near Pocatello (Trimble, 1976; Link et al., 1985b; Kellogg et al., 1989; Kellogg, 1990, 1992; Platt, 1995; 1998; Kellogg et al., this volume). West of Marsh Valley, low-angle normal faults that place the Salt Lake Formation and Ordovician rocks on Upper Proterozoic rocks north of Hawkins Creek (Platt, 1985), and Cambrian carbonate rocks on the Brigham Group along Mink Creek (Platt, 1995) are also part of this regional fault system. The breakaway fault in the southern Portneuf Range (Valley fault of Sacks and Platt, 1985) appears to continue north at least to the latitude of South Putnam Mountain (Rember and Bennett, 1979; Kellogg, 1992). Sacks and Platt (1985) suggested that the detachment system might extend as far south as Huntsville, Utah, about 100 km to the south, based on mapping by Crittenden (1972). If the working hypothesis of this research is confirmed, namely, that the Bannock detachment system of Late Cenozoic age accommodated large amounts of extension and underlies this entire region, then this structure rivals the Sevier Desert detachment in scale and significance.



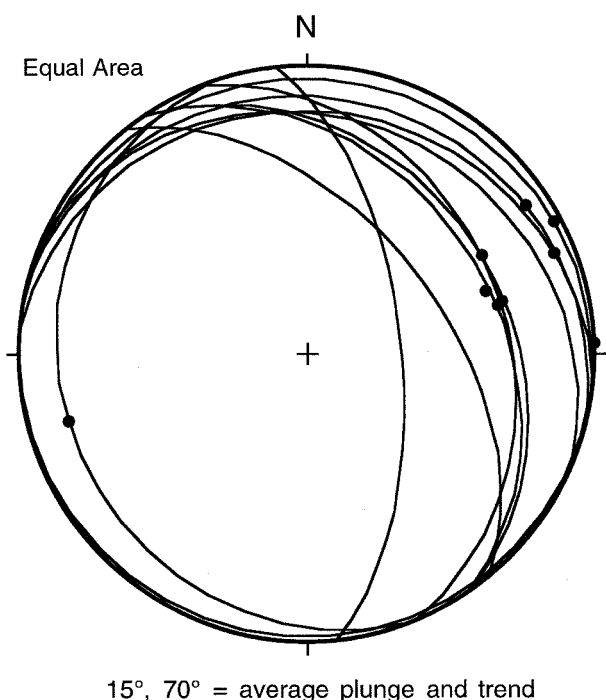


Figure 5. Stereogram of foliations (great circles) and lineations (dots) within the Pocatello Formation east of Oxford Peak. The lineations could record either Sevier shortening or Miocene-Pliocene extension.

## Folds

Extensional folds deform the Salt Lake Formation in the greater Cache Valley region at both the outcrop and map scale. A partial inventory, based on both previous mapping and new field studies revealed more than 40 well-documented extensional folds in all eight sub-basins of the Cache Valley rift basin (Willard, 1972; Sacks and Platt, 1985; Smith et al., 1994; Smith, 1997; Smith et al., 1997b; Evans and Janecke, 1998; R.Q. Oaks Jr., K. Goessel, M. Swenson, J.C. Evans and S.U. Janecke unpublished data). The axes of most of these folds parallel the associated normal faults and are therefore longitudinal folds according to the classification system of extensional folds (Schlische, 1995; Janecke et al., 1998) but transverse folds, at a high angle, and oblique folds, at an intermediate angle to the normal faults, are also common. Most of the folds are gentle but vertical to overturned beds mark the limbs of some of the folds (see stops 3 and 4).

## STRATIGRAPHY

Neoproterozoic to Paleozoic rocks in the study area are overlain by the Eocene Wasatch Formation and the Miocene to Pliocene Salt Lake Formation. Erosional remnants of younger alluvial fan deposits cap some high surfaces, and lacustrine deposits of Lake Bonneville cover most low areas.

Pre-Tertiary units exposed in the study area are Neoproterozoic through Silurian sedimentary and metasedimentary rocks. We have divided them into four groups in the figures. These include (Fig. 7): 1) Neoproterozoic Pocatello Formation, 2) Neoproterozoic-Cambrian Brigham Group 3) Cambrian carbonate rocks, and 4) Ordovician-Silurian rocks. The Pocatello Formation consists of

metagraywacke and metadiamicrites of the Scout Mountain member and metabasalts and metavolcaniclastic rocks of the Bannock Volcanic member (Link, 1982a and b). The Brigham Group contains over 2 km of quartzites, pebbly quartzites, sandstones, and argillites comprising nine formations. The Camelback Mountain Quartzite and Mutual Formation are the two formations of the Brigham Group present within the study area in Fig. 3. The Cambrian carbonate rocks include limestones and dolostones of the St. Charles (including sandstones of the Worm Creek Member), and limestones and dolostones of the Nounan, Bloomington, and Blacksmith formations. The Ordovician-Silurian formations contain limestones, dolomites, and quartzites of the Silurian Laketown Formation, and Ordovician Fish Haven, Swan Peak (quartzite), and Garden City formations. Coarse debris derived from the Pocatello Formation (group 1), the Brigham Group (group 2) and the Paleozoic carbonate rocks (groups 3 and 4) are easy to distinguish within conglomerates of the Tertiary Salt Lake Formation.

Eocene Wasatch Formation is exposed along the western edge of the Deep Creek half graben and in isolated fault-blocks in the basin. This unit is a synorogenic deposit of the Sevier fold and thrust belt (Coogan, 1992; Oaks and Runnells, 1991) and had been mapped previously in scattered small exposures in the western part of the Deep Creek half graben (Axtell, 1967; Wach, 1967).

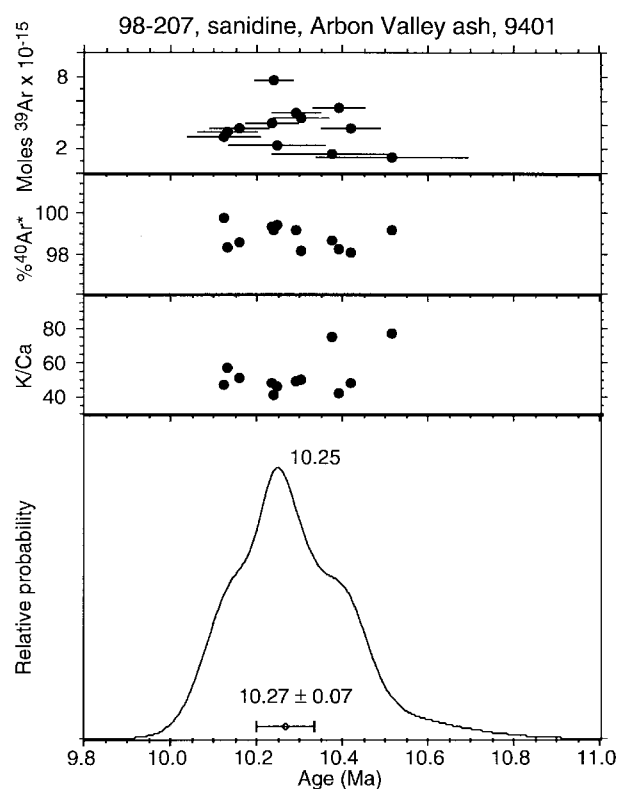


Figure 6. Age-probability distribution diagram (Deino and Potts, 1990) of single-crystal laser-fusion analyses of sanidine crystals from ash low in the Cache Valley member of the Salt Lake Formation (lower panel). The age and K/Ca ratio shows that this tuff is correlative with tuff of Arbon Valley. Upper panels are auxiliary plots showing moles of K-derived  $^{39}\text{Ar}$ , percent radiogenic yield, and K/Ca ratios. Upper panel also shows 1 sigma analytical uncertainty for each crystal. Lower panel shows weighted mean age and 2 sigma uncertainty.

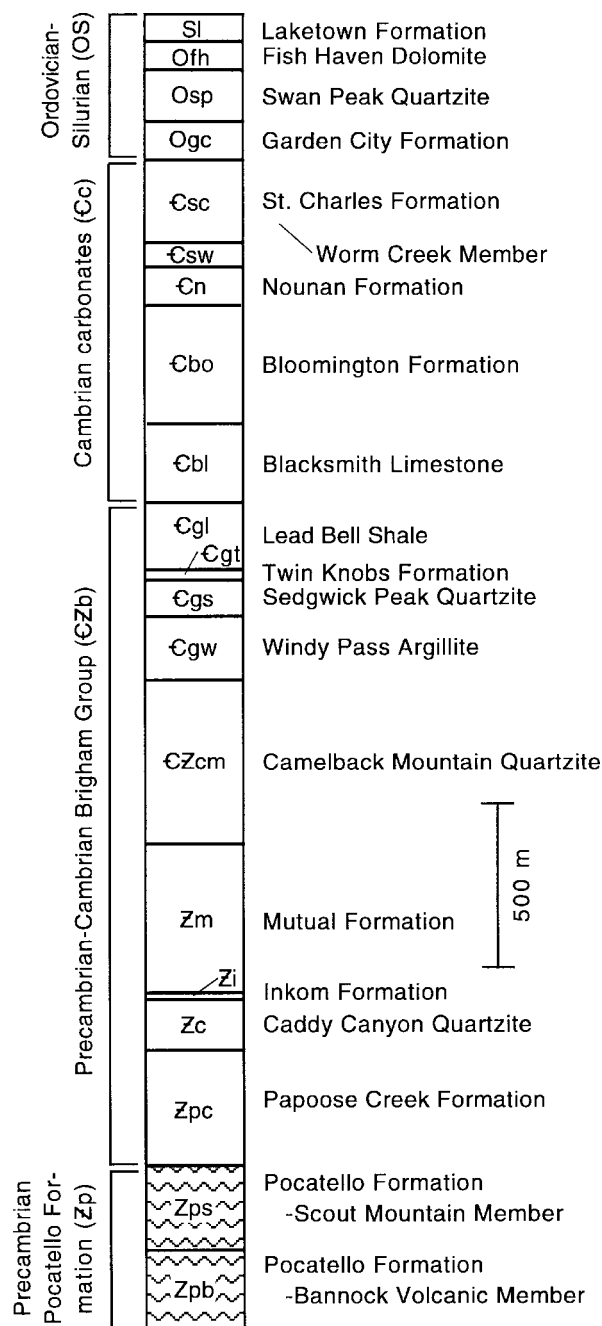


Figure 7. Stratigraphic column of the pre-Tertiary rocks exposed in the Deep Creek half-graben modified from Link, 1982b. Nomenclature on the left shows the generalized groupings that are used in the maps and cross-sections.

It is a red sandy to conglomeratic deposit that contains large boulders of quartzite up to 6.25 m in diameter from the Ordovician Swan Peak Formation in thicker sequences (Axtell, 1967; S. U. Janecke, unpublished mapping). Previous workers included these quartzite boulders in the Salt Lake Formation (Oriell, unpublished mapping) or in post-Salt Lake Formation boulder beds (Axtell, 1967; Wach, 1967). The thickness of the Wasatch Formation is extremely variable (0-35 meters in the study area, but may be as thick as 200 meters to the south). The red matrix of this deposit easily distinguishes it from the overlying Skyline member of the Salt Lake Formation, and is the main reason that we correlate it

with the Wasatch Formation. Its stratigraphic position at the base of the Tertiary sequence is also consistent with this correlation.

The regional tectonic setting of Basin-and-Range faulting in the northeastern Great Basin is controversial (e.g. compare Rodgers et al., 1990; Miller, 1990; Bryant et al., 1990) in part because the key synextensional basin-fill deposit, the late Cenozoic Salt Lake Formation, is poorly exposed, poorly understood, and of uncertain age (Platt, 1988; Platt and Royse, 1989; Bryant et al., 1990). This tuffaceous siltstone to conglomeratic unit is widely distributed across northern Utah and southern Idaho and typically fills the modern grabens and half grabens (Adamson et al., 1955; Bryant et al., 1990; Perkins et al., 1998). It is thought to be a synextensional deposit (Bryant et al., 1990) but few studies have tied deposition of the Salt Lake Formation to slip on specific normal faults (Sacks and Platt, 1985; Danzl, 1982; Smith, 1997, are exceptions). The uncertainty about the geometry of the original depositional basins and the insufficient timing constraints (Platt, 1988) make it difficult to formulate and test tectonic models of Basin-and-Range extension.

The Salt Lake Formation is exposed in the foothills of the Bear River Range, along the margins of the Wellsville, Malad, and Bannock Ranges, and in three large half grabens uplifted within the Portneuf, Malad, and Bannock Ranges (Fig. 1). Similarities in the stratigraphy of the Salt Lake Formation across much of the region and the presence of the Salt Lake Formation at the crests of some mountain ranges west of Cache Valley (Oviatt, 1986a; Burton, 1973; Wach, 1967; K. Goessel, J.C. Evans, S.S. Oriell, unpublished mapping) suggests that the formation was once more widely distributed north and west of Cache Valley than it is now. Erosional remnants of the Salt Lake Formation are lacking on ridge tops in the Bear River Range (Oriell and Platt, 1980; Evans, 1991; Dover, 1995).

Other workers in the Cache Valley area of Idaho and Utah have subdivided the Miocene-Pliocene Salt Lake deposits into (from base to top) the Collinston Conglomerate, Cache Valley Formation, and Mink Creek Conglomerate (Adamson, et al., 1955; Danzl, 1982; 1985), thus attempting to elevate the Salt Lake Formation to group status. We follow more recent usage (Sacks and Platt, 1985; Smith, 1997; Perkins et al., 1998; Smith et al., 1997a and b) and refer to the unit as a formation. We also introduce new informal names for most of the members of the Salt Lake Formation in the Deep Creek study area because they differ somewhat from the previous subdivisions and because the Deep Creek basin is probably in a different depositional basin from the type areas. Because of the uniqueness of the Cache Valley member, however, we have retained that name for the fine tuffaceous lacustrine deposits in the study area.

The best studied sections of the Salt Lake Formation near our study area are in the northeastern foothills of Cache Valley (Adamson et al., 1955; Danzl, 1982; Sacks and Platt, 1985). Danzl (1982) described three members of the Salt Lake Formation (north-east of Preston, Idaho) using the stratigraphic nomenclature of Adamson et al. (1955) (Fig. 1): 1) the Collinston Conglomerate composed of clasts of Cambrian limestone, chert, and quartzite in a silty, calcareous matrix; 2) the Cache Valley Formation consisting of interbedded tuff, non-marine limestone, and tuffaceous sandstone; and 3) the Mink Creek conglomerate composed of

clasts of Precambrian, Cambrian, and reworked Tertiary Cache Valley Formation interbedded with reworked tuff beds. Sacks and Platt (1985) studied the Salt Lake Formation in the southern Portneuf Range (Fig. 1). They divided the Salt Lake Formation into four informal members: 1) red non-tuffaceous conglomerate; 2) tuffaceous conglomerate; 3) limestone-tuff, and 4) an upper conglomerate member. These members are reported to intertongue with one another. Sacks and Platt (1985) interpreted a progressive unconformity in the hanging wall of the listric Valley fault based on vertical to overturned dips in the lower Salt Lake Formation and shallow dips in the upper members. Along strike to the south, Danzl (1982) described uniform dips within the same sequence.

### Tertiary Stratigraphy of the Deep Creek Half Graben

The principal basin-fill deposit of the Deep Creek half graben is the Miocene-Pliocene Salt Lake Formation. Four distinct members of the Salt Lake Formation have been identified and mapped within the Deep Creek basin (Fig. 8). These units include, from base to top, the Skyline member (Ts, conglomerate with a tuffaceous matrix interbedded with limestone), Cache Valley member (Tcv, tuffaceous mudstone, siltstone, limestone, sandstone, and minor conglomerate), Third Creek member (Ttc, tephra interbedded with conglomerate and limestone), and New Canyon member (Tnc, conglomerate and gravel). These members interfinger and some do not persist across the half-graben (Figs. 3 and 8).

The basal unit (Skyline member) is a poorly sorted pebble to cobble conglomerate with some thin interbedded tephra and limestones. It is poorly exposed and occurs on the western edge of the basin and along the south side of Deep Creek, west of Deep Creek Reservoir (Fig. 3). The unit is matrix-supported to matrix-rich in rare exposures (stop 6) and has a tuffaceous, calcareous, and sandy matrix. Beds range from a few centimeters to > 30 cm in thickness and may contain outsized clasts. Clasts vary from angular to subrounded, with a high percentage of clasts being subangular. This member ranges from 0 to 370 meters within the study area, but it may be significantly thicker several kilometers to the south. We interpret the Skyline member as an alluvial fan deposit.

Overlying the Skyline member are the tuffaceous sedimentary rocks and tuffs of the Cache Valley member. The contact between the two members is sharp to gradational, and there are few conglomeratic beds or lenses of the Skyline member within the lower Cache Valley member. The Skyline member pinches out to the east in the basin, where the Cache Valley member is in depositional contact with Cambrian and Eocene rocks (Fig. 3).

The Cache Valley member is the most widespread member of the Salt Lake Formation. The unit is 125 to ~590 meters thick in the study area and is exposed in the easternmost, central, and western edges of the basin (Fig. 3). Most of this unit is composed of slightly reworked tuffaceous sedimentary rocks, including mudstone, siltstone, limestone, silicified limestone, shale, sandstone, and rare pebbly conglomerates, as well as some primary tuffs and tephra. Limestone beds are common near the base and top of the Cache Valley member. It is massive to rhythmically bedded, with beds from < 1 cm (in the shales) to > 10 m thick (in the massive beds). Color is variable, but light brown, off-whites,

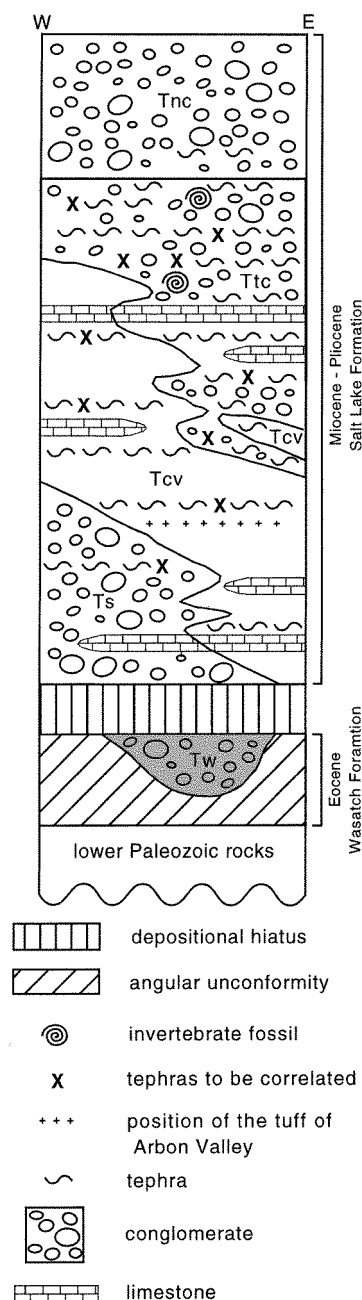


Figure 8. Schematic stratigraphic column of the Tertiary units within the Deep Creek half-graben. Abbreviations for members of the Tertiary Salt Lake Formation are: Tcv = Cache Valley, Tnc = New Canyon, Ts = Skyline, Ttc = Third Creek, Tw = Tertiary Wasatch Formation.

and green rocks are most common. The rocks are generally characterized by a silica or clay cement and are noticeably more indurated than the tuffaceous rocks of the overlying Third Creek member of the Salt Lake Formation. The Cache Valley member contains pervasively silicified limestone west of Deep Creek Reservoir. A rhyolite tuff in the lower part of the Cache Valley member of the Salt Lake Formation is a distal exposure of the 10.2 to 10.3 Ma tuff of Arbon Valley (see above). The Cache Valley member is interpreted as a lacustrine deposit. The apparent absence of sedimentary structures (ripple marks, cross-bedding, rip-up clasts)

and the presence of laterally continuous, parallel laminations and bedding suggest deposition below wave base in a relatively deep lake. The lake served as a catchment for the ash fall deposits originating from the Yellowstone hot spot in the Snake River Plain.

Overlying and interfingering with the Cache Valley member is the Third Creek member. It is exposed along the eastern edge of the half-graben (Fig. 3). Excellent exposures in the northern part of its outcrop belt indicate that this member is composed mostly of poorly consolidated white to gray tephra and slightly tuffaceous limestones. Conglomerate is prominent near the bottom (stop 4) and at the top (stop 5) of the member. Matrix of the conglomerate is variably tuffaceous, sandy, and calcareous. The thickness of this member ranges from 85 to 530 meters. Individual conglomerate beds range from < 10 cm to > 15 meters in thickness. Tephra and limestone beds vary from < 10 cm to > 3 meters. Clasts within conglomerate beds are generally well-rounded pebbles, but a few beds contain cobbles. Prominent large-scale planar cross-bedding in parts of the upper section of the unit are well-exposed both within the study area (stop 5, Figs. 16-18) and a few kilometers north. Some of the limestones interbedded with the conglomerates are oolitic and contain shell fragments. Tephra in this member are much less consolidated and cemented than those of the Cache Valley member, indicating that they may have been deposited in a subaerial or shallow water environment.

Sedimentary structures of the Third Creek member indicate that near-shore or beach processes were responsible for deposition of the top and bottom of the member (well-sorted and well-rounded conglomerate beds, foreset and topset beds, planar cross-beds, oolitic limestones, and shell fragments), whereas the middle of the member is partly a fluvial deposit (conglomerates filling channels, subaerial (?) tephra, and mudcracks). The upper part, with its abundant planar cross-beds, formed in a large gravely Gilbert delta (see stop 5, Figs. 16-18).

The uppermost member in the basin, the New Canyon member, is exposed along the northeastern margin of the half graben (Fig. 3), but is poorly consolidated within the study area. Excellent exposures of the New Canyon member 3-4 km to the north of

the study area in Fig. 3, west of Oxford Peak, show that the unit is a parallel-bedded pebble to cobble conglomerate. The member is clast-supported and the clasts are uniformly well-rounded. In the study area the member is not lithified, but a few bedding traces on aerial photographs allow its attitude to be estimated. West of Oxford Peak the New Canyon member is parallel-bedded, moderately well-sorted with no fining- or coarsening-upward sequences. The member contains only minor amounts of interbedded tephra, concentrated near the base. The contact between the Third Creek and New Canyon members is sharp and placed where distinctive red conglomerates of the lowermost New Canyon member overlie white calcite-cemented conglomerates of the uppermost Third Creek member. In the study area, the New Canyon member has a maximum thickness of > 180 m. Reconnaissance mapping suggests that more than 1 km of section is preserved west of Oxford Peak. The depositional environment is interpreted to be fluvial because the clasts are so well-rounded and relatively well-sorted, and beds are clast-supported.

The composition of clasts in conglomerates and gravels of the Salt Lake Formation changes dramatically upsection. Clasts in the Skyline member (Ts) consist mostly of Cambrian through Silurian carbonate rocks but siliciclastic debris from the Ordovician Swan Peak (Eureka) Quartzite, Cambrian Worm Creek member of the St. Charles Formation, and small tuff clasts are also present (Fig. 9). This clast assemblage is consistent with derivation from the underlying Paleozoic rock on the western (hanging wall) side of the half-graben. The composition of clasts in the conglomerate beds of the Third Creek member is highly variable, but clasts include Brigham Group quartzites, Paleozoic carbonate rocks, and abundant clasts (> 85% in some beds) reworked from the underlying Cache Valley member (Fig. 9). The presence of a significant number of tuffaceous mudstone and siltstone clasts recycled from the Cache Valley is a distinguishing feature of the Third Creek member. The New Canyon member (Tnc) contains mostly clasts of Brigham Group and Cambrian carbonate rocks and chert, with only a minor amount of material reworked from the Cache Valley member (Fig. 9). The Brigham Group that is widely exposed in the footwall of the Deep Creek half-graben

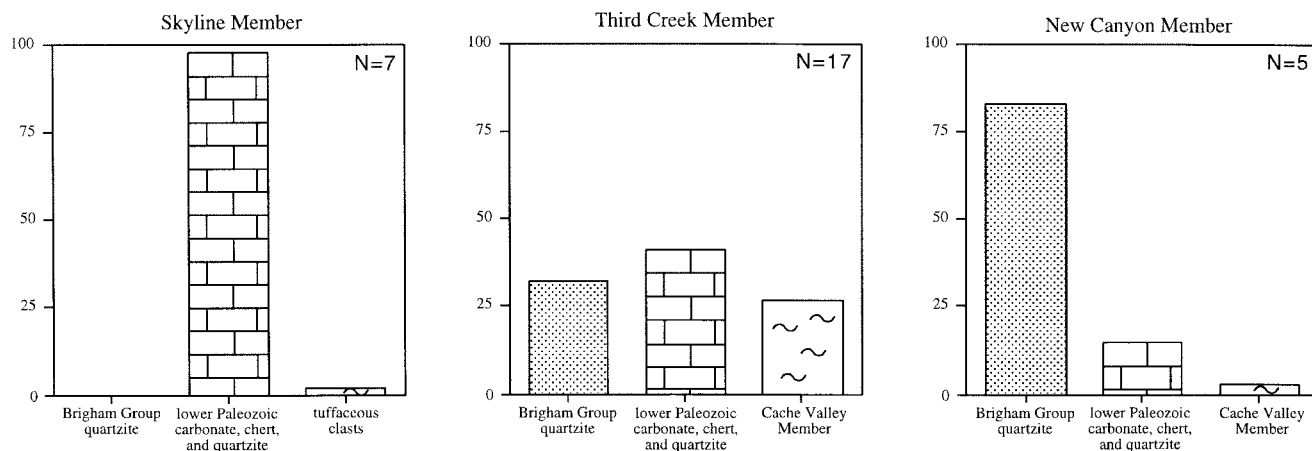


Figure 9. Clast counts within the conglomerates and gravels (Skyline, Third Creek, and New Canyon members) of the Salt Lake Formation. *N* = number of clast counts in each member (50 or 100 clasts were identified for each clast count within an ~1m<sup>2</sup> area of outcrop). Note the increase in clasts of Brigham Group quartzite upsection and the presence of tuffaceous clasts recycled from the underlying Cache Valley member. Also note that there are no metavolcanic or metasedimentary clasts of the Neoproterozoic Pocatello Formation in any of the units.

was probably the source of the quartzite clasts in the New Canyon and Third Creek members, but we cannot rule out a more distant source in the southern Portneuf Range or western Bear River Range. There are no clasts derived from the metamorphic rocks of the Precambrian Pocatello Formation in any of the members. Deposition of all four members of the Salt Lake Formation thus occurred before the footwall of the Clifton detachment fault was exposed at the surface.

Although interpretation of these provenance data is complicated by the presence of Cambrian carbonate rocks in both the footwall and hanging wall of the Deep Creek half graben, the provenance data define a classic unroofing sequence. This reverse stratigraphic pattern is consistent with progressive tectonic and erosional unroofing of the footwall during detachment faulting. The provenance data also suggest that deposition of the Salt Lake Formation was syntectonic with slip on the Bannock detachment system. Danzl (1982) and Sacks and Platt (1985) both noted a similar inverted stratigraphic relationship between the composition of conglomerates of the Salt Lake Formation and the pre-Tertiary rocks in the footwall of the breakaway fault in northeastern Cache Valley.

## ROAD LOG

The field trip guide begins at the Downey Exit of I-15, approximately 40 miles south of Pocatello, Idaho. Mileages are given from the exit.

### Incremental & Total Mileage

0.0	0.0	Begin road log. Drive south on Highway 91 toward Preston, Idaho.
2.2	2.2	Oxford Peak is the prominent peak visible at the south end of Marsh Valley at 1:30 o'clock. The Bannock detachment system is faulted down beneath the south end of Marsh valley along small north-dipping normal faults (Link, 1982a). Alternatively, the detachment may plunge beneath the valley along a north-plunging anticline that folds the detachments in the Oxford Ridge area.
3.3	5.5	Downey, Idaho.
1.0	6.5	The road drops in elevation from the high pediment surfaces flanking Marsh Valley into an inset valley with an underfit stream. The Bonneville flood roared through this valley about 15,000 years ago on its way to the Pacific ocean.
1.3	7.8	Conglomerates of the Salt Lake Formation are exposed in railroad cuts on the left.
4.3	12.1	Highway 91 crosses into Cache Valley at Red Rock Pass. The geological marker is on an erosional remnant of one of the many landslide deposits that were washed away during the Bonneville flood. More information on the Quaternary history of this region can be found in Bright and Ore (1987) and Link et al. (this volume).
3.8	15.9	Swan Lake, Idaho.
1.6	17.5	There are exposures of the Salt Lake Formation in road cuts on the left.

- 1.5 19.0 **Stop 1.** Turn right onto Coulam Road, proceed a short distance and stop for an overview of Oxford Ridge and the northern end of Cache Valley. Coulam Road angles south from Highway 91 and is called the Stockton Exchange road on the northeast side of the intersection.

This stop illustrates the crosscutting relationships between the active Basin-and-Range normal faults and the Miocene-Pliocene detachment faults. Stop 3-3 of Link et al. (1985a) also describes this area.

The gently WSW-dipping Clifton detachment fault is visible on the east slope of Oxford Peak, the highest point on Oxford Ridge. The fault places east-dipping light colored Brigham Group rocks over darker metasedimentary rocks of the Pocatello Formation along a gently WSW-dipping fault (Raymond, 1971; Link, 1982a and b). The structurally higher New Canyon detachment fault cuts out the Clifton detachment fault north of Oxford Peak, and then wraps around to the west slope of Oxford Ridge (Link, 1982a and b). The Clifton detachment fault is repeated four times east of Oxford Peak in fault blocks bounded by younger Basin-and-Range normal faults (S.U. Janecke, unpublished mapping; Link, 1982a). Two of these fault blocks are visible from here.

The Oxford-Dayton range-front fault forms a steep escarpment at the base of the Oxford Ridge portion of the Bannock Range along the west side of Cache Valley. This east-dipping normal fault is the dominant structure in the northern end of Cache Valley and is obviously an active normal fault based on the steep topography and relief of the Oxford Ridge area. The vertical displacement across the Oxford-Dayton fault east of Oxford Peak is approximately 500 m based on the difference in elevation of the Clifton detachment fault in Cache Valley (about 5400 ft, west of Oxford) and its elevation in the footwall of the Oxford-Dayton fault. Two additional ENE-dipping normal faults in the footwall of the Oxford-Dayton normal fault raise the detachment fault an additional 450 m to the crest of the range (about 8600 ft). The throw across the three east-dipping Basin-and-Range normal faults (950 m) is thus almost identical to the vertical relief between Oxford Ridge and Cache Valley. These data are consistent with a very young age for the Oxford-Dayton fault system. Note that the total amount of vertical displacement across the Oxford-Dayton fault (500 m) is quite small, however, for a major range-front fault.

Notice how subdued the topography is along the northeast side of Cache Valley near this stop. We interpret this area as the breakaway zone for the Miocene-Pliocene Bannock detachment system. Sacks and Platt (1985) described vertical sedimentary rocks of the Salt Lake Formation in the hanging wall of the listric WSW-dipping breakaway fault. They infer that the normal fault flattens at about 4 km depth. This fault has not been very active in latest Cenozoic time.

Return to Highway 91 and proceed south toward Preston. The Bear River Range, along the east side of Cache Valley, becomes visible farther to the south. The Clifton detachment fault stays in view on the east flank of the Oxford Ridge. Bedrock knobs are fairly common in the northern two-thirds of Cache Valley and indicate that the basin is quite shallow. Gravity data (Peterson

and Oriel, 1970; Zoback, 1983) also show that the basin fill is thin here. Cache Valley is disrupted by a number of intrabasinal normal faults in this area. One northeast-trending ridge of bed-rock exposures, north of stop one, extends from the base of Oxford Ridge all the way across the valley to the foothills of the Portneuf Range, just south of Swan Lake (Link, 1982a). Faulted Camelback Mountain quartzite, of the Brigham Group, and Salt Lake Formation are exposed in this ridge (Link, 1982a). A narrow NNW-trending horst of even older rocks is exposed west of the highway south of Twin Lakes (Oriel and Platt, 1980).

- 6.0 25.0 The Bear River Range is now clearly visible to the southeast. The low rolling foothills of the Portneuf Range between 9 and 1 o'clock consist of the Salt Lake Formation in the near distance. These are faulted against the Brigham Group and overlying carbonate rocks in the far distance.
- 2.8 27.8 Highway 91 begins its descent to the Bear River. The river has incised its current flood plain into the large Bear River delta that formed near the end of the Bonneville lake cycle. Many generations of mass movements have modified the terrace risers (Mahoney et al., 1987; Link et al., 1987).
- 1.7 29.5 The road crosses the Bear River.
- 0.5 31.0 Follow the broad curve to the left (east).
- 0.1 31.1 Turn right onto a gravel road. At the turnoff, hangars of the Preston airport are visible at the top of the hill.
- 0.1 31.2 Take the left fork and stay on the public gravel road.
- 0.3 31.5 **Stop 2.** The road curves up and to the left at a sandy cutbank on the left. Stop and climb onto the top of the sand pile for an overview of the Oxford Ridge area.

This stop provides another view of the Bannock detachment system and the younger Basin-and-Range normal faults along the west side of Cache Valley. The Oxford-Dayton normal fault defines the obvious escarpment at the base of the range. The Clifton detachment fault is exposed at the top of the prominent mountain-scale ledge two-thirds of the way up from the base of the mountain, east of Clifton basin. Clifton basin is a high reentrant into the range west of Clifton, Idaho. There the Clifton detachment fault places the east-dipping Salt Lake Formation in the hanging wall on the Pocatello Formation in the footwall. This is one of the critical localities where the detachment faults cut the Salt Lake Formation. North of Clifton basin the detachment cuts down into the Brigham Group in its hanging wall whereas south of the basin it carries lower Paleozoic carbonate rocks (Raymond, 1971; S.S. Oriel, unpublished mapping). Notice how the detachment fault climbs gently to the north toward Oxford Peak, possibly because slip across the Oxford-Dayton fault increases to the north.

The foothills of Oxford Ridge consist of tilted (to vertical) and folded rocks of the Salt Lake Formation that are caught between the Oxford-Dayton normal fault on the west and an unnamed ENE-dipping normal fault on the east (Raymond, 1971; S.S. Oriel, unpublished mapping; S.U. Janecke, unpublished map-

ping). The foothills of the Bear River Range, north of Logan, Utah, have a nearly identical structure (Brummer, 1991; Brummer and McCalpin, 1995; McCalpin, 1994). The elongate ridge to the north-northwest of this stop (Little Mountain, southeast of Twin Lakes Reservoir) is a horst block of Pocatello Formation exposed near the middle of Cache Valley (Oriel and Platt, 1980).

Turn around and return to US Highway 91. Turn right and continue into Preston, Idaho.

- 1.9 33.4 The junction of US Highway 91 and Idaho Highway 36 is at the northern end of Preston. Continue south on Highway 91.
- 0.9 34.3 At the traffic light near the middle of town, turn right onto Oneida street (Highway 36) and follow the signs towards Dayton, Idaho.
- 2.2 36.5 The road crosses the Bear River.
- 3.5 40.0 The road crosses some railroad tracks.
- 0.9 40.9 Take a left in Dayton south of the high school and follow the signs towards Weston and Malad (this is still Highway 36).
- 2.0 42.9 Notice the steep escarpment of the Oxford-Dayton normal fault to the right of the road. The dark rocks in the footwall are diamictites of the Upper Proterozoic Scout Mountain member of the Pocatello Formation (Link and LaFebre, 1983).
- 3.2 46.1 Turn right on Highway 36 (towards Malad).
- 0.9 47.0 The next couple of miles offers views to the north of the west-dipping Bannock detachment system. The detachment places the Miocene-Pliocene Salt Lake Formation and Cambrian carbonate rocks on the Precambrian Pocatello Formation. Further field studies are needed but preliminary reconnaissance indicate a flat-on-flat geometry along this part of the detachment fault.
- 3.1 50.1 Flat lying clays and gravels of Quaternary Lake Bonneville are exposed in a roadcuts on the left of the road over the next 3 miles.
- 1.0 51.1 The turnoff to Dry Canyon Road is on the left. Dry Canyon Road connects with Skyline Road and then Two Mile Road east of stop 6. Continue straight on Highway 36.
- 2.1 53.2 The road enters Weston Canyon. The SE-dipping limestone cliffs are composed of the Cambrian Blacksmith, Bloomington, and Nounan Formations (Murdock, 1961).
- 2.6 55.8 The road crosses the Oneida County line.
- 0.1 55.9 The road crosses an unnamed west-dipping low-angle normal fault along the east side of the Deep Creek half graben (Fig. 10). This fault places Tertiary Salt Lake Formation (Cache Valley/Third Creek member) against the Cambrian St. Charles Formation. Murdock (1961) mapped a steeper W-dipping normal fault within the Paleozoic rocks about half a kilometer to the east of here.
- 0.1 56.0 The Cache Valley member of the Salt Lake Formation is exposed in a roadcut on the right (~25° south-west-dipping). This roadcut is the most accessible

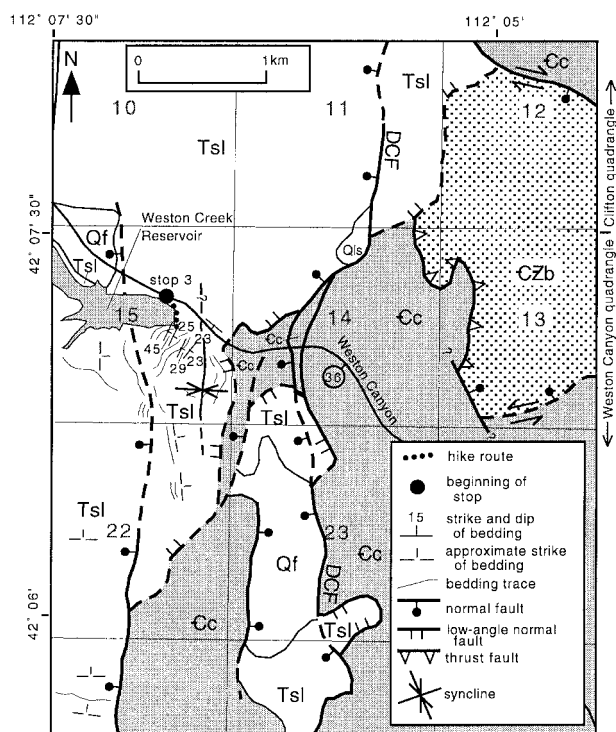


Figure 10. Photogeologic map showing the area around Stop 3. Section lines and numbers are shown for reference. The geology of the pre-Tertiary rocks is modified from Murdock (1961). Cc = Cambrian carbonate rocks, CZb = Neoproterozoic Brigham Group, DCF = Deep Creek fault, Qf = Quaternary alluvial fan deposits, Qls = Quaternary landslide deposit, Tsl = Tertiary Salt Lake Formation.

exposure of the Cache Valley member along the field trip route.

- 0.2 56.2 **Stop 3.** Park on the left at the parking lot for the Weston Canyon dam and cross the dam to its south abutment. Bulldozer cuts extending east and west from the south abutment provide exposures of east-dipping tuffaceous rocks of the Salt Lake Formation (Fig. 10).

This stop provides an introduction to the geology of the Deep Creek half graben, illustrates a common type of extensional syncline, provides a view of the Weston Canyon thrust fault, and allows for a hands-on examination of the tuffaceous rocks of the Salt Lake Formation. The stop is south of our current study area but is included here because it illustrates several types of features that are less accessible to the north. The photogeologic map of the area around Stop 3 (Fig. 10) has not been field-checked.

### Structures of the Deep Creek Half Graben

The sedimentary rocks in the Deep Creek half graben generally dip gently east and lie in the hanging wall of the Clifton, New Canyon, and unnamed higher detachment faults (Fig. 3). The present eastern margin of most of the basin, however, is the younger Deep Creek normal fault (Figs. 3 and 4). The supradetachment basin is 20-25 km long in a north-south direction and 8 km wide at its widest point. The Deep Creek normal fault dips ~65° west-southwest and extends for > 35 km along the

east side of the basin from south of stop 3 to the northernmost end of the Oxford Ridge segment of the Bannock Range (Fig. 3 and Link, 1982a and b). The western margin of the basin is a faulted depositional contact between the Skyline member of the Salt Lake Formation and Cambrian through Silurian rocks. Locally the Eocene Wasatch Formation crops out along the basin margin. North-, northeast-, northwest-, and NNW-striking, east-dipping normal faults complicate the western margin of the basin (Fig. 3; Skyline, Maple Hollow, and Little Valley faults).

Numerous high-angle normal faults in the center of the Deep Creek basin bound horsts and grabens (Fig. 3). These faults are generally north-south striking and are better exposed in the southern end of the basin than in the northern half because the horsts in the south expose resistant pre-Tertiary bedrock. These faults have only a few meters to hundreds of meters of offset and roughly parallel the Wasatch and Oxford-Dayton Basin-and-Range normal faults. Some north-south striking normal faults displace Quaternary-Tertiary alluvial fan deposits in the southeastern part of the basin. This suggests that all the north-south striking normal faults, including the Deep Creek fault, are Basin-and-Range normal faults. An older history is also possible.

The north-south striking Basin-and-Range normal faults cut older northeast- and northwest-striking high-angle faults. The best exposures of these "cross faults" are in pre-Tertiary rocks in the footwall and hanging wall of the basin (Fig. 3). Cross faults include the Two Mile and Maple Hollow faults (stop 6; Fig. 3), and the large northwest-striking cross fault that truncates the Weston Canyon thrust at its northern end (visible at this stop; Figs. 3, 10, and 11). These cross faults have large normal or possible strike-slip offsets. West and northwest of Deep Creek Reservoir a northwest-striking normal fault clearly cuts the Salt Lake Formation (Fig. 3), indicating that at least some of the cross faults are late Cenozoic in age. In the western part of the basin, northeast-striking normal faults parallel to the Two Mile fault cut the Salt Lake Formation and appear to displace the northwest-striking and northeast-dipping Maple Hollow fault (Fig. 3). Further detailed mapping is needed to confirm the relative ages of these distinct geometric sets of faults.

Low-angle normal faults of the Bannock detachment system are exposed in the footwall of the Deep Creek normal fault (Fig. 3). The Clifton, New Canyon, and at least two other unnamed detachments crop out in this part of the range. These faults dip generally westward between 20° and 28°. The Clifton and New Canyon detachments cut up and down section, and the entire Clifton sheet is locally excised by the overlying New Canyon detachment fault (Fig. 3). The end result is a structurally and compositionally complex footwall to the Deep Creek half-graben that consists of Neoproterozoic Pocatello Formation, Neoproterozoic – Cambrian Brigham Group quartzites and Cambrian carbonate rocks.

Extensional folds scattered throughout the Deep Creek half-graben vary in size and geometry. Stereographic analysis of bedding in some of the larger and more prominent structures are summarized below and in Figure 12. Because of the age of the folded deposits (the Miocene-Pliocene Salt Lake Formation) and the tectonic evolution of the area, we are certain that these folds formed in an extensional setting. In the Deep Creek half-graben the ma-

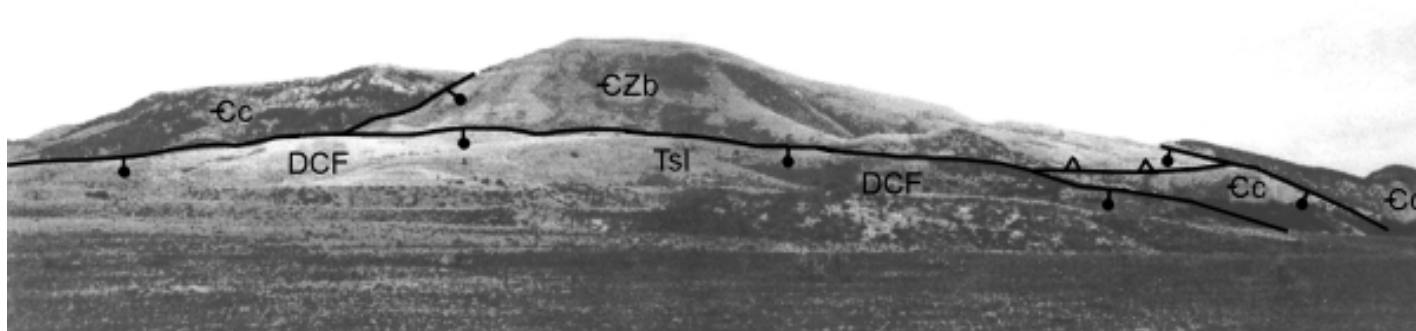


Figure 11. Panoramic photographs of Weston Canyon thrust fault visible from stop 3. View is to the east. Cc = Cambrian carbonate rocks, DCF = Deep Creek fault, Tsl = Tertiary Salt Lake Formation, CZb = Neoproterozoic - Cambrian Brigham Group.

majority of the extensional folds have a gentle interlimb angle ( $> 120^\circ$ ), a slight plunge ( $< 15^\circ$ ), and a near-vertical bisecting surface (Fig. 12). These folds are parallel, transverse, and oblique to their associated normal faults, creating general north-, northwest-, east-, and northeast-trending sets of folds. They likely formed contemporaneous with slip on the north-, northwest-, and northeast-striking fault sets, as well as during Miocene-Pliocene detachment faulting. Some folds have nonlinear hingelines and were probably refolded during a younger episode of normal faulting (c.f., AV syncline, Fig. 12). The AV syncline formed in the hanging wall of the northeast-dipping Maple Hollow fault, but its western end was refolded in the hanging wall of the younger Skyline Basin-and-Range normal fault.

North-south trending folds dominate in the west-central edge of the study area in association with north-south Basin-and-Range normal faults (Fig. 12). The largest of these folds are probably roll-over anticlines and adjacent synclines. On the east side of the basin NNW-trending synclines fold the Tertiary Salt Lake Formation in both the footwall and hanging wall of the Deep Creek fault. The syncline at this stop (stop 3) is along strike of the hanging wall syncline of the Deep Creek fault to the north (Deep Creek HW syncline; Fig. 12). Gently northeast- and east-plunging folds characterize the northwest part of the area, whereas east- and northwest-plunging folds dominate farther south. A zone of northwest-trending folds, including the Highway syncline (Fig. 12), parallel to the southeast end of Deep Creek, could have formed adjacent to and along strike of a subsurface northwest-striking and southwest-dipping normal fault (see stop 4). Nearly all of the folds in the basin are longitudinal folds, with the exception a few transverse to oblique folds in the north.

### Geology around Stop 3

Several generations of faults and folds are visible from stop 3. Immediately east of the stop a west-dipping normal fault places tuffaceous rocks of the Salt Lake Formation on Lower Paleozoic rocks including the Worm Creek Member of the St. Charles Formation. The unnamed fault has a shallow dip on either side of Weston Creek (Fig. 3) but is cut out by the steeper west-dipping Deep Creek normal fault to the north east. Murdock (1961) mapped this steeper fault within the Paleozoic rocks. Together the Deep Creek and low-angle west-dipping normal faults bound

the eastern edge of the Deep Creek half graben at this latitude.

The Salt Lake Formation in the hanging wall of the Deep Creek normal fault is folded into a north-trending symmetric syncline that parallels the unnamed low-angle normal fault (Fig. 10). The axis of the syncline is 200-300 m west of the trace of the fault. Four synclines within the study area to the north have a nearly identical geometry, and also lie in the immediate hanging walls of normal faults (Deep Creek HW syncline, AV syncline, the syncline in the hanging wall of the Skyline fault, and the ESE-plunging syncline southwest of Deep Creek reservoir; Fig. 12). The geometric association between the normal faults and the hanging wall synclines suggests that the folds may be fault-drag, fault-propagation, or fault-bend folds (Janecke et al., 1998). Further study is needed to discriminate between these options.

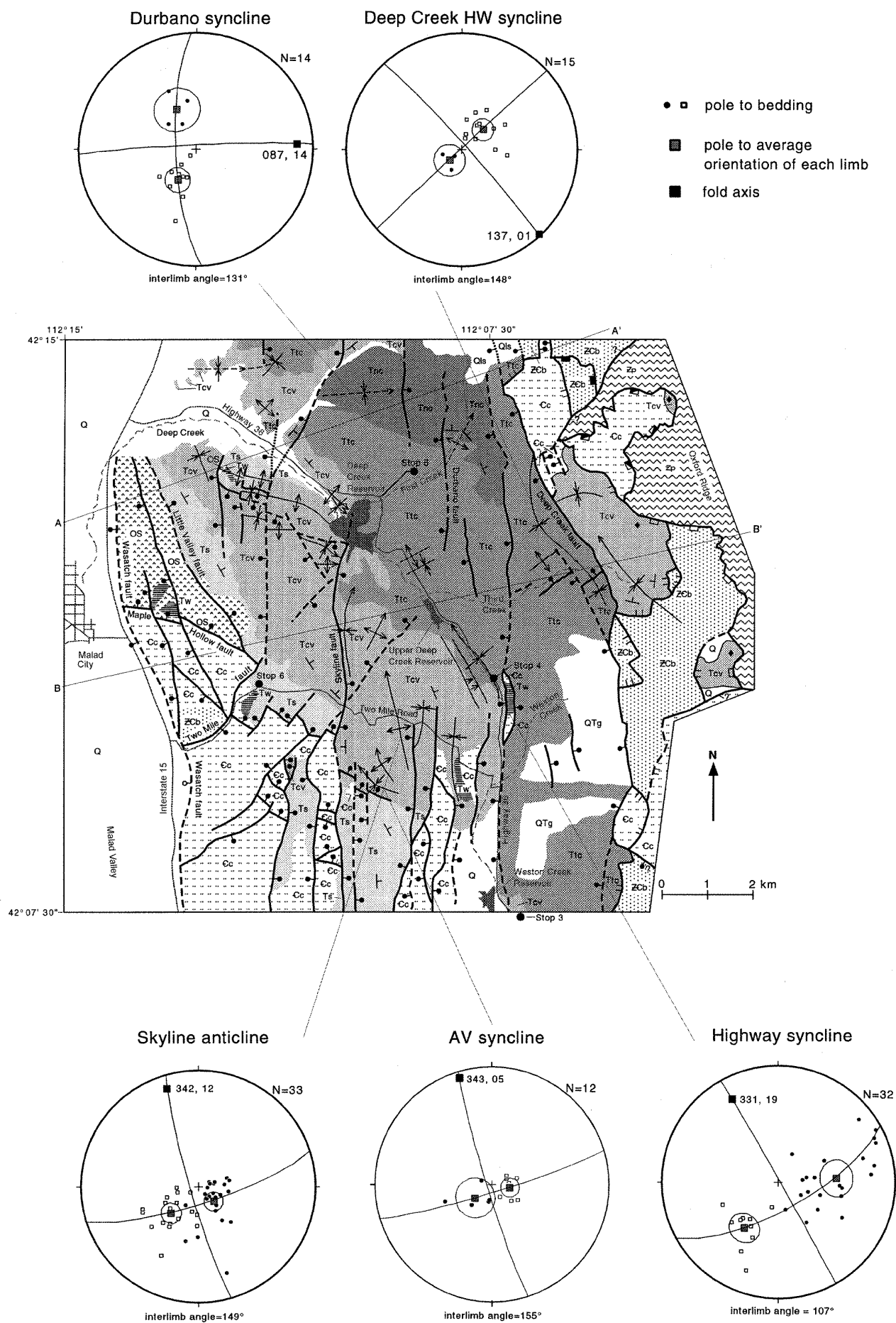
Three large faults in the footwall of the Deep Creek fault (Murdock, 1961) include the Weston Canyon thrust and two steep normal or strike-slip faults that bound the north and south end of the thrust sheet (Fig. 11). The Weston Canyon thrust places orange to tan rocks of the Brigham Group over gray, southeast-dipping Cambrian carbonate rocks (Fig. 10). The cross fault at the northern end of the thrust sheet has a southeast strike whereas the steep fault at the southern end strikes east-northeast. Detailed mapping is needed to determine their sense of slip and relative age.

The tuffaceous rocks of the Salt Lake Formation at stop 3 are on the western limb of the north-trending, fault-parallel, hanging-wall syncline. They are medium to thin-bedded, massive to well-laminated, off white, and variably calcareous. A limestone-clast pebble to cobble gravel near the western edge of the exposure does not contain any quartzite clasts from the Weston Canyon thrust sheet to the east. The tuffaceous rocks are intermediate between the Cache Valley member and the Third Creek member of the Salt Lake Formation, as we define them to the north. Features of both members will be illustrated here. Return to the vehicles and continue north on Idaho Highway 36.



Figure 12. Map showing locations of extensional folds and stereograms of poles to bedding in the Salt Lake Formation within the Deep Creek study area. Base map is Fig. 3. Folds have a range of trends. See text for discussion.





- 1.3 57.5 A normal fault that places Tertiary Cache Valley member of the Salt Lake Formation on Cambrian carbonate rocks is exposed across Weston Creek to the left. The higher hills to the left (west) are composed of the Skyline member of the Salt Lake Formation.
- 1.1 58.6 A large landslide of Paleozoic rocks is visible high up on the ridge line to the right (1 to 2 o'clock).
- 0.2 58.8 USFS 051 (Two Mile Road, 2400 South) is on the left. Continue straight on Highway 36. Alluvial terraces are exposed straight ahead and to the right. A gravel pit on the right exposes alluvial fan deposits of one of the alluvial terraces.
- 0.6 59.4 The Cache Valley member of the Salt Lake Formation is (poorly) exposed on both sides of the road. The Cache Valley member is faulted against a horst of Cambrian carbonate rocks and Eocene Wasatch Formation on the west side of the road.
- 0.2 59.6 A roadcut exposes the Cache Valley member on the right.
- 0.2 59.8 The road passes over the drainage divide between the Deep Creek and Weston Creek drainages.
- 0.4 60.2 The contact between the Cache Valley and the Third Creek members of the Salt Lake Formation is on the left side of the road. This contact is not visible from the road. The Cache Valley member is in fault contact with Cambrian carbonate rocks and Eocene Wasatch Formation on the right side of the road.
- 0.2 60.4 The northeast limb of a syncline (the Highway syncline, stop 4) in the Third Creek member of the Salt Lake Formation is visible straight ahead.
- 0.2 60.6 **Stop 4.** Highway syncline. Pullout on the left, park and prepare for a short hike. We will look at the steeply southwest-dipping to vertical beds of the lower Third Creek member of the Salt Lake Formation on the northeast limb of the Highway syncline. The southwest limbs are southwest of the highway and are poorly exposed.

The purpose of this stop is: 1) to examine a major well-exposed syncline that formed during regional extension, and 2) to interpret the depositional environment of limestones and conglomerates at the base of the Third Creek member (Fig. 13). The conglomerates exposed in this syncline also provide indirect evidence for progressive unconformities within the Salt Lake Formation. If time permits, we will also take a look at the Tertiary Wasatch Formation in a horst block east of the stop.

The Highway syncline deforms the Third Creek member of the Salt Lake Formation and has the geometry of a box fold with 4 to 5 monoclinial hinges (Fig. 14). From southwest to northeast across this box fold the dip direction of the Salt Lake Formation changes from north to northeast to northwest to west-southwest to west, and ranges in dips from 10° to 90° (Fig. 15). The Highway syncline is at least 3 km long and is truncated by a Basin-and-Range normal fault at its southeast end. The syncline plunges to the northwest (Fig. 12) and is one of several northwest-trending folds in this part of the basin. Other northwest-trending folds

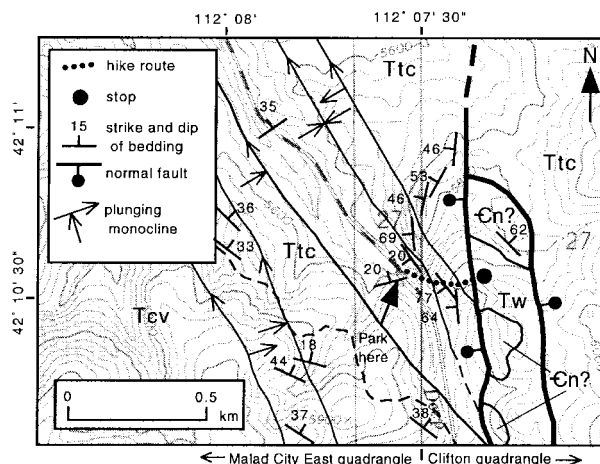


Figure 13. Map showing area of stop 4. Topographic base is the Malad City East and Clifton 7.5' quadrangles; contour interval is 40 feet. Cn? = probable Cambrian Nounan Formation, Tcv = Cache Valley member of the Salt Lake Formation, Ttc = Third Creek member of the Salt Lake Formation, Tw = Tertiary Wasatch Formation.

include the AV syncline (Fig. 12), to the southwest, and a series of anticline-syncline pairs west, northwest, and southwest of Deep Creek Reservoir (Fig. 12).

The northwest trend of the Highway syncline is difficult to explain because all the mapped normal faults in this area strike north-south (Figs. 3 and 13). This fold could be a fault-propagation fold above a subsurface northwest-striking, and southwest-dipping normal fault. The fold roughly parallels this portion of Deep Creek and probably influenced the location of the creek.

During our traverse we will hike through the lower part of the Third Creek member of the Salt Lake Formation. This part of the member contains both tuffaceous limestone and overlying conglomerate beds (Fig. 15). Limestone beds vary from < 20 cm to ~ 1 meter, and most are massive. Some of the limestones are oolitic and contain shell fragments, molds of gastropods, and trough cross-beds, indicating a high-energy environment of deposition.

Individual conglomerate beds range from < 10 cm to > 1 meter in thickness. Bedding is parallel and laterally continuous. Clasts within the conglomerate beds are generally well-rounded pebbles. The matrix of the conglomerate is calcareous and slightly tuffaceous. We interpret the lower Third Creek member as a near-shore or beach deposit around fluctuating lakes.

The composition of clasts in the conglomerates of the lower Third Creek member is striking because of the abundance of reworked clasts from the underlying Cache Valley member. Many conglomerate beds contain 60-90% reworked Cache Valley clasts. A conglomerate bed at road level on the northeast side of the highway is a particularly good example of this. Thus, some tilting or faulting must have been taking place in the basin while the Third Creek member was being deposited. Other clasts in the conglomerate beds are Cambrian carbonate rocks or Neoproterozoic - Cambrian Brigham Group quartzite. The latter is only exposed in the footwall of the Deep Creek normal fault and the Bannock detachment system. Return to the vehicles and continue northwest along Idaho Highway 36.

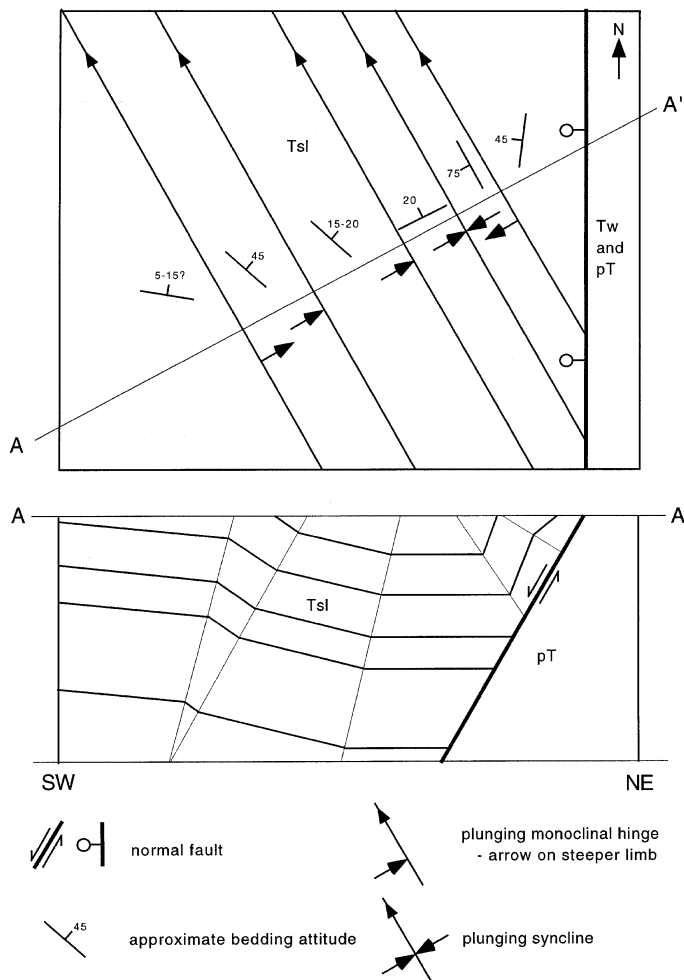


Figure 14. Schematic map and cross-section of the Highway syncline showing the numerous monoclinial fold hinges that comprise this fold. pT = pre-Tertiary rocks, Tsl = Salt Lake Formation, Tw = Tertiary Wasatch Formation.

- 0.2 60.8 Roadcuts provide excellent exposures of tephra, conglomerates, and limestones of the Third Creek member of the Salt Lake Formation on the right side of the road over the next 3 miles. These rocks all dip to the northwest, except at a small northeast-trending anticline-syncline pair 2.3 miles ahead.
- 1.4 62.2 Upper Deep Creek Reservoir is on the left.
- 0.2 62.4 300 North (Third Creek Road) is on the right. Continue straight on Highway 36.
- 0.7 63.1 The roadcut exposes southeast-dipping beds of the Third Creek member of the Salt Lake Formation. They define the southeastern limb of a small anticline. Beds on the northwest limb of this anticline are exposed 0.1 miles ahead.
- 0.2 63.3 A large roadcut on the right shows northwest-dipping beds of the Third Creek member of the Salt Lake Formation and several small normal faults. These faults are interpreted to have rotated with bedding and thus were active when bedding was still horizontal.
- 0.4 63.7 Deep Creek Reservoir is on the left.

0.7 64.4 Turn right. This intersection is poorly marked (there is a small sign labeled "First Creek" just before the turnoff and a yellow house on the right just after the turnoff). Follow the gravel road as it curves to the left and then to the right.

0.6 65.0 **Stop 5.** Park in front of the gate that blocks an unmaintained road going straight, near the entrance to a ranch and private property on the left. This stop involves a ~4 km long hike up a low ridge and is weather-dependent. Follow the map (Fig. 16) up into Second Creek to near the base of the large prominent cliff of conglomerate on the north. Climb up toward the western base of the exposure to examine the beds of conglomerate (stop 5A). Turn around (look west) for an excellent view of enormous foreset and topset beds in the conglomerate (Fig. 17)(stop 5B). Angle uphill to the northwest for a view to the north across First Creek of another quite different exposure of cross-bedded conglomerate

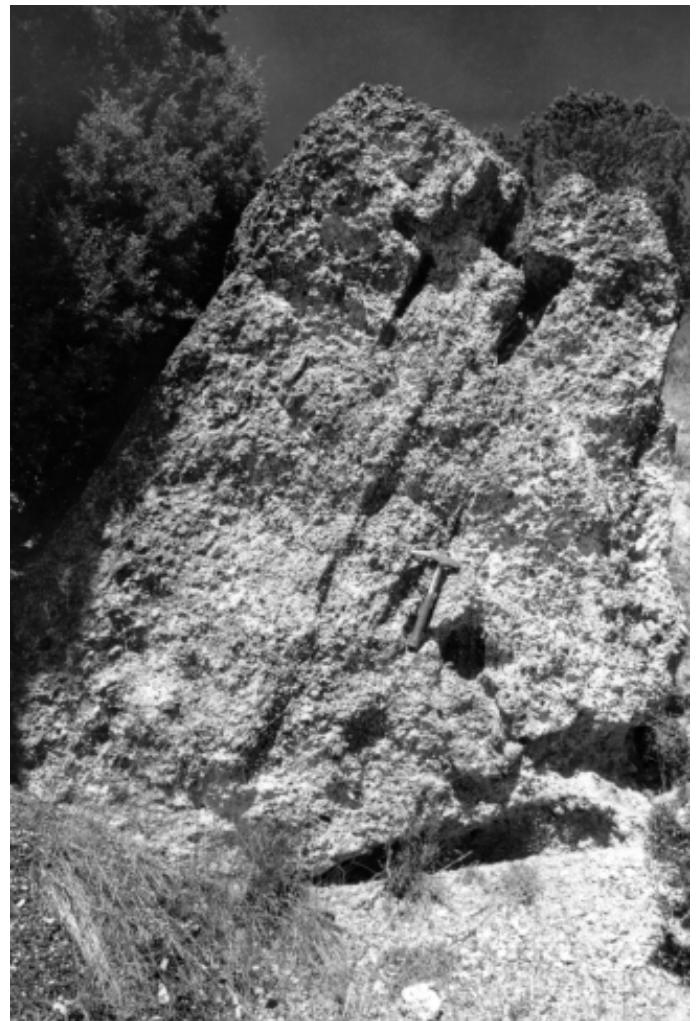


Figure 15. Photograph showing steeply west-dipping (~70°) beds of the lower Third Creek member of the Salt Lake Formation. These beds are on the northeast limb of the Highway syncline. View is to the north.

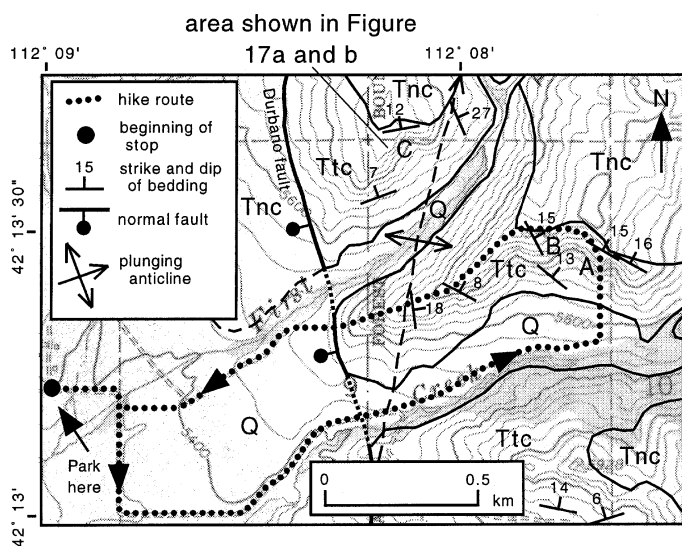


Figure 16. Map showing area of stop 5. Topographic base is the Malad City East 7.5' quadrangle; contour interval is 40 feet. Letters A, B, and C show localities referred to in the text. Q = Quaternary alluvial deposits, Tnc = Tertiary New Canyon member of the Salt Lake Formation, Ttc = Tertiary Third Creek member of the Salt Lake Formation.

(Fig. 18a and b)(stop 5C). Continue west along the ridge and drop back down to First Creek to return to the vehicles.

The purpose of this stop is to examine excellent exposures of conglomerates in the uppermost part of the Third Creek member of the Salt Lake Formation. The conglomerates are uplifted in the footwall of the Durbano normal fault, a west-dipping Basin-and-Range fault with moderate amounts of displacement.

In the northern half of the Deep Creek half graben the uppermost unit of the Third Creek member is a well-cemented, pebble conglomerate composed of rounded to well-rounded clasts of Brigham Group quartzite, Cambrian carbonate and chert, and some reworked clasts derived from the underlying Cache Valley member of the Salt Lake Formation (Fig. 9 and 19). Reworked clasts of the Cache Valley Formation are much less abundant here at the top of the Third Creek member than at the base (compare with stop 4). Note that none of the conglomerates in the Deep Creek half graben contain clasts derived from the Pocatello Formation.

The higher proportion of quartzite clasts from the Brigham Group here at the top of the Third Creek member than in the base of the member (stop 4), or in the Skyline member (stop 6), is consistent with unroofing of the footwall of the basin during deposition of the Salt Lake Formation. This unroofing sequence continues upsection into the New Canyon member, which contains even greater proportions of Brigham Group clasts than the underlying members (Fig. 9) and appears to contain a larger proportion of clasts from stratigraphically lower parts of the Brigham Group. The unroofing sequence and the presence of clasts reworked from underlying members of the Salt Lake Formation indicate that deposition of the Salt Lake Formation was synchronous with normal faulting.

The conglomerate subunit at stop 5 has a white calcite cement that imparts the characteristic white color to this conglomerate

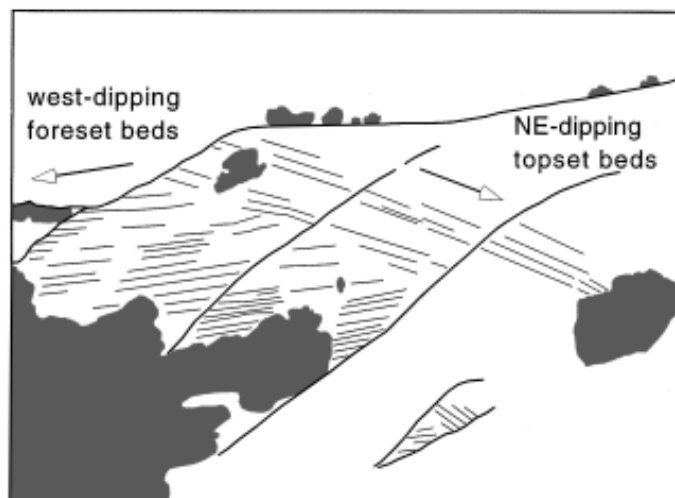


Figure 17. Photograph and sketch of large foreset and topset beds of a Gilbert-type delta in the upper Third Creek member of the Salt Lake Formation. Note person in center of photo for scale. This view is towards the west-northwest.

and makes it an excellent marker unit within the northern part of the Deep Creek half graben. The overlying New Canyon member of the Salt Lake Formation is noticeably darker in color, forms reddish to brown hillslopes, has a slightly larger grain size (including cobbles and occasional boulders), and is less well-cemented at this stop. A tuffaceous limestone bed locally marks the contact between the Third Creek and New Canyon members. Excellent exposures of the New Canyon member crop out on the west side of Oxford Peak north-northeast of stop 5.

The white conglomerate subunit of the Third Creek member overlies tephra and tuffaceous sedimentary rocks, limestones, and occasional conglomerate beds that comprise most of the Third Creek member. The conglomerate beds within the middle tuffaceous part of the Third Creek member display trough cross-stratification, channel cross sections, scour surfaces, and mud cracks indicative of a fluvial environment. Flow within some of these conglomerate beds north of First Creek was toward the north-northwest (Fig. 20a).

The excellent exposures at stop 5 show a range of sedimentary structures. Most impressive are the enormous (>20 m) foreset and topset beds within the conglomerates at stop 5B (Fig. 17) that resemble Gilbert-type delta deposits. The tilt-corrected

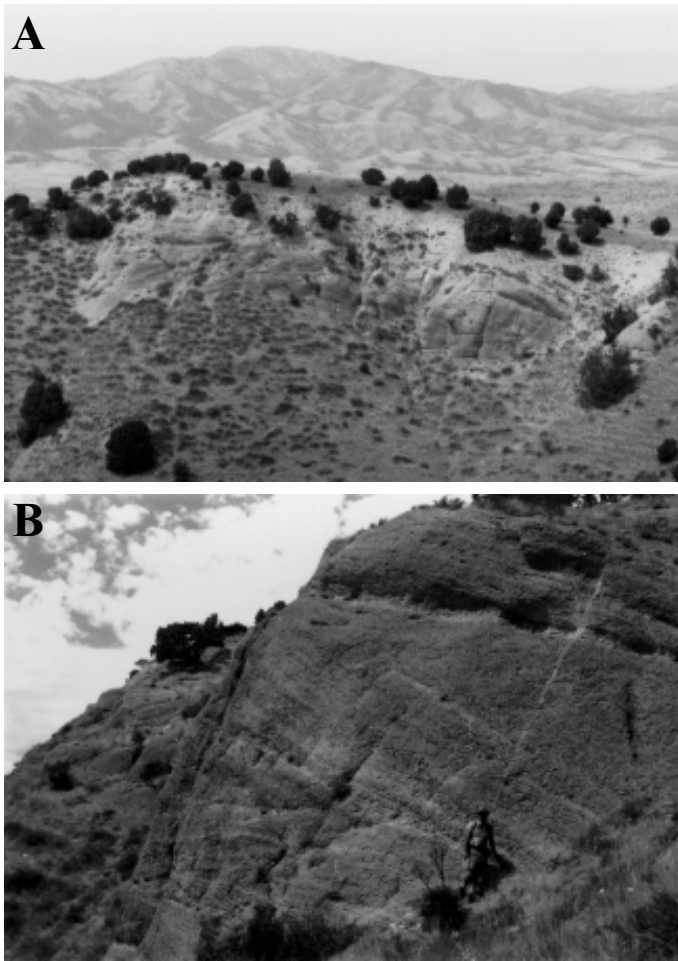


Figure 18a and b. View to the north-northwest of a large exposure of cross-beds of the upper Third Creek member of the Salt Lake Formation. These cross-beds are smaller and more variable than those in Figure 17 (see text for discussion).

foresets dip to the west (Fig. 20c). These exposures are interpreted to have been along the eastern margin of a major lake.

The conglomerate beds at stop 5A and 5C overlie and are along strike of the delta deposits at stop 5B yet show different sedimentary structures. Stop 5C provides a view of a seemingly chaotic cliff of well-rounded and cross-stratified pebble conglomerates (Figs. 18a and b). The compositions, degree of rounding and sorting resemble that at stop 5A and 5B but the cross stratification consists of large planar cross stratification (Fig. 17). The dip of the cross stratification is quite variable and many sets appear to dip in opposite directions (Figs. 18a and 20b). Individual foresets display a fairly high degree of sorting and alternating coarse and fine conglomerate beds (Fig. 18b). These probably represent individual flood events or sorting by storms. Inverse grading is also present. The degree of rounding, and 180° spread in flow directions (from west-northwest to southeast, Fig. 20), is consistent with deposition in a nearshore environment along the margins of a lake, possibly in river-mouth bars, a braid delta, or braided stream. The difference between the sedimentary structures in the conglomerate at stop 5B and 5C is striking and must indicate a different depositional environment.



Figure 19. Sub-rounded to rounded clasts of predominantly Brigham Group quartzite in the upper Third Creek member of the Salt Lake Formation. Note the relatively well-sorted nature of the deposit, and alteration between smaller and larger clasts in adjacent beds of conglomerate.

Participants will also discuss whether the quartzite clasts in these conglomerates could have been derived from the Brigham Group exposed in the footwall of the Deep Creek half graben, as little as 4 km to the east. Is a more distant source area needed to explain the well-rounded clasts of the white conglomerate sub-unit? How can the apparent northeastward flow at stop 5C be reconciled with the westward flow at stop 5B?

Return to the vehicles and head back on the gravel road towards Highway 36.

- |     |      |   |
|-----|------|---|
| 0.7 | 65.7 | Return to Highway 36 and turn right (west).   |
| 0.1 | 65.8 | Reworked clasts of the New Canyon member of the Salt Lake Formation are exposed on the right of the road.   |
| 0.1 | 65.9 | A layered clay deposit of unknown origin containing clasts of the Cache Valley member of the Salt Lake Formation is exposed on the right in a small roadcut. This deposit is too high to be a Quaternary Lake Bonneville deposit.   |
| 0.3 | 66.2 | Access to Deep Creek Reservoir is on the left.  |
| 0.6 | 66.8 | Skyline and Cache Valley members of the Salt Lake Formation compose the hills to the far left. The Cache Valley member of the Salt Lake Formation (northeast-dipping) is to the right of the road.  |
| 0.9 | 67.7 | USFS 049 (3000 North, Dry Creek Road) is on the right. This road provides access to excellent exposures of Third Creek and New Canyon members of the Salt Lake Formation, but four-wheel drive vehicles are recommended on its eastern end. Continue straight on Highway 36.  |
| 0.8 | 68.5 | An outcrop of Ordovician Fish Haven and Swan Peak Formations is exposed approximately half way up the wash to the left. This outcrop is bounded by a west-dipping Basin-and-Range fault on the west and a SSW-dipping WNW-striking normal fault on the south (Fig. 3). Quaternary Bonneville clays are exposed in roadcuts to the right for the next 1.5 miles. |

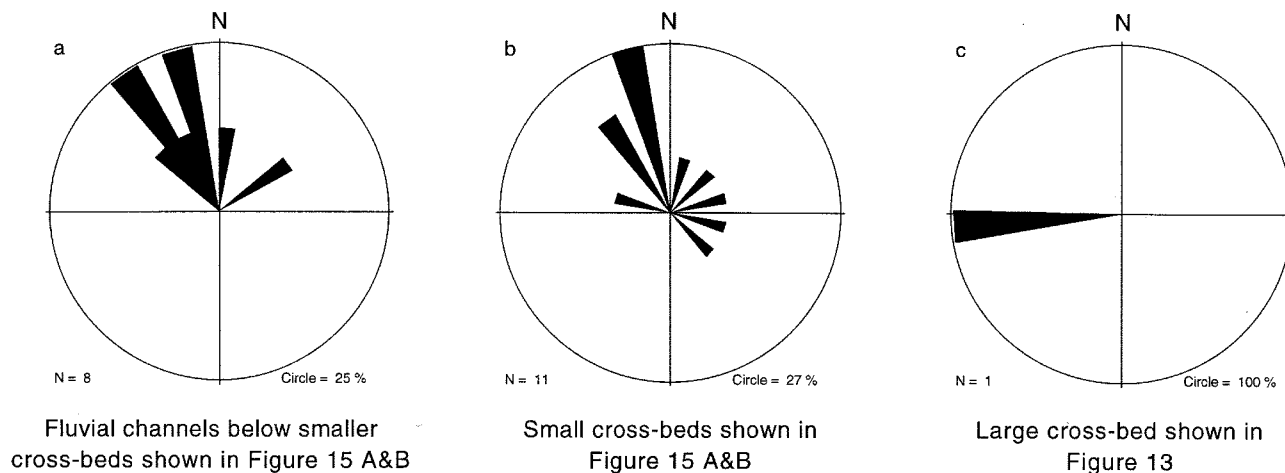


Figure 20. Rose diagrams showing flow directions determined from the dip of planar cross-beds and the trend of fluvial channels in the Third Creek member of the Salt Lake Formation. All measurements were corrected for subsequent tilting. a) Paleocurrents from fluvial conglomerate in the middle part of the Third Creek member. Two bidirectional indicators were inverted to conform to the flow direction suggested by the unidirectional indicators. b) Paleocurrents from the upper conglomerates of the Third Creek member at view stop 5C, north of First Creek (Figs. 18a and 18b). c) Paleocurrents from the Gilbert-type delta in the upper conglomerate of the Third Creek member at stop 5B (Fig. 17). See Figure 16 for locations.

- 1.2 69.7 The hills on the left show east-dipping Cache Valley member of the Salt Lake Formation in fault contact with west-dipping Ordovician Fish Haven and Silurian Laketown Formations. The flat surface lower on the hills marks the Quaternary Lake Bonneville shoreline.
- 0.2 69.9 You are now entering Malad Valley and crossing the northern end of the Malad City segment of the Wasatch fault (Machette et al., 1991, 1992). This is considered to be the northernmost segment of the Wasatch fault. The Wasatch fault, however, appears to bend to the northwest and continue across the interstate along the southwest side of Elkhorn Mountain, the range visible in the distance. Malad Valley is also continuous in the hanging wall of the fault. The Lower Paleozoic rocks of Elkhorn Mountain are cut by a bewildering array of normal faults (Oriol et al., 1991).
- 0.3 70.2 Turn left (south) onto Interstate-15 towards Malad, Idaho.
- 1.5 71.7 Interstate-15 runs parallel to the Malad City segment of the Wasatch fault. The fault can be seen on the left and straight ahead. The segment is 17 km long and had no latest Quaternary surface ruptures (Machette et al., 1991, 1992).
- 0.9 72.6 Take exit 13 (Malad) and continue west on 50 South.
- 0.8 73.4 Take a left at the first stop sign (at the "T" in the road). This is Main Street. Drive south on Main Street out of town.
- 1.7 75.1 Take a left onto 1500 South (gravel road). This is Two Mile Road.
- 0.7 75.8 The road passes underneath Interstate-15.
- 0.5 76.3 The road enters Two Mile Canyon. Link and Smith (1992) describe the top of the Brigham Group north of the road.

- 1.7 78.0 **Stop 6.** Pullout on left and park at the northernmost part of the road where it bends back to the south. We will take a short hike to an outcrop just north of the road. The purpose of this stop is to observe one of the main stratigraphic units within the Deep Creek half graben, the Skyline member of the Salt Lake Formation, and to briefly introduce two large cross faults of the Deep Creek half graben.

The Skyline member of the Salt Lake Formation represents the basal conglomerate unit of the basin fill deposits. This member is rarely consolidated and many inferences are based on observations of float. The exposures at this stop are the only good outcrops of this unit in the study area. The Skyline member consists of poorly sorted pebble to cobble conglomerate with some thin interbedded tephra and limestones. Clasts vary from angular to subrounded, with a high percentage of clasts being subangular. Beds range from a few centimeters to > 30 cm in thickness and contain some outsized clasts. The unit is matrix-supported to matrix-rich and has a sandy, calcareous, and tuffaceous matrix. Because of the poor sorting, angularity of clasts, outsized clasts within some beds at this exposure, and matrix-supported beds, we interpret this member as an alluvial fan deposit. The source was the underlying Paleozoic section and the Eocene Wasatch Formation. The reddish tint to the matrix at this exposure may reflect the incorporation of debris from the underlying Wasatch Formation.

Beds in this locality dip moderately northeast. The Cache Valley member overlies the Skyline member to the east and is well exposed in road cuts on the north side of Two Mile Road. East of this stop, Two Mile Road is impassable when wet.

Two large cross faults project into this area. The southeast-dipping Two Mile normal fault places Cambrian carbonate rocks in the hanging wall against the Camelback Mountain Quartzite in the footwall at the western end of Two Mile Canyon (Axtell, 1967;



S.S. Oriel, unpublished mapping). Eastward the fault repeats units of the Cambrian carbonate sequence. The fault continues into the Salt Lake Formation at its northeastern end for at least another 3 km, but the offset is small. The northeast-dipping Maple Hollow normal fault also projects into this area (Axtell, 1967; S.S. Oriel, J.C. Evans, unpublished mapping) and appears to be cut by the Two Mile fault and several parallel faults to the southeast (Fig. 3). Spotty exposures in the Salt Lake Formation complicate efforts to trace these faults eastward through the Tertiary rocks.

End of road log. To return to Pocatello, retrace the route back to I-15 and drive north. To return to Cache Valley, continue east along the Two Mile road to Idaho route 36. Turn right and follow the paved road to Weston, Idaho.

## Summary

Several lines of evidence show that multiple generations of normal faults deformed the northeastern Basin-and-Range province in the Late Cenozoic. The active Basin-and-Range normal faults generally strike north-south and dip both east and west. These include both the prominent range-front faults and smaller intrabasin normal faults (see stop 3). The older Miocene-Pliocene normal faults include at least three geometric sets of normal faults. These include, from youngest to oldest: northeast- and northwest-striking high-angle normal or strike-slip faults and WSW-dipping detachment faults. The WSW-dipping detachment faults of the Bannock system were active during and after deposition of the late Miocene to Pliocene Salt Lake Formation, accommodated large magnitude extension, and exhumed lower greenschist grade rocks in their footwall. Extensional folds developed in association with every set of normal faults, have a wide range of geometries, and are almost as common as normal faults within the Deep Creek supradetachment basin.

The crosscutting relationships between the detachment faults of the Bannock system and the Salt Lake Formation show that large magnitude extension in the northeastern part of the Basin-and-Range province was very young, and occurred after 10 Ma. This, and evidence for late Cenozoic extension in the Raft River Range to the west (Compton, 1983; Todd, 1983; Covington, 1983), and along the Sevier Desert detachment fault to the south (Coogan and DeCelles, 1996), shows that a recent, elegant model by Stewart (1998) of WSW-ward younging of large-magnitude extension along detachment faults, followed by WSW-ward younging of smaller-magnitude extension along steeper Basin-and-Range normal faults, provides an incomplete view of the time-space patterns of extension in the North American cordillera. Our data show that large-magnitude extension along detachment faults began or continued to affect a large portion of the northeastern and eastern margins of the northern Basin-and-Range province after 10-5 Ma. The modern Basin-and-Range faults in this area are therefore very young features (Pliocene to Recent). The ~17 Ma age traditionally assigned to initial Basin-and-Range normal faulting is thus more than 10 my too old. This conclusion is in accordance with data from other part of the northeastern Basin-and-Range province, including the northern end of the Blackfoot Range (Allmendinger, 1982), Portneuf Range (Kellogg and Marvin, 1988), Sand Hollow basin (Miller and Schneyer, 1994), and the young age of basin-fill deposits in the easternmost part of the

province (Perkins et al., 1998).

The large WSW-dipping detachment fault, or system of faults, active in the northern Cache Valley basin of southeastern Idaho during Miocene-Pliocene time, resembles the well-known Sevier Desert detachment fault in both geometry, structural setting, scale, and age. Both systems dip gently west and extend the structurally highest thrust sheet at that latitude. Thick sequences of latest Proterozoic to early Paleozoic quartzites are key features of both thrust sheets. Extension on the Sevier Desert detachment began earlier (Oligocene) and continued after (to Recent) extension on the Bannock detachment system. If future work confirms our regional model of the Bannock detachment system, then the system persists along strike (north-south) for about 150 km. This exceeds the 80-130 km along strike extent of the Sevier Desert detachment (Planke and Smith, 1991). Because active Basin-and-Range faults have partially dismembered the Bannock detachment system, it, unlike the Sevier Desert detachment, is exposed at the surface. Detailed structural analysis of the Bannock detachment system may help resolve some of the recent controversy surrounding the Sevier Desert detachment (Anders and Christie-Blick, 1994).

## FUTURE WORK

1. Does the active East Cache fault, which bounds the eastern margin of Cache Valley in Utah, coincide with, reactivate, or cut out the breakaway of the Bannock detachment system?
2. Might the quartzite clast conglomerates and gravels of the Third Creek and New Canyon members of the Salt Lake Formation in the Deep Creek half-graben have a source in the Bear River Range or Portneuf Range to the east?
3. We hypothesize that the younger members of the Salt Lake Formation were deposited in individual half-grabens. Early deposits of the Salt Lake Formation, such as the Cache Valley member, may have been deposited in a larger basin that was later dissected by normal faults. This hypothesis needs to be tested by examination of the Salt Lake Formation east of the Deep Creek half-graben.
4. What is the regional extent of the Bannock detachment system and how does it interact with other Miocene detachment systems in the region?
5. Is the Weston Canyon thrust fault a significant regional structure and what is its lateral extent?

## ACKNOWLEDGMENTS

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