# Evolution of a late Cenozoic supradetachment basin above a flat-on-flat detachment with a folded lateral ramp, SE Idaho

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# ABSTRACT

Uplift and exposure of the Bannock detachment system and the synextensional basin fill deposits of the Salt Lake Formation provide a unique exposure of the threedimensional geometries of a low-angle normal fault system and the stratal architecture of the overlying supradetachment basin. Within this system, structural and stratigraphic analyses, outcrop patterns, tephra geochronology, and geological cross sections document several important relationships: (1) the Bannock detachment system developed above the Sevier-age Cache-Pocatello culmination and resembles the Sevier Desert detachment in its geometry, structural setting, and kinematic evolution; (2) the Bannock detachment system initiated and slipped at low angles; (3) flaton-flat, ramp-flat, and lateral ramp geometries, as well as excision, can significantly affect the hanging wall deformation style due to the shallow depth (~2–4 km) of the Bannock detachment fault during late stages of slip; (4) late Miocene–Pliocene tuffaceous synrift deposits of the Salt Lake Formation record deposition in a supradetachment basin, display an unroofing sequence, and a three-stage evolution that includes pre-translation, translation, and breakup phases. Recycled pre-translation and trans-

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lation phase deposits are diagnostic of this evolution; and (5) beginning in mid- to late Pliocene time, high-angle, north-striking Basin and Range faults disrupted and dismembered the Bannock detachment system.

Keywords: detachment, basin evolution, lateral ramp, Salt Lake Formation, extensional fold.

# INTRODUCTION

# **Field Trip Goals**

On this field trip, we will visit critical exposures of the late Miocene–Pliocene Bannock detachment system and its associated supradetachment basin in southeastern Idaho (Fig. 1). We illustrate several field relationships in the Malad City East and Clifton quadrangles that were described previously in Janecke and Evans (1999), Janecke et al. (2003), Carney and Janecke (2005), and Carney et al. (2004), and these sources provide more detailed information. Our main focus is on two more recent studies in the Weston Canyon and Henderson Creek quadrangles that test, update, and refine earlier analyses. New geologic mapping in the Weston Canyon, Henderson Creek, Clifton, and Malad City East quadrangles forms the core of our data sets (Carney et al., 2004; Long et al., 2004; Steely and Janecke, 2005; Evans et al., 2000).

Hanging wall and footwall exposures of the Clifton strand of the Bannock detachment system along Rattlesnake Ridge in the Weston Canyon quadrangle comprise the majority of stops on this trip. Initial work provided evidence for slip on a subhorizontal normal fault in the form of a flat-on-flat low-angle detachment (Carney and Janecke, 2005), and subsequent mapping and analysis refine this relationship. At Stops 5 through 9, we examine this now well established relationship, discuss its implications, and investigate a ~850–1100-m-high folded lateral ramp along the same detachment fault. We also examine basin-fill deposits that record early translation and later breakup of the detachment's hanging wall.

A secondary focus is new work in the Henderson Creek quadrangle. Field studies in the southwest edge of the late Miocene–Pliocene Salt Lake Formation sedimentary basin identified and dated syntectonic conglomerates shed from the antithetic Steel Canyon normal fault in the hanging wall of the Bannock detachment fault (Long, 2004). Stop 1 briefly describes some of the key results of Long's research (Long, 2004; Long et al., 2004).

# **Regional Geology**

The late Cenozoic Bannock detachment system developed at the transition between the preexisting Cordilleran hinterland and the fold-and-thrust belt. A pre-Tertiary subcrop map of this area shows that the detachment formed above a major culmination related to uplift above the Paris-Willard thrust system during the Sevier Orogeny (Fig. 2). The Cache-Pocatello culmination is NNW-trending, 150 km long, and 25–30 km wide before Cenozoic extension. It exposed lower Cambrian rocks in its core (Fig. 2) and was first recognized by Rodgers and Janecke (1992). The culmination was named and refined by Carney (2002) and Long (2004). It likely formed east of the frontal Malad ramp of the Paris-Willard thrust system as a hanging wall ramp anticline on a footwall flat.

At least two phases of Cenozoic extension followed the Sevier Orogeny in the western United States (Stewart, 1998). Typically, the first phase of extension was accommodated by listric- to low-angle normal faults that developed in the hinterland and fold-and-thrust belt of the Cordillera. This extensional episode produced Eocene-Miocene metamorphic core complexes such as the top-to-the-east Raft River-Albion-Grouse Creek metamorphic core complex located ~125 km west of the Bannock detachment system (Fig. 3) (Wells et al., 2000). The structural style of the Bannock detachment system resembles this early phase of extension but the age and the magnitude of extension is less than that of most core complexes (Carney and Janecke, 2005).

The second major phase of extension in the western United States began in late early Miocene to Pliocene time and was accommodated by moderately- to steeply-dipping, planar to listric normal faults. These faults bound present-day mountain ranges that trend ~N-S (Figs. 1 and 4) and are regularly spaced ~30 km apart between the Sierra Nevada ange and the Colorado Plateau. Recent syntheses suggest that initiation of this phase of Basin and Range extension was not synchronous, but rather has migrated both east and west through time (Stewart, 1998; Henry and Perkins, 2001; Stockli, 2000; Janecke et al., 2003). The Bannock and Malad Ranges are both uplifted on the east and west by active north-striking Basin and Range normal faults. The Malad Range is uplifted on the west by northern segments of the Wasatch Fault, which extends southward 370 km through Utah (Machette et al., 1992; Chang and Smith, 2002). A new gravity data set presented here shows that the two normal fault zones that bound Cache Valley, the next basin to the east, have throws similar to the northern Wasatch fault (Oaks et al., 2005).

# **Tectonic Problems along Low-Angle Normal Faults**

Although low-angle normal fault systems have been widely recognized throughout the Basin and Range province, they are not uniformly distributed (e.g., Wernicke, 1992; Stewart, 1998). Some have suggested that they localize near "contractional welts" or culminations in the lithosphere (Coney and Harms, 1984; Spencer and Reynolds, 1991). The Bannock detachment system has a close spatial association with the Cache-Pocatello culmination (Fig. 3), and Carney and Janecke (2005) proposed that the additional gravitational potential energy and residual topography associated with the culmination helped to localize the Bannock detachment system. The collapse of culminations is a recurrent theme in extensional orogens that deform older contractional belts, and there are many examples of major normal faults localized above culminations within the western United States including the Sevier Desert detachment, Wasatch fault, and Salmon, Idaho, area detachment faults (Fig. 3) (Coogan and DeCelles, 1996; Yonkee, 1992; Janecke et al., 2000; Janecke and Blankenau, 2003). The Bannock and Sevier Desert detachment systems are similar in structural style; both are located 100-125 km east of metamorphic core complexes, and both developed above regional Sevier-age culminations (Fig. 3) (Carney and Janecke, 2005, and references therein).

Three models may explain the geological record of lowangle normal faults (Fig. 5A). Such faults may form and slip at low angles (Wernicke, 1981; Allmendinger et al., 1983; Lister and Davis, 1989; Davis and Lister, 1988), rotate to lower angles via domino-style extension (Proffett, 1977; Wernicke and Burchfiel, 1982; Gans and Miller, 1983; Rodgers et al., 2002), or back-rotate isostatically at a rolling-hinge (Buck, 1988; Wernicke and Axen, 1988; Brady et al., 2000). A specific suite of structures and relationships is predicted if a detachment fault initiates and slips at low angles (Wernicke, 1985; Davis and Lister, 1988; Carney and Janecke, 2005). Some hanging walls of detachment faults are structurally intact, but, as the amount of extension increases, some hanging walls break up internally along planar and listric high- to low-angle normal faults that are either cut by, or sole into, the master fault (Wernicke, 1985, 1992; Fedo and Miller, 1992; Fowler et al., 1995; Janecke et al., 2003; Carney and Janecke, 2005). As overburden thickness decreases in the hanging wall due to crustal extension, footwall mid-crustal rocks, as well as the bounding master fault, may dome upward to create a broad antiform at high angles to the extension direction (Spencer, 1984). During this process, the master fault may cut up into (excise) hanging wall rocks and may produce a secondary breakaway (Fig. 5B) (John, 1987; Davis and Lister, 1988; Carney and Janecke, 2005). Excision

Figure 1. Simplified geologic map showing the distribution of the Salt Lake Formation around Cache Valley and the active Basin and Range normal faults. Some older normal faults are also shown (gray). The Clifton horst is the up-thrown block between the Deep Creek and Dayton-Oxford faults. CV—Cottonwood Valley; DCF—Deep Creek Fault; DCHG—Deep Creek half graben; DOF—Dayton-Oxford Fault; ECF—East Cache Fault (N—northern; C—central; S—southern segment); OP—Oxford Peak; Q—Quaternary sediment; RRP—Red Rock Pass; Tsl—Salt Lake Formation; WCF—West Cache fault zone (CM—Clarkston Mountain; JH—Junction Hills; W—Wellsville segment); WF—Wasatch Fault. Some buried faults (dotted) from Zoback (1983). This map is modified from Janecke et al. (2003), with updates from unpublished gravity data of Oaks et al., 2005 (see Fig. 15) and Eversaul (2004).





Figure 2. Subcrop map showing the location and age of rocks beneath the Tertiary unconformity. Also shown are Mesozoic folds and thrusts of the Servier Orogeny, the location of the Oxford Peak anticline (OPA), and the location of the Cache Pocatello culmination. Modified from Carney (2002). In mountain ranges, the age of the youngest exposed rock unit was also used to construct the subcrop map. The E-W extent of the culmination is 50%–60% greater than it was at the end of the Sevier thrusting because of subsequent extension. DOF—Dayton-Oxford Fault; EDOF—East Dayton-Oxford Fault; WF—Wasatch Fault.



Figure 3. Regional map showing the major active normal faults adjacent to the Eastern Snake River Plain (ESRP), the NNW-trending Cache-Pocatello culmination (CPC), and other culminations of the thrust belt. Note that the Bannock detachment system coincides with the Cache-Pocatello culmination and has the opposite vergence as the partly coeval Raft River detachment (Wells et al., 2000). A Cambrian and older pre-Tertiary subcrop defines the extent of the Sevier, Wasatch, and Salmon area and most uplifted portions of the Cache-Pocatello culminations. The extent of the Devonian and older subcrop is shown for the CPC. SC-Sevier Desert culmination; SAC-Salmon area culminations; WC-Wasatch culmination; SDD-Sevier Desert detachment; YH-Yellowstone hotspot. Modified from Carney and Janecke (2005).



Inferred lateral extent of the breakway for the Bannock detachment and Sevier Desert systems



Figure 4. Simplified geologic map of Clifton, Henderson Creek, Malad City East, and Weston Canyon 7.5' quadrangles. See Fig. 2 for location. Compiled from Evans et al. (2000), Carney (2002), Long (2004), and Steely and Janecke (2005).



Figure 5. (A) Schematic diagrams showing three models of extensional low-angle normal faults. (B) Schematic diagram showing excision: 1—original geometry; 2—slip on detachment fault; 3—doming; 4—creation of a new low-angle listric breakaway. Higher angle faults are cut by the low-angle fault; 5—continued slip juxtaposes synrift deposits in the hanging wall with rocks in the footwall of the detachment fault for the first time. Excised fault block is shaded. Modified from Carney and Janecke (2005).

was important during the evolution of the Bannock detachment fault (Carney and Janecke, 2005).

The original three-dimensional geometry of low-angle normal faults is critical to understanding how folds and corrugations evolve within the fault system and how hanging wall deformation is affected by fault geometry. Because some detachment faults slip within a few kilometers of Earth's surface (Smith, 1984; Otton, 1995; Axen et al., 1999; Carney and Janecke, 2005), ramp-flat and lateral ramp geometries can significantly affect the hanging wall thickness and consequently may play a pivotal role in determining the deformational style of the hanging wall. These fault geometries may also affect sedimentation patterns in the overlying supradetachment basin.

An important feature of low-angle normal fault systems is the formation of supradetachment basins and their associated fill. These basin-fill deposits allow us to reconstruct the timing of deformation events through careful analysis of stratigraphy, sedimentology, and structural geology, coupled with geochronology. Recent work (VanDenburg et al., 1998; Janecke et al. 2003; Janecke and Blankenau, 2003; Janecke, 2004), building on earlier work by Friedmann and Burbank (1995), has shown that distinct stratal architectures result from the two-stage evolution of many supradetachment basins. The first phase, called the translation phase, is marked by conformity to subtle-fanning dips within widespread basin fill deposited during simple translation. The second phase of evolution begins as the basin breaks up internally into smaller half graben above the master detachment fault. This phase is commonly marked by angular and progressive unconformities, dramatic decreases in basin size, the potential for more lateral variations in depositional systems relative to the translation phase, and the presence of clasts recycled from translation-phase deposits. The recycled clasts are particularly significant because they demonstrate that some areas of the previously intact basin were uplifted and eroded during breakup

(Janecke and Evans, 1999; VanDenburg et al., 1998; Janecke et al. 2003; Janecke and Blankenau, 2003).

# STRATIGRAPHY OF STUDY AREA

Bedrock strata in the study area consist of the Neoproterozoic Pocatello Formation, Neoproterozoic to Cambrian Brigham Group rocks, and Cambrian to Devonian miogeoclinal carbonates and shales deposited within the Cordilleran miogeocline (Fig. 6). Silurian to Permian rocks crop out to the west of the study area in the Samaria Mountains and to the east in the Bear River Range (Platt, 1977). Any late Paleozoic to Mesozoic units that once covered the area were eroded from the Cache-Pocatello culmination before Eocene time (Fig. 2).

The Paleocene to Eocene Wasatch Formation, late Miocene to Pliocene Salt Lake Formation, and Pliocene-Pleistocene(?) piedmont gravel deposits overlie the Paleozoic and older rocks along an angular unconformity (Fig. 6). The distinctive lithologies of the pre-Tertiary bedrock in the study area allowed reconstructions of specific source areas for the late Cenozoic basin-fill deposits. Quaternary lacustrine and near-shore deposits of the Lake Bonneville cycle cover most areas below ~1,560 m (5,120 ft) in elevation.

# **Pre-Cenozoic Stratigraphy**

#### Neoproterozoic Pocatello Formation

The Neoproterozoic Pocatello Formation is divided into three distinct members: the Scout Mountain Member, the Bannock Volcanic Member, and an unnamed upper member (Fig. 6) (Link, 1982a, 1982b; Link et al., 1993; Smith et al., 1994). Together the Pocatello Formation has an aggregate thickness of 450 m just north of the study area (Link, 1982a). All of the members have been metamorphosed to greenschist facies (Link, 1982a) and are foliated in the Clifton and Weston Canyon quadrangles. Only the Scout Mountain Member is present within Weston Canyon quadrangle, where it crops out from north of Fivemile Canyon to the southern end of Rattlesnake Ridge in the south and attains a minimum thickness of ~350 m (Fig. 4). The Bannock Volcanic Member is exposed along Oxford Ridge in the Clifton quadrangle (Carney, 2002). 709 Ma zircons in a metatuff in the Clifton quadrangle indicate that the Scout Mountain Member is Sturtian in age (Fanning and Link, 2004).

Within the Weston Canyon quadrangle, the Scout Mountain Member consists of green to green-brown siltstone, fine- to coarse-grained sandstone, and diamictite, with local interbeds of 1-3-m-thick tan to tan-gray limestone marble along the uppermost exposures of Rattlesnake Ridge. The Scout Mountain Member is composed dominantly of siltstone and rare to locally abundant matrix-supported, pebble to cobble conglomerate. Clasts dispersed in the diamictite include metavolcanics, quartzites, and granitoids. In the footwall of the Bannock detachment system, weaker pebbles (metavolcanics) are stretched where a pervasive weak to strong foliation is also present, and sometimes preserve two lineations. Some areas have two foliations at acute angles to one another.

Because foliation has overprinted primary bedding within most of the footwall rocks, understanding the relationship between these two fabrics is crucial in constraining the cut-off angle between footwall rocks and the Bannock detachment fault. Several locations within the Weston Canyon quadrangle document primary bedding of the Pocatello Formation and confirm that it is parallel to subparallel with foliation fabrics where both are observed on the west limb of the Oxford Ridge anticline. Outcrops at A on Figure 7 expose well-bedded siltstone and sandstone, which are overprinted by bedding-parallel foliations. The north end of Rattlesnake Ridge (B on Fig. 7) exposes thin- to medium-bedded siltstone, sandstone, and small pebblegranule conglomerate with bed-parallel foliations. Along the southern part of Rattlesnake Ridge, the outcrop pattern of a thin marble bed is parallel to foliation in the underlying and overlying diamictite (C on Fig. 7). Bedding parallel foliations like these are documented at the base of the Paris-Willard thrust sheet along structural strike to the south (Yonkee et al., 1997).

# Late Neoproterozoic-Cambrian Brigham Group and Paleozoic Strata

The late Neoproterozoic to Cambrian Brigham Group contains ~1.6 km of quartzite, pebbly quartzite, sandstone, vitreous quartzite, and micaceous argillite (Fig. 6) (Link et al., 1987; Carney et al., 2002). Only the upper five of eight units of the Brigham Group crop out within the Weston Canyon quadrangle (Fig. 6; Mutual Formation, Rocky Peak Phyllite Member, Camelback Mountain Quartzite, Windy Pass Argillite, and Sedgwick Peak Quartzite). Cambrian to Devonian rocks of the Cordilleran miogeocline crop out throughout the four quadrangles and have a composite thickness of ~2.9 km (Fig. 6) (Biek et al., 2003; Carney et al., 2002; Long, 2004). These rocks are dominantly composed of limestone, dolostone, calcareous to non-calcareous shale, and lesser sandstone and quartzite.

The distinctive lithologies of four main groups of pre-Tertiary rocks (Pocatello Formation, Brigham Group, middle to lower Paleozoic rocks, and upper Paleozoic rocks) allow us to determine the source of conglomerates and to reconstruct the paleogeography of the Tertiary deposits. Within the Paleozoic rocks, several key lithologies allow us to further refine the approximate stratigraphic level exposed. Some of these key lithologies are a vitreous bright white quartz arenite of the Swan Peak Formation, which is readily distinguished from the red to purple quartzites of the Brigham Group quartzite. Black chert from the Garden City Formation, tan chert from the St. Charles Formation, and reddish-orange–weathering sandy limestone of the Oquirrh Formation are also distinctive.

#### **Cenozoic Stratigraphy**

#### Wasatch Formation

The Wasatch Formation is an early to middle Eocene deposit of the Sevier fold-and-thrust belt in the Idaho-Wyo-ming-Utah region (Coogan, 1992; Oaks and Runnells, 1992;

Oaks et al., 1999; Long, 2004). The unit is considered syntectonic with late main-stage movement on the frontal Hogsback thrust in western Wyoming (DeCelles, 1994) but also laps across the entire thrust belt as far west as the Malad Range. It was deposited in both N-S- and E-W-trending Eocene grabens (Oaks and Runnells, 1992; Long, 2004) above the Paris-Willard thrust sheet after movement ceased on this thrust (Coogan, 1992).

The Wasatch Formation either unconformably overlies or is faulted against Cambrian through Devonian rocks in the Malad Range and Oxford Ridge area (Fig. 6) (Carney, 2002; Long, 2004). It generally consists of red, moderately to poorly consolidated, matrix-rich, pebble to boulder conglomerate with a thickness of <189 m in the Henderson Creek quadrangle. It is interpreted as a braided stream and locally-derived alluvialfan deposit that shows evidence for syndepositional tilting and faulting in an asymmetric south-tilted half graben (Fig. 8) (Long, 2004). The Wasatch Formation is dominated by locallyderived middle Paleozoic-age clasts (Fig. 9).

#### Salt Lake Formation

The Salt Lake Formation is the sedimentary product of extension in the northeast Basin and Range province (Janecke and Evans, 1999; Oaks et al., 1999; Goessel et al., 1999; Janecke et al., 2003; Kruger et al., 2003). A strong spatial association exists between the Salt Lake Formation and highly extended areas above detachment faults (Carney and Janecke, 2005). Within the Bannock and Malad ranges, all but the basal Skyline Member of the Salt Lake Formation has been interpreted as synextensional basin fill deposits above the Bannock detachment fault system (Janecke and Evans, 1999; Janecke et al., 2003). The Skyline Member filled early, pre-detachment half-graben (Janecke et al., 2003; Long, 2004). It was overlain by the Cache Valley Member of the Salt Lake Formation, which filled one continuous supradetachment basin above the Bannock detachment fault. The Valley fault in the Portneuf Range, its along-strike continuations, and the ancestral-East Cache fault are interpreted as the breakaway for the Bannock detachment system (Fig. 1) (Janecke and Evans, 1999; Janecke et al., 2003; Eversaul, 2004).

After a period of translation this large basin broke up internally. Smaller half graben formed above the detachment fault, and older synrift strata were uplifted, eroded, and redeposited as clasts in younger synrift strata of the Third Creek and New Canyon members of the Salt Lake Formation (Janecke et al., 2003).

The Salt Lake Formation consists of four members (Figs. 6 and 8), and three of these crop out in the Weston Canyon and Henderson Creek quadrangles (Skyline, Cache Valley, and Third Creek members). The maximum intact and unfaulted exposure of Salt Lake Formation is ~2.5–2.7 km thick west of Rattlesnake Ridge in the Weston Canyon quadrangle (Fig. 7). The Salt Lake Formation has a composite thickness of >4.3 km in the Malad and SE Bannock ranges.

*Skyline Member.* The Skyline Member is the basal unit within the Salt Lake Formation, and lies along angular uncon-



Figure 6. Generalized stratigraphic column of strata exposed in the field trip area and plot showing the provenance of Tertiary conglomeratic basin fill deposits. Note the overall unroofing sequence, absence of Pocatello Formation in basin fill, and recycling of Tertiary rocks in the Third Creek Member.



Figure 7. Simplified geogic map of the northeastern Weston Canyon and southeastern Clifton quadrangles. Note the concordance of the gravity saddle with the trend of the lateral ramp in the detachment fault. BDF-Bannock detachment fault system (includes the Clifton and Bannock faults); ORA-Oxford Ridge anticline. Modified from Steely and Janecke (2005) and Carney (2002).



(Weston Canyon quadrangle)

Qbo



n=26 sites

<3%

Recycled

Tertiary

tuffaceous

siltstone and

limestone

n=9 sites

Recycled

Tertiary tuffaceous

siltstone and

limestone

19%

Upper

Paleozoio

sandstone

siltstone and

limestone

Eocene

14%

\_

Upper

Paleozoic

sandstone,

siltstone, and

limestone



Figure 9. Combined clast count data from conglomeratic basin-fill deposits of the Clifton, Henderson Creek, Malad City East, and Weston Canyon 7.5' quadrangles (see Fig. 4 for quadrangle locations). Note the unroofing sequence shown by upsection increases in Brigham Group quartzites with a simultaneous decrease in Paleozoic clasts. Also note the sudden influx of recycled clasts of tuffaceous and calcareous Salt Lake Formation during deposition of the Third Creek Member. Clast count data is from this study (n = 21 for unit Ttc; n = 6 for Tcv conglomerates); Janecke and Evans (1999), Carney (2002), and Long (2004) (n = 58); n—number of clast counts in each chart (each count represents either 50 or 100 clasts at a single location).

formity on the Wasatch Formation and lower Paleozoic rocks. It is preserved in the western Deep Creek half graben within the Skyline subbasin at the southern end of the Malad City East quadrangle and the north end of the Henderson Creek quadrangle (Fig. 4) (Janecke and Evans, 1999; Long, 2004).

The Skyline Member is up to 685 m thick in the Henderson Creek quadrangle (Fig. 8), and most beds are >30 cm thick. The unit consists of poorly sorted, tuffaceous, pebble to cobble conglomerate with interbedded tephra beds and locally interbedded lacustrine limestone (Janecke and Evans, 1999; Janecke et al., 2003; Long, 2004). Tephra beds are light-colored, up to 5 m thick, and commonly contain angular gray and black glass shards.

Clasts within conglomeratic intervals are composed dominantly of lower and middle Paleozoic carbonate, chert, and minor quartzite but include some upper Paleozoic units as well. However, light-colored tuffaceous to calcareous siltstone clasts are also present within the Skyline Member. These clasts are either rip-ups from Miocene limestone and tephra units within the Skyline Member of the Salt Lake Formation or were derived from surrounding areas where Salt Lake Formation deposits were being uplifted and recycled. A 90-m-thick section of crystalline and micritic white limestone is present near the base of the member in the Henderson Creek quadrangle. This limestone deposit suggests that earliest deposition of the Salt Lake Formation may have occurred in small lacustrine basins. Conglomerates of the Skyline Member are interpreted as alluvial-fan deposits that filled a local east-tilted half graben (Janecke et al., 2003; Long, 2004).

Tephra correlations from the Skyline Member reported in Long (2004) indicate an age of  $11.93 \pm 0.03$  Ma near the base and 10-11 Ma near the top, but these ages are being reevaluated in light of a large population of 14–15 Ma detrital zircons in a slightly reworked tephra near the top of the Skyline Member. The Skyline Member may be correlative with the Collinston Conglomerate farther south (Goessel et al., 1999). Both deposits are coarse basal units of the Salt Lake Formation and fill local half graben above west-dipping normal faults.

Cache Valley Member. The Cache Valley Member overlies the Skyline Member along a gradational to sharp contact in the Skyline half graben (Janecke and Evans, 1999; Long, 2004). Elsewhere it overlies lower Paleozoic rocks and the Wasatch Formation along a slight angular unconformity (Fig. 8). It is exposed primarily on the west and south sides of the Deep Creek half graben and on the east and west sides of Oxford and Rattlesnake Ridges in the hanging wall of the Bannock detachment fault (Fig. 4). It is at least ~617 m thick based on map measurements west of Rattlesnake Ridge. This thickness is similar to a thickness of 610 m of lacustrine beds in the Henderson Creek quadrangle (Long, 2004), and a minimum thickness estimate of 600 m in the Clifton quadrangle (Carney, 2002). Oaks (2000) estimated >746 m thickness of the Cache Valley Member along the northern Wellsville Mountains, and Goessel et al. (1999) and Biek et al. (2003) showed >975 m between the base and their overlying oolitic subunit in the Junction Hills and southern Clarkston Mountain. The relatively uniform thickness of the Cache Valley Member in the Malad and SE Bannock ranges contrasts sharply with the abrupt lateral thickness changes of the overlying and underlying members of the Salt Lake Formation (Fig. 8).

A rhyolite tuff at the base of the Cache Valley Member in the Malad City East quadrangle is a distal exposure of the tuff of Arbon Valley dated at  $10.21 \pm 0.03$  Ma (Morgan and McIntosh, 2005). This tuff has a distinctive mineralogy of smoky quartz, sanidine, plagioclase, and biotite crystals and provides a useful marker when present. Long (2004) observed the tuff of Arbon Valley in the basal Cache Valley Member and obtained a tephra correlation of  $9.16 \pm 0.03$  Ma from high in the lacustrine Cache Valley Member in the Henderson Creek quadrangle. This is the youngest preserved Cache Valley Member in our area (Fig. 8). Elsewhere, Cache Valley lithofacies had been replaced by conglomerate-bearing Third Creek lithofacies by this time.

Within the Weston Canyon quadrangle the Cache Valley Member consists of interbedded tan-white limestone to silty limestone with white to green tuffaceous mudstone, siltstone, and sandstone. Lesser calcareous mudstone and siltstone, silicified laminated limestone, rare fine- to medium-grained sandstone and discrete beds of poorly sorted granule to rare small boulder conglomerate crop out in the quadrangle. Bedding within the unit ranges from laminated to thick and poorly bedded. A slight overall upsection increase in sandstone content within the Cache Valley Member occurs west of Rattlesnake Ridge. Rare conglomerate beds in the Cache Valley Member are localized within the Weston Canyon and Henderson Creek quadrangles near the base

of the unit. Within the Weston Canyon quadrangle, one to three conglomerate beds extend from the north edge of the quadrangle to the southern end of Rattlesnake Ridge across a distance of  $\sim$ 7 km (Fig. 7). These beds are 1–4 m thick, composed of poorly sorted, matrix- to clast-supported, subangular to well-rounded granules to cobbles and rare small boulders of lower-middle Paleozoic carbonate, lesser Paleozoic quartzite, locally abundant black and tan chert, and green quartzite. This green quartzite is probably stained Eureka Quartzite Member of the Ordovician Swan Peak Formation because the other possible source of green quartzite, in the upper Brigham Group, is interbedded with distinctive purplish to pink quartzite that is not present in the conglomerate beds of the Cache Valley Member (Figs. 9 and 10A). The conglomerate matrix is dominantly light-colored micrite mud, although some beds have a calcareous sand groundmass. These beds appear to overlie tuffaceous siltstone and sandstone along gradational to sharp contacts and are overlain along sharp contacts with micritic limestone or silicified laminated limestone. Just east of Fivemile quarry in the Weston Canyon quadrangle, conglomerate beds constitute ~5% of the lower ~220 m of the Cache Valley Member and pinch out north and south along strike into white to tan tuffaceous to calcareous siltstone, sandstone, or mudstone. Conglomerate beds persist 100-500 m along strike.

Lateral facies changes in the Cache Valley Member in the Henderson Creek quadrangle reflect a southwestward shoaling toward an intrabasinal fault block. Exposures in the western part of the Henderson Creek quadrangle are dominated by ledgeforming tufas interbedded with micritic limestone, reworked tuffaceous siltstone and sandstone, and primary tephra beds. The tufa-facies interfingers with and passes laterally eastward into micrite-dominated limestone and tuffaceous rocks. Micritic limestone is white to light gray, thin- to medium-bedded, and also contains thin silicified stringers. Both the micrite- and tufa-bearing facies locally contain ostracodes, gastropods, and pelecypods. These lithologies interfinger westward with a ~5.7-kmlong lens of syntectonic conglomerate shed from the then active Steel Canyon fault in the upper 60% of the Cache Valley Member (Long, 2004). The oldest conglomerate is  $9.67 \pm 0.09$  Ma (Long, 2004), approximately the age of the oldest conglomeratic Third Creek Member farther to the north (Janecke et al., 2003). These data show that Cache Valley lithofacies overlap in age with Third Creek lithofacies in the Henderson Creek quadrangle (Fig. 8).

In the Weston Canyon, Clifton, and Malad City East quadrangles, tuffaceous rocks of the Cache Valley Member have been altered to clays and zeolites to varying degrees (Janecke et al., 2003). These rocks are most commonly greenish, but may also locally be off-white, yellow, and tan, and are locally much more indurated than unaltered rock. A hackly fracture pattern is common. These highly altered rocks are in marked contrast to silvery, light gray primary tephras of the Third Creek Member (discussed below), which are much less altered and are poorly consolidated (Janecke et al., 2003).

Interpretation. We interpret the Cache Valley Member to represent widespread lacustrine deposition during "translation-





Figure 10. (A) Conglomerate bed in lower Cache Vallye Member at Stop 5. Note angularity and micrite supported clasts of dominantly gray Paleozoic rocks (inset). Green clasts are stained quartzite of the Ordovician Swan Peak Formation (q in photo). (B) Conglomerate of the Third Creek Member. Recycled clasts of the Salt Lake Formation (green; Tsl) outnumber quartzite clasts from the Brigham Group in this bed (red; CZb). Clasts are much more rounded than in conglomerates of the Cache Valley Member. (C) Exposure of the Bannock detachment with down-dip slickenlines developed on brecciated Cambrian-Neoproterozoic Camelback Mountain Formation. Fault places lower Cache Valley Member against Cambrian and Neoproterozoic rocks. Slickenlines trend WSW (Fig. 12D). View is to the east.

phase" westward motion of the relatively coherent hanging wall of the Bannock detachment fault (Fig. 11). This member is present in every part of the Salt Lake basin and is relatively uniform in its maximum thickness across lateral distances of ~20–30 km.

Conglomerate beds in the lower Cache Valley Member in the Weston Canyon quadrangle are interpreted as distal alluvial fan deposits that interfinger with near shore lacustrine deposits. The micrite matrix within the conglomerates suggests that they were deposited during a time of reduced ash input to the lacustrine system. The presence of pebble conglomerates in the lake suggests that there were highlands nearby, likely to the east, that were eroding during deposition of the lower Cache Valley Member deposition. These highlands may have been produced either by slip on an early intrabasinal breakup fault or there may have been remnant topography from older faults. The disappearance of these conglomerates upsection indicates that: (1) the remnant topography was fully eroded, (2) the intrabasinal fault ceased movement, or (3) progradation of conglomerates into the "Cache Valley lake" is controlled by the amount of ash covering local topography.

Relationships in the Henderson Creek quadrangle suggest that intrabasinal fault-bounded horst blocks began to produce subbasins within the large Cache Valley lacustrine system as early as 9.6 Ma. Despite localized conglomeratic input from the footwall of the Steel Canyon fault, the lake filled mostly with ash from the Yellowstone hotspot and with micrite and tufa. Carbonate deposition was localized in the shallower parts of the lake between major volcanic eruptions, with tufa near the shoreline and micrite in more offshore positions (Long, 2004).

Facies patterns show that the apparent change in water chemistry was accompanied by shoaling to the south and west. The lake beds locally passed laterally into syntectonic intrabasinal alluvial-fan conglomerates in the Henderson Creek and eastern Weston Canyon quadrangles. Persistent lacustrine conditions may reflect a relatively stable sill and steady input



Figure 11. Reconstructed paleogeographic maps and cross sections of the northern Cache Valley area between the Samaria Mountains and the Bear River Range. Faults that developed during the next episode of deformation are shaded and dashed. (A) Initiation of slip on the detachment system and development of freshwater–saline-alkaline lake conditions with small intrabasinal highlands (Cache Valley Member). (B) Hanging wall breakup of the detachment system along southwest-dipping normal faults. Smaller half grabens formed; older Tertiary basin fill of the Salt Lake Formation was uplifted and recycled into younger freshwater lacustrine, nearshore, and fluvial deposits (Third Creek Member). Modified from Janecke et al. (2003).

of water into the lacustrine system. Overall, the "Cache Valley lake" system was widespread and was the only laterally-continuous depositional system in the Salt Lake Formation.

Third Creek-Cache Valley Transitional Member. The transitional member was only mapped separately in the Weston Canyon quadrangle where the presence of two marker tuffs helps to distinguish it (Figs. 4 and 7). There it lies conformably above the Cache Valley Member. Overall, clastic interbeds within this unit coarsen upward from the tuffaceous and calcareous Cache Valley Member into the conglomerate-bearing Third Creek Member (Fig. 8). The base of the transitional unit is placed at the first appearance of red to pink quartzite grains (Brigham Group) in sandstone. This change coincides with the lower of two prominent tuffaceous siltstone marker beds, except locally where lithofacies of the Cache Valley Member and the transitional member interfinger (D on Fig. 7). The top of the transitional unit is defined by the lowest persistent pebble to cobble conglomerate of the Third Creek Member. These lens-shaped conglomerate beds crop out just below the upper prominent tuffaceous siltstone marker bed (Figs. 4 and 7). Where conglomerates are not present, the contact is placed at the base of the upper marker bed.

The transitional unit consists of tan-gray limestone, gray tufa, fine- to coarse-grained sandstone, white to light-green tuffaceous siltstone and sandstone, and poorly exposed white- to light-green tephra. Red quartzite and tuffaceous sand grains are derived from the Brigham Group and Salt Lake Formation, respectively. Rare flat pebble conglomeratic sandstone with Cache Valley Member clasts crops out locally. This unit marks the first appearance of widespread gray tufa that locally preserves tufa heads with a spongy texture. The limestones in this unit are petroliferous when fresh or exposed to HCl, are usually laminated to thinly bedded, locally oolitic, and locally contain whole gastropod shells and shell fragments in oolite-rich beds.

The thickness of this unit varies along strike west of Rattlesnake Ridge where several large west-plunging folds are present (Fig. 7). Based on map measurements, the transitional member thins from 368 m in the core of the southern major syncline to 198–217 m on the two flanking anticlines. Just south of Fivemile Creek, a smaller anticline-syncline pair complicates the hinge zone of a second enveloping syncline (Fig. 7). The lowest conglomerates of the Third Creek Member are localized in these enveloping synclines and pinch out over the crests of adjacent anticlines (Fig. 7). Outcrop patterns and map relationships show that these folds deform the lower transitional member and the underlying Cache Valley Member equally. Strata of the lower Third Creek Member are less deformed than the transitional member.

*Interpretation.* The transitional member marks a change from widespread, open water lacustrine deposition of the Cache Valley Member into shallower water, lacustrine, and near-shore deposits. Thickness changes across W-plunging folds (Fig. 7) indicate that the folds were active during and after deposition of the transitional member. They likely initiated during deposition of the transitional member and did not persist after deposition of the lower Third Creek Member. The growth folds within this member may be precursors to breakup of the hanging wall of the Bannock detachment system (see below). The presence of some recycled Salt Lake Formation clasts within the transitional member supports this interpretation.

*Third Creek Member.* The Third Creek Member crops out extensively in the Weston Canyon quadrangle west of Rattlesnake Ridge and in the Malad City East and Clifton quadrangles (Figs. 4 and 7). In the Weston Canyon quadrangle, this unit lies without noticeable discordance on the transitional member (Fig. 8). The lower contact is marked by the first persistent conglomerate beds or the base of the upper prominent tuffaceous marker bed where conglomerates are absent. The conglomerate beds are distinctive because they are rich in colored quartzite clasts derived from the Brigham Group.

An unfaulted section of Third Creek Member between Rattlesnake Ridge and the Clarkston-Junction fault exposes a minimum thickness of 1.7 km (Fig. 7). The Third Creek Member is thinner in the Malad City East and Clifton quadrangles to the north where 320–1100 m of this unit are preserved (Janecke and Evans, 1999; Carney, 2002). Though Long (2004) does not report any Third Creek Member in the Henderson Creek quadrangle, his 380 m upper conglomerate unit of the Salt Lake Formation (Tscu) is dominated by lithologies that are typical of the Third Creek Member, and these two units may be correlative (Fig. 8).

The base of the Third Creek Member contains a 9.6 Ma tephra (Janecke et al., 2003), and the top contains the 4.4 Ma Kilgore ash (M. Perkins, 2005, personal commun.) in the Malad City East and Clifton quadrangles. The absence of the regionally-extensive 6.62 Ma Blacktail Creek and 6.29 Ma Walcott ashes within the upper Third Creek Member in the Malad City East and Clifton quadrangles suggests that there may be an unconformity within the Third Creek Member in those areas (Janecke et al., 2003). This hypothesized missing stratigraphy might be preserved in the unusually thick and continuous Third Creek Member exposed in the Weston Canyon quadrangle (Fig. 8). Our correlation of Long's (2004) upper "Cache Valley Member" conglomerate unit with the Third Creek Member is supported by the similar 9.6 Ma age of tephras at the base of these two conglomerate units.

Within the Weston Canyon quadrangle, the Third Creek Member consists mostly of gray to tan or white medium- to coarse-grained calcareous and tuffaceous sandstone, tuffaceous and/or calcareous siltstone, white to tan nonpetroliferous limestone, poorly consolidated silvery-gray primary tephra, and lesser pebble to cobble conglomerate. Tuffaceous and limestone lithologies account for ~80%–90% of the Third Creek Member but are difficult to study because they are less consolidated and more poorly exposed than conglomerate beds.

Conglomerate beds are 2-8 m thick, structureless to poorly bedded, well- to moderately-sorted, with subangular to rounded pebbles and cobbles (Fig. 10B). Locally, several normally-graded beds are present within a larger conglomerate package. White to gray, poorly consolidated limestone, calcareous sandstone, tuffaceous siltstone, or tephra usually overlie conglomerate beds. The conglomerates have sharp erosional bases or 10-100 cm gradational contacts with underlying gray, tan, or white tuffaceous and calcareous sandstone, pebble-granule sandstone, limestone, and/ or tephra. Individual conglomerate beds are discontinuous, may be lens shaped in map view, and crop out through along-strike distances of 0.2-2.2 km (Figs. 4 and 7). Locally, lateral accretion structures are present in smaller lensoid conglomerate beds. Two observations of clast imbrication suggest an east-directed paleoflow direction. East or west paleoflow is consistent with the observed north-south pinch-outs of the conglomerate beds. To the northwest in the Malad City East quadrangle, a westwardflowing conglomeratic Gilbert-type fan delta in the Third Creek Member was shed from a rising paleo-Oxford Ridge (Janecke and Evans, 1999).

Clasts within the Third Creek Member are composed of red, purple, and off-white Brigham Group quartzite, gray Paleozoic limestone and dolomite, bright white Paleozoic quartzite, and recycled tuffaceous siltstone and limestone clasts from the underlying Salt Lake Formation (Figs. 9 and 10B). In the Weston Canyon quadrangle, 46% of clasts are Brigham Group, 35% are Paleozoic, and 19% are recycled green to tan tuffaceous siltstone and limestone from the Salt Lake Formation (n = 21) (Fig. 9), but compositions vary widely from bed to bed. Some conglomerate beds consist of ≥80% of the recycled clasts. Recycled clasts within conglomerates of the Third Creek Member in the central and western part of the Weston Canyon guadrangle are dominated by green to light green tuffaceous siltstone. However, in the Deep Creek half graben on the western edge of the quadrangle, recycled Salt Lake clasts are dominantly derived from tan lacustrine limestone.

*Interpretation and Unroofing.* Clast count data from Salt Lake Formation conglomerates in the Malad City East and Clifton quadrangles reveal an unroofing sequence of middle Paleozoic (early) to Neoproterozoic rocks (late) (Janecke and Evans, 1999; Janecke et al., 2003). The addition of 27 new clast counts from this study and 52 counts from Long (2004) expand the evidence for sequential unroofing stratigraphically lower into the Skyline Member and the Wasatch Formation (Figs. 6 and 9). Upper and middle Paleozoic rocks were eroded during deposition of the Wasatch Formation. Fault-induced erosional exhumation eventually exposed upper Neoproterozoic Brigham Group rocks during deposition of the Third Creek Member (Figs. 6 and 9). The Pocatello Formation in the footwall of the detachment

fault was never exposed and did not supply sediment to the Salt Lake Formation (Janecke et al., 2003). A sudden influx of clasts recycled from the older Salt Lake Formation occurred during deposition of the Third Creek Member (Fig. 6).

The Third Creek Member differs from the underlying laterally continuous Cache Valley Member by preserving a wide range of depositional environments in aerially restricted subbasins. Overall, this unit records near-shore lacustrine deposition with episodic input of coarse clastics from uplifting highlands. Depositional environments in the Third Creek Member include near-shore freshwater to brackish (?) lacustrine, fluvial-deltaic, fluvial, and beach environments. The influx of recycled Salt Lake clasts in this unit (19%) suggests that some parts of the previously intact supradetachment basin were uplifted and eroded. These distinctive recycled clasts record hanging wall breakup and basin reorganization above the Bannock detachment system (Fig. 11). In the southwest portion of the depositional basin Cache Valley lithofacies were still being deposited when Third Creek lithofacies were being deposited to the north and east.

The coarsest facies in the Third Creek Member are localized in the north in the Malad City East and Clifton quadrangles. These are also the only areas that preserve pebble to cobble conglomerate of the overlying New Canyon Member (Janecke and Evans, 1999; Carney et al., 2004). This southward fining trend in the Salt Lake Formation continues into northern Utah into the Clarkston Mountain and Junction Hills areas (Goessel et al., 1999; Oaks, 2000; Biek et al., 2003) and may be due to concentrated extension and uplift near Oxford Ridge.

Summary. New work in the Weston Canyon and Henderson Creek quadrangles shows that small amounts of extension began during Eocene time. Lacustrine facies of the Cache Valley Member vary and reflect increasing water depths adjacent to emergent intrabasinal fault blocks. This member is widespread and fairly uniform in thickness in the Malad Range. New tephra-correlation dates from the Salt Lake Formation within the Henderson Creek quadrangle provide better age control within the Skyline and Cache Valley members, show that deposition of the Skyline Member was under way by late middle Miocene time, and confirms that deposition of the Cache Valley Member began just before  $10.21 \pm 0.03$  Ma (Long, 2004). Another important finding is that the Third Creek Member is up to four to five times as thick in the Weston Canyon quadrangle (up to ~1700 m thick) as it is in the Malad City East and Clifton quadrangles. No conglomeratic New Canyon Member lithofacies were identified in the Weston Canyon quadrangle despite the great unfaulted thickness of the Salt Lake Formation. This may reflect southward fining within the upper Salt Lake Formation and suggests that New Canyon lithofacies change laterally into Third Creek lithofacies.

# STRUCTURAL GEOLOGY

The Cenozoic structural geology of the Bannock and Malad ranges records multiple episodes of three-dimensional extension. Consequently, spatial patterns of faults and folds are complex and overlapping. The oldest structures are E-striking normal to oblique-slip faults of Eocene age localized in the northern Henderson Creek quadrangle (Fig. 4). The faults were coeval with the final stages of Sevier-aged eastward shortening in the thrust belt, but developed in the passively transported older thrust sheets riding "piggyback" above the younger, deeper thrusts.

Several episodes of ENE-WSW to E-W extension initiated in latest middle Miocene time. The oldest normal faults dip west and localized deposition of the basal Skyline and Collinston members of the Salt Lake Formation (Goessel et al., 1999; Janecke et al., 2003; Long, 2004). Small, conglomerate-filled half grabens began forming before ca. 11-12 Ma and ended before  $10.21 \pm 0.03$  Ma and are localized in a fairly narrow N-S-trending belt (Goessel et al., 1999; Long, 2004).

Starting shortly before  $10.21 \pm 0.03$  Ma, the Bannock detachment system developed and became the dominant structure in the area. Its complex evolution from a brief yet extensive early translation phase to a later protracted breakup phase involved the creation of an isostatic anticline (Oxford Ridge anticline), propagation of a new breakaway fault at low angles, and excision and internal extension within the hanging wall of the detachment system (Janecke et al., 2003; Carney and Janecke, 2005; this study). Roughly 50% extension occurred during this main phase of extension (Carney, 2002). Many of the extensional folds in this area date from the detachment phase of deformation.

A poorly-characterized episode of cross faulting disrupted the detachment faulting locally, but the main cross-cutting phase of deformation began with Basin and Range–style faulting in middle Pliocene time (Janecke et al., 2003; Carney and Janecke 2005). From west to east, the younger faults include the northern Wasatch and Deep Creek faults and the Clarkston-Junction and Dayton-Oxford strands of the West Cache fault zone (Fig. 1). These faults account for ~10% extension and exposed the footwall of the Bannock detachment fault for the first time within postdetachment horst blocks like the Clifton and Dry Creek horsts (Fig. 4) (Janecke and Evans, 1999; Carney and Janecke, 2005).

#### **Bannock Detachment System**

This field trip focuses on the Bannock detachment fault system, and its most prominent fault, the Clifton detachment. Several low-angle normal faults comprise the Bannock detachment system. The structurally highest Clifton fault is the most continuous and omits the most section across it, but in the Clifton horst there are at least three smaller, offset, low-angle normal faults in its footwall (Fig. 4) (Carney and Janecke, 2005). The Clifton detachment strikes NNW and persists >39 km N-S. It has a low-angle geometry through its entire extent, with an average dip of 15° to the WSW, and exhibits slight waviness along strike. Sparse but excellent exposures of the fault surface (Fig. 10C) confirm its low dip (strike of 158.6° and dip of 19.6° WSW  $\pm$  11.6°; n = 5) and WSW slip direction. Slickenlines trend 255° and plunge 33° on average; n = 9 (Fig. 12D). These exposures and breccia bodies coincide with the flat-on-flat



Figure 12. Stereograms of important structural features. (A) Measurements documenting the flat-on-flat relationship along southern Rattlesnake Ridge in the Weston Canyon quadrangle. Plot shows bedding in the hanging wall (Salt Lake Formation) and footwall (Pocatello Formation) and compares these with the attitude of the intervening Bannock detachment fault. Note the overlap of the three mean vectors. This is consistent with a flat-on-flat relationship. (B) Oxford Ridge anticline in the Clifton and Weston Canyon quadrangles. Bedding and foliation orientations from the Pocatello Formation in the footwall of the Bannock detachment fault system define a subhoriztonal NNW-SSE-trending anticline. (C) Attitudes of growth folds south of Fivemile canyon within the Transitional and lower Third Creek members of the Salt Lake Formation. Bedding from the Salt Lake Formation defines an overall W-WNW-trending, moderately plunging fold axis. Note the plunge of the fold axis is very similar to the bedding dips. (D) Slickenlines and fault planes from southern Rattlesnake Ridge. Note the overall WSW-trending slickenline measurements and low dip of the Bannock detachment fault. Also note that the trend of the Oxford Ridge anticline (B) is approximately parallel to the strike of the Bannock detachment fault (D).

portion of the fault and preclude interpretations of the contact as an unconformity.

The Neoproterozoic Pocatello Formation comprises the footwall of the Clifton detachment, whereas hanging wall rocks vary along strike from rocks of the Neoproterozoic to Cambrian Brigham Group, Cambrian to Ordovician Formations, and the Miocene-Pliocene Salt Lake Formation (Fig. 8). In the Weston Canyon and parts of the Clifton quadrangle, the Clifton detachment juxtaposes late Cenozoic Salt Lake Formation and omits up to 6 km of rocks. None of the clasts within conglomerates of the Salt Lake Formation above the detachment fault were derived from the Pocatello Formation beneath the detachment (Figs. 6 and 9).

The hanging wall of the Clifton detachment contains lowangle and high-angle normal faults. These younger WSW- and ENE-dipping normal faults sole into or are cut by the master Clifton detachment fault. The spacing between hanging wall faults varies widely but is generally close in the Clifton quadrangle north of the lateral ramp near Fivemile Creek (see below). There are no faults in the hanging wall of the detachment south of the lateral ramp (Fig. 4).

#### Flat-on-Flat Geometry across the Detachment Fault

Along most of Rattlesnake Ridge, footwall and hanging wall rocks have approximately the same strike and dip and parallel the intervening detachment fault (Fig. 12A). A potentially complicating factor of this analysis is that 3-point determinations of the dip of the detachment fault are  $10^{\circ}-20^{\circ}$  lower than the dip measured in outcrop. This difference reflects the position of the 3-point measurements closer to the crest of the Oxford Ridge anticline, whereas direct measurements sampled the limbs of the anticline farther west. Our structural cross sections (Fig. 13) suggest that bedding in the Third Creek Member may also be parallel to the detachment fault north of Fivemile Creek. This



Figure 13. Geological cross sections from the Weston Canyon quadrangle (see Fig. 7 for locations). A–A' crosses the upper flat of the Bannock detachment system and shows the eroded Clifton fault merging with the older and underlying Bannock fault near the crest of the Oxford Ridge anticline. Note the cut-off angle between strata above and below the Clifton fault near the anticline. This geometry is expected during the process of excision. B–B' crosses the lower flat of the Bannock system and shows similar geometries to the northern section.



Figure 14. Strata in the hanging wall of the Bannock detachment fault (BDF) as a function of distance from the southern tip of Rattlesnake Ridge. These are compared against the units within thin fault blocks (horses) of the underlying detachment fault. Note the northward younging of hanging wall strata across the Fivemile lateral ramp. The brecciated Camelback Mountain Formation coincides with the upper and lower footwall and hanging wall flats, whereas the Blacksmith Formation coincides well with the lateral ramp of the detachment fault. See text for additional discussion of the lateral ramp. Although the significance of younger rocks in horses along the ramp is uncertain, it helps to define the extent of the lateral ramp.

flat-on-flat geometry is one of 10 arguments that suggest the Bannock detachment fault formed and slipped at low angles (Carney and Janecke, 2005).

The depth to the detachment fault while it was slipping can be constrained by the thickness of the supradetachment basin fill above the fault. In the Weston Canyon quadrangle, only the Salt Lake Formation lies above the detachment fault, and post detachment deposits such as the Quaternary-Tertiary piedmont gravels of Janecke et al. (2003) are only a few hundred meters thick at most and were deposited after the death of the detachment fault. This suggests that unless a significant thickness of unrecognized post–New Canyon Member deposits were eroded from the area, the ~2.5–4.3 km thickness of the Salt Lake Formation comprised the only rocks above the detachment fault. Because of the unique flat-on-flat geometry, this further suggests that the originally subhorizontal Bannock detachment fault was slipping at depths of <2.5–4.3 km.

# Lateral Ramp in Hanging Wall and Footwall of the Detachment Fault

In contrast to areas areas north and south, hanging wall and footwall rocks are truncated by the detachment fault in the vicinity of Fivemile Creek (Fig. 7). Figure 14 illustrates changes in hanging wall stratigraphy as a function of distance along-strike of the detachment fault. Along the southern segment of the fault, the lowest stratigraphic levels of the Salt Lake Formation within the Weston Canyon quadrangle are faulted against the Pocatello Formation. However, starting ~4 km north of the southern tip of Rattlesnake Ridge, progressively younger rocks are faulted against the Bannock detachment fault (Fig. 14). At the sharp northward bend in the detachment fault along Fivemile Creek, the fault has cut significantly upsection and faults lower Third Creek Member against the Pocatello Formation. This upsection truncation of hanging wall units is expressed in map view near Fivemile Creek (Fig. 7). Mapping of the Pocatello Formation in the footwall shows a complimentary pattern of stratal truncations.

We suggest that stratal truncation of footwall and hanging wall rocks is created by footwall and hanging wall lateral ramps in the Bannock detachment fault, herein called the Fivemile lateral ramp. The flat-on-flat geometry north and south of the lateral ramp (Fig. 14) and the thickness of the Tertiary units truncated by the ramp define the original height of the lateral ramp. We estimate an original height of ~850-1100 m along a fault-strike distance of ~4-4.5 km. This estimate takes into account the full thickness of the transitional member (198-368 m), most of the measured minimum thickness of the Cache Valley Member (~600 m), and a small thickness of the Third Creek Member. The amount of truncated Third Creek Member is poorly constrained, but an estimate of 50–150 m is reasonable based on map patterns. Overall, these data show that the Fivemile lateral ramp had an original south-southeast dip of  $13.0^{\circ} \pm 2.3^{\circ}$  and was approximately perpendicular to the strike of the detachment fault. The lateral ramp is spatially coincident with a change in the lithology of fault-bound slivers along the detachment fault (Fig. 14).

Major changes in the amount of hanging wall deformation occur across the Fivemile lateral ramp. Above the southern, lower flat along Rattlesnake Ridge, the hanging wall is unfaulted, whereas north of the Fivemile lateral ramp the hanging wall is internally faulted above the northern upper flat (Figs. 4 and 7). Because the lateral ramp cuts out at least ~850-1100 m of stratigraphy, the depth to the northern flat during transport was <1.6–2.6 km, depending on whether the additional thickness of the New Canyon Member was once present or not. We suggest that the increased faulting above the northern, upper flat is a result of decreased overburden thickness above the detachment fault. This pattern is consistent with two-dimensional structural models of detachment faults that show more highly extended thin hanging walls and less faulted thicker hanging walls. Detailed gravity data confirm the south to north decrease in basin depth across the lateral ramp that our model predicts (Fig. 15).

The Fivemile lateral ramp is an ENE-trending structure that coincides with a major north to south change in structural style above the Bannock detachment fault. The westward projection of the ramp coincides with (1) the interaction zone between the younger Deep Creek fault and Clarkston-Junction strand of the West Cache fault; (2) an anomalous NE-striking part of the Clarkston-Junction fault; (3) the ENE-trending fault block at the south end of the Skyline half graben; (4) a major segment boundary in the Wasatch fault; and (5) a bedrock ridge beneath Malad Valley (Figs. 4 and 15). Eastward the Dayton-Oxford fault has a branch point and a left bend along this trend. The alignment of these major lateral structural changes might reflect structural inheritance within this ENE-trending belt (Fig. 4).

#### **Excision of Hanging Wall Rocks**

Cross sections across the Bannock system in the Weston Canyon quadrangle (Fig. 13) suggest that two detachment faults are present east of the crest of the Oxford Ridge anticline. The lower fault (Bannock fault) is preserved in two small outcrops near Fivemile quarry and one ~2 km south of the quarry (Fig. 7). In all three locales hanging wall rocks consist of Cache Valley Member and bedding is parallel to subparallel with the dominantly east-dipping detachment fault (Fig. 13).

The higher detachment fault strand is inferred above the current level of exposure (Fig. 13). Farther east it may be faulted below Cache Valley on the east strand of the Dayton-Oxford fault zone. The higher strand merges with the Bannock fault near the crest of the Oxford Ridge anticline. East of the Oxford Ridge anticline, the higher strand cuts down section through the Salt Lake Formation to the west (Fig. 13).

Fault excision is an important process of the Bannock detachment system in the Clifton quadrangle to the north (Carney and Janecke, 2005). We believe that excision also played a major role in the development of the Bannock system in the Weston Canyon quadrangle and is responsible for the Clifton detachment fault cutting upsection into the synextensional Salt Lake Formation (Fig. 16). A minimum of ~4 km of slip is documented on the Clifton fault in the Clifton quadrangle



Figure 15. Isostatic residual gravity contour map of north-central Utah and southeastern Idaho. Contour interval is 4 mGal. Hachures indicate gravity lows. Most of the anomalies reflect the density contrast between Cenozoic basin fill and pre-Cenozoic bedrock. Note that many of the Basin and Range normal faults are associated with prominent gravity gradients, with lower values on the downthrown side of the fault. New detailed data sets include Oaks et al. (2005), Eversaul (2004), Goessel (1999), and Smith (1997). HF—Hawk fault; CM—Clarkston Mountain.

where other data further suggest a total displacement of ~15 km (Carney and Janecke, 2005).

# Folds

Within the Weston Canyon quadrangle, there are extensional folds of several orientations. Descriptions of these structures will be limited to those that occur in the hanging wall and footwall of the Bannock detachment system (Fig. 4). The folds within the study area can be subdivided into two main geometries: N-NNW-trending longitudinal folds parallel to the normal faults of the Bannock detachment system and transverse folds with W-WSW trends perpendicular and/or oblique to the Bannock detachment system.



Figure 16. Schematic illustration of excision of the Bannock detachment fault system. (A) Unloading above the Bannock fault creates a broad isostatic uplift (Oxford Ridge anticline) that back-tilts the detachment fault into an unfavorable geometry for continued slip. (B) The Clifton fault cuts upsection into the hanging wall (excises) and merges with the Bannock fault at the crest of the anticline. Flat-onflat geometries suggest that slip on the Clifton fault has removed the ramp-flat relationship that would initially develop above the excising fault and transported it down-dip. This is schematically shown with the location of stars above the Clifton fault. Note the expected cut-off between strata above and below the Clifton fault near the anticline. Dashed red lines indicate future faults of the Dayton-Oxford fault. Legend is same as Figure 13.

#### Longitudinal Folds

One longitudinal fold deforms rocks in the Weston Canyon quadrangle. This fold continues northward into the Clifton quadrangle where Carney and Janecke (2005) first described the structure and named it the Oxford Ridge anticline. In the Weston Canyon quadrangle the axial trace of the Oxford Ridge anticline trends along Rattlesnake Ridge for ~9 km before plunging south beneath Quaternary deposits at the southern end of the ridge (Fig. 7). Regionally, the Oxford Ridge anticline is more than 40 km long (Carney and Janecke, 2005), similar to the >39 km exposed length of the Bannock detachment fault

The Oxford Ridge anticline is defined by changes in the dip of the Bannock detachment fault, the Neoproterozoic Pocatello Formation in the footwall, and Salt Lake Formation in the hanging wall (Fig. 7). Within the Weston Canyon quadrangle, 43 footwall bedding and foliation measurements define the Oxford Ridge anticline as an open fold trending 155° and plunging 1° southeast (Fig. 12B). This is in close agreement with the 345° trend and 0° plunge of the Oxford Ridge anticline in the Clifton quadrangle to the north (Carney and Janecke, 2005). Combining these two data sets yields an average 160° trend and 02° plunge (Fig. 12b; n = 78).

A ~7 km long N-S-trending anticline in the SE part of the Henderson Creek quadrangle (Fig. 4) appears to be a composite double rollover anticline. Its west-dipping limb formed during slip on the NE-dipping Steel Canyon fault between ca. 9.6 and <9.2 Ma. The east-dipping limb dates from the post–4.4 Ma Basin and Range phase of faulting on the west-dipping Deep Creek fault (Long, 2004).

#### Transverse Folds

Folds with WNW-SW trends in the Weston Canyon quadrangle can be further subdivided into those that deform both footwall and hanging wall rocks of the Bannock system and those that deform only hanging wall rocks. Folds that deform the entire Bannock detachment system are located near Fivemile Creek west of the Dayton-Oxford fault (Fig. 7). These folds plunge WSW and have tight to open geometries. Cross-cutting relationships show that these are younger than west-plunging folds 0.7 km farther south that deform only hanging wall rocks.

Folds that only deform hanging wall rocks are localized primarily in the upper Cache Valley to lower Third Creek members of the Salt Lake Formation south of Fivemile Creek (Fig. 7). The northern three folds also define an overall syncline similar in scale to a prominent syncline located ~2 km to the south. Mapping and stereonet analyses of these structures define an average trend of 281° and plunge of 38° (Fig. 12C) with wavelengths of ~1.3–1.6 km for the larger-scale, more widely spaced folds. Data discussed in the "Stratigraphy" section show that the transitional unit thickens and thins across these folds.

#### Interpretation

The longitudinal Oxford Ridge anticline was interpreted as an isostatic fold that formed in response to crustal unloading above the Bannock detachment fault (Carney and Janecke, 2005). Our new data strengthen this interpretation by showing that the fold is perpendicular to slip on the detachment fault (Fig. 12) and by documenting that the Oxford Ridge anticline deforms the entire N-S extent of the detachment fault. The formation of an isostatic anticline suggests significant amounts of extension on the Bannock fault. The current westward dip of both bedding and fold axes west of Rattlesnake Ridge is due to a combination of steepening on the west flank of the Oxford Ridge anticline and slip on the E-ESE–dipping Clarkston-Junction strand of the West Cache fault.

Two generations of subparallel folds plunge west. The younger set near Fivemile Creek deforms the lateral ramp in the Bannock detachment fault and accentuates the map view truncation of hanging wall rocks. We interpret these folds as forming after deposition of the Third Creek Member, likely after main-stage movement on the Bannock detachment system. The older W-plunging folds south of Fivemile Creek are confined to the hanging wall and are interpreted as growth folds active during deposition of the Salt Lake Formation. Folding likely began during deposition of the lowermost transitional member, or less likely, during deposition of the uppermost Cache Valley Member.

# **Basin and Range Normal Faulting**

Steep to moderately dipping Basin and Range normal faults generally strike north and dip both east and west, forming horsts, grabens, and half grabens (Figs. 1 and 4). Prior studies (Machette et al., 1992; Evans and Oaks, 1996) have noted the major, active, west-dipping Wasatch and East Cache fault zone. Our mapping indicates that the intervening Deep Creek and West Cache fault zones are also major structures at this latitude. The Clarkston–Junction Hills strand of the West Cache fault zone dies out northward near 42°7.5′ but overlaps for more than 30 km with the Dayton-Oxford normal fault to the east. Between these two east-dipping en echelon strands of the West Cache fault zone, the Salt Lake Formation and the Bannock detachment system dip westward.

The west-dipping Deep Creek normal fault bounds intermontane basins in the Malad and SE Bannock ranges. It has the greatest throw in the Clifton quadrangle, where a  $\sim 1-1.5$ -km-deep sedimentary basin is preserved in its hanging wall (Evans et al., 2000; Eversaul, 2004). Southward, the Deep Creek fault becomes more complex, steps right in several relay ramps and breached relay ramps, and loses displacement. A slip minimum coincides with an E-W-trending bedrock ridge of Ordovician rocks in the hanging wall of the Deep Creek fault in the northeastern Henderson Creek quadrangle and NW Weston Canyon quadrangle (Fig. 4).

The location of this slip minimum is consistent with the location of an interaction zone between the Deep Creek and West Cache fault zones north of the bedrock ridge of Ordovician rocks (Fig. 4). Numerous small to moderate displacement normal faults in this interaction zone cross Weston Canyon and connect the oppositely dipping West Cache and Deep Creek faults across the Dry Creek horst block (Fig. 4). This complex fault network probably transfers extension between the two normal faults and explains both the drop in displacement across the Deep Creek fault that occurs south of the interaction zone and the drop in slip on the West Cache fault north of the interaction zone.

#### Wasatch Fault and Relay Ramp

The Wasatch fault is an active, north-striking, west-dipping normal fault system that extends from central Utah to southeast Idaho (Machette et al., 1992). In the Henderson Creek quadrangle, the Wasatch fault system consists of two right-stepping N-NW– striking segments, which are separated by a relay ramp and bedrock ridge in the hanging wall (Figs. 1 and 4). The Clarkston Mountain segment is a 19-km-long segment along the southwestern edge of the Malad Range and Clarkston Mountain (Machette et al., 1992). Throw on this segment decreases to the north, as it is progressively transferred to the Malad City segment. The Malad City segment of the Wasatch fault defines the western boundary of the northern part of the Malad Range (Fig. 4). The two faults overlap for ~10 km, and form a 2.5–3.5-km-wide en echelon right step.

New gravity data collected in the greater Cache Valley region highlight the relative throws of the Basin and Range normal faults, locations of subbasins and buried structural ridges (Fig. 15) (Oaks et al., 2005). The aerial extent and amplitude of the gravity lows are a proxy for the size and depth of the Cenozoic basins. Using this as a guide, two basin systems dominate the gravity field. The Cache Valley basin system is in general deeper and wider than the basins west of the Wasatch fault. However, in the central part of the area, between 42°7' and 41°45', the two-basin system is replaced by three, elongate, subparallel NNW-trending basins. The change from two to three basins in this latitudinal band shows that the east-dipping West Cache fault zone is a major structure in this region and rivals the Wasatch and East Cache fault zones in its throw.

#### **FIELD TRIP**

This field trip guide starts at the Woodruff/Samaria exit of I-15, 2.1 mi north of the Utah-Idaho state line and 95.2 mi north of Exit 311 of I-15 (400 S.) in Salt Lake City, Utah. Mileages are given from the north end of the Woodruff/Samaria off-ramp. All UTM coordinates are in reference to Zone 12 of the NAD27 datum.

Mileage		
Interval	(Cumulative)	Description
0.1	0.1	Turn right on Woodruff Lane at the end of the Woodruff/Samaria off ramp and park in pullout by 2000 W.

# Stop 1: Overview of Southern Malad Range; UTM 0399932E 465422N

The purpose of this stop is to discuss recent work by Long (2004) and Long et al. (2004) in the Henderson Creek quadrangle. This work identified the probable location of the monocline at the west edge of the Cache-Pocatello culmination and refined the age, sedimentological, and structural interpretations of the Skyline and Cache Valley members of the Salt Lake Formation. Work in the Cache Valley Member characterized two different lacustrine facies and documented the Late Miocene age of the Steel Canyon normal fault.

Mileage		
Interval	(Cumulative)	Description
0.2	0.3	Return to Woodruff Lane and drive west ~0.2 mi to the intersection with Old
		Highway 191. Turn right (north).
8.9	9.2	Drive north to 1500 S. and turn right
		(east).
3.7	13.2	Drive east 0.8 mi on 1500 S. and cross
		under I-15 where 1500 S. becomes Two
		Mile Creek road. Cross the Wasatch
		fault into the Malad Range. Continue
		2.9 mi up Two Mile Creek to Stop 2.

Alternate route (if roads are very wet and muddy—skip stop 2): Do not turn right at 1500 S. from Old Hwy 191—continue straight (north) into Malad City ~1.5 mi. Turn right and get on I-15 North. Drive north and exit at Hwy 36 East (Exit 17). Turn right (east) and drive on Hwy 36 for 7 mi past Deep Creek Reservoir to a large pull-out on the right. Rejoin the field guide at Stop 3 and reset mileage.

# Stop 2: Examine Altered Tuffaceous Lake Beds; UTM 0403322E 4668926N

Make a brief stop along Two Mile Canyon to examine green altered tuffaceous siltstone of the Cache Valley Member of the Salt Lake Formation. Notice that the tuffaceous sedimentary rocks are structureless to finely laminated. Other sedimentary structures are lacking. These deposits and interbedded lacustrine limestones up and down section suggest that ash fall beds were deposited below wave base in an open lake.

The Cache Valley Member in this area overlies ~200–250 m of the conglomeratic Skyline Member of the Salt Lake Formation. As we drive east along this road we will cross a narrow horst block of Cambrian carbonates shortly before a T intersection with Highway 36. The west-dipping Red Knoll fault on the western margin of this horst block was the basin-bounding normal fault during deposition of the Skyline Member (Janecke et al., 2003; Long, 2004). The Red Knoll fault was inactive when the overlying Cache Valley Member was deposited across the older fault block.

Mileage		
Interval	(Cumulative)	Description
0.7	(13.9)	Skyline road joins from the right; con-
2.7	(16.6)	Continue on Two Mile Road over the
	()	Malad Range divide down to a T-inter- section with Hwy 36.
1.7	(18.3)	Turn left (north) onto Hwy 36 and drive 1.7 mi to a large pull-out on the
		left (west) side of the road just north of milepost 108.

# Stop 3: Extensional Monocline and Breakup Deposits of the Salt Lake Formation; UTM 0406959E 4669904N

This stop will examine facies within the Third Creek Member of the Salt Lake Formation and observe extensional monoclines in the hanging wall of a concealed normal fault. Cross to the east side of Hwy 36 and locate a gate in the fence near the obvious wash. This stop will illustrate (1) the variable lithologies of the Third Creek Member; (2) the presence of voluminous clasts of reworked tuffaceous sediment from the underlying Cache Valley Member of the Salt Lake Formation; and (3) some of the well-developed extensional folds that deform the hanging wall of the Bannock detachment fault.

An exposure of pebble conglomerate near road level is composed of recycled clasts of the Cache Valley Member of the Salt Lake Formation. Notice the degree of sorting and rounding of these clasts. This bed and one near the parked cars dip gently down the road (to the NW). Go through the gate and walk up the wash. Notice that the strike of the beds has change to NW and dips steepen as we walk NE through the wash. In beds SE of the wash the Third Creek beds are nearly vertical (up to 87°). The gentle beds along the highway and these steeper beds define a synformal monoclinal hinge of a NNW-plunging fold (best-fit plunge and trend of the cylindrical fold axis is 19°, 331°; n = 32). Steep beds flatten at structurally higher levels and represent the antiformal hinge of the NW-plunging monocline. Individual tilt panels range from NW- to SW- to NE-dipping and define at least four monoclinal hinge zones with NNW plunges.

Altogether, the monoclinal folds define a plunging kink-like rollover fold in the hanging wall of the NE-dipping Hawk normal fault (Evans et al., 2000). The Hawk fault is nowhere exposed and/or is covered by alluvium, but it is needed to explain the stratigraphic and structural relationships on the geologic map. Gravity data across this normal fault shows a ~7 mGal drop from the footwall (SW) to the hanging wall side of the fault, consistent with moderate displacement across this fault (Evans et al., 2000; Eversaul, 2004). The NW-striking Hawk fault formed during Miocene to Pliocene detachment faulting, is antithetic to the Bannock detachment fault, and may be one of the late stage breakup faults that formed above the detachment system during deposition of the Third Creek and New Canyon members of the Salt Lake Formation.

Notice exposures of conglomerate on either side of the wash as you walk to the east. Some pebbly beds contain ooids and gastropods in the matrix. We interpret the beds here as the distal toes of alluvial fans at the margin of a lake. Keep walking up the wash to observe an exposure of a thick vitric ash on the left (north) bank of the wash beneath the lake-margin deposits. Tephra correlations show that this ash is the  $7.9 \pm 0.5$  Ma Rush Valley Ash (Janecke et al., 2003). After examining the late Miocene ash, climb up on the slopes SE of the wash to exposures of nearly vertical conglomerate beds. This vantage point provides a better view of the monoclinal fold train in the hanging wall of the Hawk fault.

A horst block of Cambrian limestone with a thin carapace of red weathering Eocene Wasatch conglomerates is to the east. This horst block is bounded by N-S-striking normal faults that cut across and postdate the NW-striking faults and folds that we just examined. Cross-cutting relationships like these allow us to distinguish between the many phases of normal faulting and folding in the area. The N-striking normal faults are from the youngest Basin and Range phase of extension. Return to the vehicles, turn around, and drive south on Hwy 36.

Mil	leage	
Interval	(Cumulative)	Description
7.0	(25.3)	Cross Clarkston-Junction strand of the West Cache fault. Drive along Weston Creek through tilted Salt Lake Forma-
5.9	(31.2)	shore and lake deposits. Cross the buried trace of the Dayton- Oxford fault and also note the thick roadcut of Bonneville-age gravel depos-
0.7	(31.9)	its north of the road. Turn north (left) onto Franklin County D1/Hwy 36 and drive toward Dayton,

Idaho. Notice Rattlesnake Ridge to your left (west side of road) in the footwall of the east-dipping Dayton-Oxford fault.

- 4.9 (36.8) Enter Dayton. At the T-intersection turn left to stay on Franklin County D1 and continue north to Clifton.
- 5.4 (42.2) Turn left on 100 S. at the dark-colored sign for Clifton Cemetery (on right side) and continue on this winding dirt road. Turn left on Cemetery Rd. Drive up in the Bannock Range to the end of the road in Davis Basin. High clearance is advisable.
  6.3 (48.5) Park at the end of the road and walk
- NNE up a trail ~3/4 mi to a trail junction between the trail along Oxford Ridge and the E-W trail to Mine Hollow. Leave the official trail and hike SW along a ridgeline until you have a clear view of the rocks to the north. There should be brecciated quartzite underfoot.

# Stop 4: View Excision along the Clifton Detachment Fault; UTM 0412275E 4673135N

We will stop at a high point with a view to the north of Oxford Ridge. The Clifton detachment fault forms a near dip slope on the WSW edge of Oxford Ridge and we can view it a few kilometers to the north of us. There the fault dips gently WSW and truncates (excises) numerous SW- and some NE-dipping normal faults in its hanging wall (Carney and Janecke, 2005). These hanging wall faults repeat lower Paleozoic rocks, overlying Wasatch Formation, and the Cache Valley Member of the Salt Lake Formation. The rusty-weathering rocks with a dense cover of small trees are the Neoproterozoic Pocatello Formation. Its foliation (and bedding) is subparallel to the detachment in this area. A cross section, detailed description of these relationships, and the evidence for excision are presented in Carney and Janecke (2005). These relationships indicate slip on the Clifton fault at a low dip angle within a few kilometers of Earth's surface.

A short distance NE of here in northern Cache Valley one can see large ancient meanders produced by the outflow stream of Lake Provo. These meander bends are preserved in Oxford Slough and show evidence for northward flow when they were active. Flow directions have reversed since the Bonneville lake system drained, and Oxford Slough is now integrated into the south-flowing Bear River system. Return to vehicles and retrace path back to Franklin County D1 in Clifton.

Mileage		
Interval	(Cumulative)	Description
6.3	(54.8)	Turn right (south) on Franklin County D1 and continue to the north end of Dayton.
5.0	(59.8)	Turn right (west) onto the access road to Fivemile Creek.

1.6 (61.4) Just past the end of the pavement, turn right (north) onto a dirt track. Wind around a small bluff to enter Fivemile quarry.

# Stop 5: Faulted Rocks above the Detachment and Conglomerates of the Cache Valley Member; UTM 0416229E 4662973N

This stop is located between two east-dipping strands of the Dayton-Oxford fault, which at this latitude is the major basinbounding structure of Cache Valley. Gravity data (Fig. 15) show that the eastern Dayton-Oxford fault has much more throw than the western Dayton-Oxford fault at this latitude, consistent with our structural analysis (Fig. 13). This stop starts in the lower Cache Valley Member of the Salt Lake Formation, located just above a tilted E-dipping portion of the Bannock detachment fault, and requires a short walk to examine thin conglomerate beds within the lower Cache Valley Member. The quarry is developed in very fractured, faulted, and locally brecciated, tuffaceous to non-tuffaceous siltstone and mudstone. The fractures and faults obscure original bedding and are likely a result of this outcrop's proximity to the underlying detachment fault. Brecciated Brigham Group Quartzite in fault blocks within the detachment fault crop out just west of the quarry (Figs. 7 and 13). The approximately concordant east dips of the Bannock detachment fault and the overlying Cache Valley Member suggests a flat-on-flat geometry. This E-dipping flat-on-flat geometry east of the crest of the Oxford Ridge anticline helps to constrain the evolution of the Bannock detachment system (Fig. 16).

To reach the conglomerates, walk NE around the edge of the quarry through a wash cut in green to white tuffaceous siltstone. Tuffaceous beds and limestone account for ~90% of the Cache Valley Member. Walk NE up the slope to the top of the ridge where conglomerates crop out at UTM 0416486E 4663294N. These conglomerates are rare in the Cache Valley Member, only crop out in the lower few hundred meters of section, and are locally present for ~7 km along strike to the south. Angular to rounded clasts within the conglomerates are derived from Paleozoic rocks. Matrix within the conglomerates ranges from calcareous sand to micrite. Micrite-matrix conglomerates are surprising due to the overwhelming dominance of tuffaceous siltstone lithologies and the lack of significant limestone in this section. We interpret these relationships to suggest conglomerate progradation and limestone deposition during times of reduced ash input to the lacustrine environment and surrounding landscape. We also suggest that highlands must be present nearby, likely to the east, to supply the conglomerates during these time periods. These highlands may have formed by an intrabasinal fault. Retrace your route to the main dirt road along Fivemile Creek.

Mileage		
Interval	(Cumulative)	Description
0.6	(62)	Turn right (west) onto the main dirt road and drive west 0.4 mi.

# Stop 6: Lateral Ramp in the Bannock Detachment System; UTM 0414359E 4662120N

Walk to the north side of the road and climb the blue-gray outcrop of Cambrian Blacksmith Formation limestone within fault blocks along the detachment fault. From this vantage point, we can see the W- to S-dipping Bannock detachment fault. The purpose of this stop is to discuss evidence for (1) a folded lateral ramp in the Bannock detachment fault system, (2) the Oxford Ridge anticline, and (3) the transitional unit between the Third Creek and Cache Valley members. The folded lateral ramp of the detachment fault can be seen in map view as northward and southward truncation of both footwall and hanging wall rocks against the detachment. To the south along Rattlesnake Ridge, the lowest outcrops of the Cache Valley Member are cut by the fault. There the hanging wall, footwall, and fault are approximately parallel and we interpret this as a flat-on-flat geometry. Here along Fivemile Creek, the fault has cut upsection into the transitional member of the Salt Lake Formation. Northwest of here, near Stop 7, the detachment fault cuts lower Third Creek Member. Our structural cross sections (Fig. 13) suggest that a flat-on-flat geometry may also exist where the Third Creek Member is cut by the fault to the north. Figure 14 shows the N-S changes in hanging wall stratigraphy above the detachment fault. We use these data to interpret an ~850-1100m-high lateral ramp in the detachment fault. Gravity data shows a gravity high along the NNW-trending Oxford Ridge anticline but also provides evidence for the ENE-trending lateral ramp in the Bannock detachment fault (Fig. 15). The depth of the basin west of Rattlesnake Ridge decreases northward across this lateral ramp according to the gravity data and in accordance with our structural interpretation.

The lateral ramp is also approximately marked by a change in the lithology of fault blocks (horses) along the detachment fault. North and south of the ramp, brecciated horses of Camelback Mountain Formation crop out, whereas within the ramp, horses of Blacksmith Formation crop out. These changes may be due to three-dimensional detachment fault geometries up-dip of the current exposures. The lateral ramp is folded by a W-plunging syncline-anticline pair that tightens the bends at the top and bottom of the ramp. We are on the west limb of the Oxford Ridge anticline. The axial trace is at the narrows of Fivemile Canyon and is well exposed along Rattlesnake Ridge. This broad, open fold is subparallel to the Bannock detachment system and formed as an isostatic response to unloading above it. This broad anticline tilted portions of the detachment fault into unfavorable geometries for continued slip and likely initiated the process of excision.

The transitional member of the Salt Lake Formation crops out near this stop to the N and NW for several hundred meters. The base and top of the transitional member can be seen to the south as the two high west-dipping ridges of zeolitized green to white tuffaceous siltstone beds (Fig. 7). There were several broad west-trending growth folds active during deposition of the transitional and lower Third Creek members south of here.

Mileage		
Interval	(Cumulative)	Description
1.5	64.7	Continue westward along the Fivemile Creek road, and then climb up to a low ridge. Pass a Y-intersection at mile 64.2 and continue north for another 0.5 mile. Park and walk south to the top of the nearby small hill.

# Stop 7: Faulted Hanging Wall above the Northern, Upper Flat in the Detachment Fault; UTM 0413284E 4663245N

The goals of this stop are to (1) observe the northward truncation of hanging wall rocks against the lateral ramp; (2) discuss the style of hanging wall deformation and how it changes across the lateral ramp; (3) document a large en echelon step of the West Cache fault zone; and (4) observe some lithologies of the Third Creek Member. We are located on the upper flat of the Bannock detachment system where the Third Creek Member of the Salt Lake Formation is juxtaposed against Pocatello Formation. Looking south you can clearly see the two prominent zeolitized tuffaceous marker beds at the top and bottom of the transitional member striking north and being truncated by the detachment fault. Looking south again, we observe the thickest unfaulted section of Salt Lake Formation within the Malad and Bannock ranges. This thick unfaulted section above the southern, lower flat differs from the internally extended rocks above the northern upper flat at this stop. We suggest that increased faulting above the upper flat is due to the substantial northward thinning of the hanging wall across the Fivemile lateral ramp.

To the west, the Clarkston-Junction strand of the West Cache fault lies along the eastern edge of the Dry Creek horst. Here it places the Third Creek Member of the Salt Lake Formation against Neoproterozoic to Lower Paleozoic rocks (Figs. 7 and 4). The West Cache fault is an active E-dipping Basin and Range normal fault that begins in southern Cache Valley, has an overall NNW strike, and a length of ~93 km (Solomon, 1999; Black et al., 2000). Our mapping shows that the Clarkston-Junction strand is the northern continuation of the West Cache fault (Steely and Janecke, 2005) and the Steel Canyon fault is not part of the West Cache fault zone as Janecke and Evans (1999) had inferred. At this latitude, two other Basin and Range normal faults are also present: the W-dipping Deep Creek fault (DCF) on the west side of the Clifton horst and the E-dipping Dayton-Oxford fault (DOF) to the east. Both of these faults have along-strike overlap with the Clarkston-Junction strand of the West Cache fault (DCF ~15 km; DOF ~27 km).

Gravity studies show a ~7 mGal gradient across the Clarkston-Junction fault in the northern part of the Weston Canyon quadrangle that increases southward to ~11 mGal (Fig. 15). Mapping shows that the Clarkston-Junction strand of the West Cache fault is linked to the Deep Creek fault by a network of normal faults that obliquely cross the Dry Creek horst. Most of the strain on the Clarkston-Junction strand of the West Cache fault steps en echelon eastward to the Dayton-Oxford fault. Thus the West Cache fault zone defines the western side of Cache Valley for its entire length.

On the way back to the vehicles, detour west down the hill to examine outcrops of conglomerate beds and tufa heads within the Third Creek Member. The conglomerates at this location consist of pebbles to rare small cobbles dominated by green to white recycled tuffaceous siltstone and limestone clasts from the Salt Lake Formation and colored quartzites from the Brigham Group. Interbedded limestone, sandstone, and tephra are common in this interval. Limestone beds may be either tan silicified laminated to bedded micrite or gray with local tufa. Several gray tufa heads 10–50 cm in diameter crop out on the western slope of this hill. These lithologies suggest that within the lower Third Creek Member at this locale, deposition of coarse clastics occurred in a freshwater shallow lacustrine to near-shore setting.

Mileage		
Interval	(Cumulative)	Description
0.4	65.1	Turn around and drive south to the Y-
		intersection. Take the right fork down into the valley of Weston Creek.
3.0	68.1	This road becomes 7200 W. and has
		an intersection with 300 South near
		some farm houses at mile 67—continue
		straight past the intersection. The road
		makes a left turn followed by a sharp
		right turn and another left. At the second
		right turn, a small dirt track joins the
		main road. Turn left (NE) onto this road.
0.2	68.3	Continue 0.1 mile and park along the
		side of the road. Take care not to drive
		across the grass; this stop is on private
		property. Walk ~100 m north to a promi-
		nent W-dipping conglomerate bed.

# Stop 8: Third Creek Member of the Salt Lake Formation and Evidence for Breakup; UTM 0413203E 4659050N

At this stop we will examine Third Creek Member conglomerate beds, discuss evidence for an unroofing sequence in the Tertiary basin-fill, and suggest an updated model of overall basin evolution. The conglomerate beds at this stop are typical of those observed throughout the Third Creek Member in the Weston Canyon and neighboring quadrangles. Although conglomerates account for less than ~20% of the entire Third Creek Member in the Weston Canyon quadrangle, they are more resistant than the under- and overlying calcareous to tuffaceous sandstone and siltstone, tephra, limestone, and localized tufa and form prominent ridges. Clast count data from the Clifton, Henderson Creek, Malad City East, and Weston Canyon quadrangles show that 52% of clasts are from the Brigham Group, 32% are from Paleozoic rocks, and 16% are recycled tuffaceous siltstone and limestone from the Salt Lake Formation (n = 68) (Fig. 9).

The sudden influx of recycled Salt Lake clasts during the Third Creek Member suggests that some parts of the supradetachment basin were being uplifted and eroded while other areas experienced continued deposition. Recycled Salt Lake clasts, coupled with the change from widespread lacustrine deposition to more aerially-restricted subbasins record internal hanging wall breakup of the Bannock supradetachment basin (Fig. 11). The major phase of breakup began with deposition of the Third Creek Member, although growth folds active during the underlying transitional member suggest incipient breakup just prior to major deposition of conglomerates in the Weston Canyon quadrangle.

Mileage		
Interval	(Cumulative)	Description
0.2	68.5	Retrace route back to the main dirt road and turn left (south). Drive 0.5 mi to the 4-way intersection (before the stop sign) and turn left (east).
2.9	71.4	Continue on this gravel road, past a sharp right turn at mile 69.9. Road turns east. Make a hard left (north) onto a
1.5	72.9	smaller dirt road between agricultural fields. Drive north 1.5 mi and park at the top of a small hill. This road may be impass- able when wet.

# Stop 9: Exposure of the Bannock Detachment Fault; UTM 0415888E 4658473N

This stop requires a short walk to visit exposures of slickenlines on the Clifton strand of the Bannock detachment fault on top of a thin brecciated fault block. Follow the route from Figure 7 east to the wash and up the other side through the juniper trees. The coordinates of the exposure are UTM 0416118E 4658251N. The slickenlines are developed between the eroded lower Cache Valley Member of the Salt Lake Formation and a fault-bounded horse of brecciated Camelback Mountain Quartzite (Fig. 10C). Faulted below the Camelback Mountain Quartzite is the Scout Mountain Member of the Pocatello Formation. Up to 6 km of stratigraphic section is omitted along this fault. Previous workers suggested that the Bannock detachment fault slipped W or WSW based on fault and fold geometries in the hanging wall (Janecke and Evans, 1999; Carney and Janecke, 2005). The slickenlines preserved here and ~1.5 km south along this same fault, coupled with data from faults within horses along the detachment fault, show that the Bannock detachment fault system has a WSW-ENE extension direction, consistent with prior analyses of fault geometries. The UTM coordinates of the second slickenline exposure are 0416320E 4656903N. Return to the vehicles and turn around.

Mileage		
Interval	(Cumulative)	Description
1.6	74.5	Retrace your route to the main gravel
1.6	76.1	Drive southeast to a T-intersection. Turn
4.0	80.1	Proceed south through the town of
19.8	99.9	becomes Utah Route 23. Continue on Route 23 for 19.8 mi. Turn
		right (east) onto Hwy 30 and drive 11.7 mi to the intersection with I-15.

# SUMMARY

Flat-on-flat relationships across  $\sim 6 \text{ km}$  of the Bannock detachment fault show that the fault was active within  $\sim 1.6$  to  $\sim 4.3 \text{ km}$  of Earth's surface yet had a negligible dip. A  $\sim 1\text{-km-high}$  lateral ramp in the detachment fault separates a highly faulted thin hanging wall above the upper flat from an intact and unfaulted hanging wall above the lower flat.

Facies relationships in the synextensional Salt Lake Formation indicate a widespread lacustrine system from ca. 10.2 to ca. 9.6 Ma as the hanging wall of the detachment slipped as a single intact fault block during a translation phase. Lacustrine deposition continued but changed in character at ca. 9.6 Ma as the hanging wall began to break up into individual fault blocks and subbasins. West-trending growth folds, recycled Late Cenozoic basin fill, and renewed coarse clastic input record the reorganization of the basin during the breakup phase.

Development of steeper Basin and Range–style normal faults postdate 4.4 Ma tephra beds within the Salt Lake Formation (Janecke et al., 2003). These faults dismembered and exposed the Bannock detachment system and form the modern topography in the area.

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