Normal Fault Block or Giant Landslide? Baldy Block, Wasatch Range, Utah

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Normal Fault Block or Giant Landslide? Baldy Block, Wasatch Range, Utah

Eric R. Meyer

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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Understanding the interplay between surficial and tectonic processes in the development of Utah’s Wasatch Range is vital to evaluating geologic hazards along the Wasatch Front. Baldy is a large (6.125 km³) block of limestone and sandstone structurally overlying shale on the western flank of Mount Timpanogos. It has been mapped as a downdropped normal fault block of Permian units, but no other trace of such a fault exists along the range. The Baldy block structurally overlies the weak Manning Canyon shale, which has produced a regional geomorphology replete with faceted spurs, landslide scarps and deposits. Structural, bio- and litho-stratigraphic mapping of the block reveals breccia deposits, bed rotation and stratigraphic and structural relations to Mount Timpanogos consistent with a landslide interpretation. Structural reconstructions of the block and calculations of stream downcutting rates help constrain the timing and sequence of events of the block’s emplacement. These results attest to the importance of surficial processes in the development of large-scale geologic structures, and demonstrate the ongoing danger of mass wasting to the communities of the Wasatch Front.

Keywords: Wasatch, landslide, normal fault, breccia, structure
ACKNOWLEDGEMENTS

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1. INTRODUCTION

Utah’s Wasatch Range is a natural laboratory for recognizing how the interplay between tectonic and surficial processes shapes the landscape and contributes to geologic hazards because it displays the effects of so many of those processes: large earthquakes and quintessential normal fault morphology, relic tectonic folds, glaciation, lake terracing and widespread mass wasting. A large (6.125 km$^3$) block of limestone and sandstone structurally overlying shale on the western flank of Mount Timpanogos (Fig. 1), known as the Baldy block, has been interpreted as either a thrust fault klippe (Baker, 1964) or as a normal fault (Armstrong, 1971; Solomon et al., 2010).
On the most recent geological map of the Orem quadrangle (Solomon et al., 2010) the Baldy block is mapped as a normal fault block consisting of the Granger Mountain Formation of the Oquirrh Group (correlated to Granger Mountain Formation elsewhere based on Permian fusulinids). They mapped the block as faulted down onto older units of the Oquirrh Group (Fig. 2), namely, the Bear Canyon Member and Bridal Veil Limestone, which comprise the bulk of the Timpanogos massif.

The Baldy block was originally mapped as a thrust klippe on a near horizontal fault plane (Baker, 1964). Evidences given for the thrust origin as explained by Baker (1964) were 1) brecciated quartz along a horizontal fault trace (thought to correlate to the basal fault of the Baldy block).

Figure 2. Stratigraphic column of the relevant rock units in and around the Baldy Block. Thicknesses are in meters. Adapted from Constenius et al., 2011.
exposed in Provo Canyon, 2) contortions of the underlying Manning Canyon Shale and Great Blue Limestone, 3) the Bridal Veil fold in Provo Canyon, and 4) the absence of lower Oquirrh Group units below Big Baldy. Armstrong (1971) disputed this interpretation, arguing that many features in the Basin and Range mapped as thrust sheets should be interpreted as blocks down-dropped on low-angle normal faults. He used the Baldy block as an example, claiming that Baker’s observations could be explained much more simply with a curved normal fault. Solomon et al. (2010) followed Armstrong’s interpretation of normal faulting to explain the Baldy block.

The normal fault interpretation avoids the need for complex fault geometries that the thrust fault interpretation requires in order to explain younger-on-older unit relations. However, the Granger Mountain Formation is at least 1700 m stratigraphically above the Bear Canyon Member that the Baldy block is interpreted as faulted against, suggesting at least that much vertical slip. A fault with this amount of vertical slip should also be traceable for some distance away from the Baldy block. Length to throw ratios from fault data bases of around 100:1 (Kim and Sanderson, 2005) predict that the Baldy fault would have to be at least 170 km long, but no fault of such a length has ever been mapped near the Baldy block or anywhere in the footwall of the Wasatch fault. Lack of evidence for a fault of this magnitude raises questions about the correlation between the strata comprising the Baldy block and the Granger Mountain Formation, and the origin of the Baldy block.

To address these questions we conducted a structural, lithostratigraphic, biostratigraphic, and geomorphological analysis of the Baldy Block to test both the normal-fault-block interpretation and other possible origins related to surficial processes. The investigation involved structural field mapping, section measuring, and aerial photo analysis of geomorphic features.
1.2 Geological Setting

The Mississippian and Pennsylvanian strata of northwestern Utah were deposited in an intracratonic basin called the Oquirrh Basin, which rapidly subsided from the Late Mississippian through the Early Permian (earlier Mississippian rocks were deposited in a smaller proto-Oquirrh basin) (Nelson and Lucas, 2011). The sandstones and limestones of the Oquirrh Group represent the Pennsylvanian strata of this basin during its period of most rapid subsidence (Nelson and Lucas, 2011). Marine and terrestrial sedimentation continued to occur atop the Pennsylvanian sediments until the eastward-moving deformational front of the Sevier Orogeny reached central Utah in Cretaceous (Albian) time (Yingling and Heller, 1992).

The rocks that make up today’s Wasatch Range were displaced as part of the Charleston-Nebo thrust sheet in the Cretaceous and likely due to later crustal thickening during the Laramide orogenic phase, and subsequently the region experienced extension (Constenius 1996). The second of these periods is the Basin and Range extension, which began about 17 Ma (Constenius et al., 2003), gave birth to the Wasatch fault. The Wasatch fault is responsible for the present relief of the Wasatch Range (Reinart and Armstrong, 2000). Differential erosion has contributed to the range’s current topography, in particular the strike valley of the Manning Canyon Shale in which the Baldy block sits. (Fig. 3).

Figure 3. 1:24000 scale map of the Baldy Block on the western flank of Mt. Timpanogos. The unit making up the Baldy block is the Bear Canyon member of the Oquirrh Group (Pobc), which is the same unit making up the upper part of Timpanogos. Pink layers are sandstone, blue are limestone and tan are alternating thin layers of each. Beige area on the south side of the block is undifferentiated units. The block is surrounded by a detachment fault with square teeth on the hangingwall. Thinner black lines are landslide scarps with teeth on the hangingwall. Red lines demote ridges where stratigraphic sections were measured, and yellow stars indicate fusulinid sample locations. The Manning Canyon shale (grey - Mmc) is a weak layer that contributes to many landslides in the area, and the Baldy block has already begun to break apart on top of it, particularly on the southern end below Little Baldy. Sackung troughs on Big Baldy show where it has begun to collapse into stream canyons to the north and south.
2. BIOSTRATIGRAPHY

The mapping of the Baldy block as Granger Mountain Formation (Solomon et al., 2010; Constenius et al., 2011) is based on claims of Permian fusulinids found in both limestone and sandstone units of the Baldy block. We obtained the thin sections of the three samples used for the interpretation from the original authors (KNC 052906-9, KNC 060707-1, and KNC 060707-1(2)) and reanalyzed them along with an additional sample we collected (13LB01). Samples KNC 060707-1, KNC 060707-1(2) and 13LB01 were found as float in talus slopes (Fig. 3 and Fig. 4), the former two from the northwest corner of Big Baldy (a sandstone and a carbonate grainstone, both with detrital crinoid, bryozoan and fusulinid fragments) and the latter from above

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Collection Location</th>
<th>Genus</th>
</tr>
</thead>
<tbody>
<tr>
<td>KNC 052906-9</td>
<td>Wackestone (biomicrite) - brownish grey, fusulinid, crinoid and fine quartz sand in wackestone</td>
<td>40° 21.208'</td>
<td>111° 39.325'</td>
<td>Little Baldy ridge, south side, in situ</td>
<td>Fusulina</td>
</tr>
<tr>
<td>KNC 060707-1</td>
<td>Sandstone - w/ detrital crinoid, fusulinid and bryozoan fragments, slightly calcareous</td>
<td>40° 22.117'</td>
<td>111° 40.410'</td>
<td>Big Baldy north face, west side, talus above Battle Creek</td>
<td>Wedekindellina</td>
</tr>
<tr>
<td>KNC 060707-1(2)</td>
<td>Grainstone (biosparite) - detrital crinoid, bryozoan and fusulinid fragments</td>
<td>40° 22.117'</td>
<td>111° 40.410'</td>
<td>Big Baldy north face, west side, talus above Battle Creek</td>
<td>Wedekindellina</td>
</tr>
<tr>
<td>13LB01</td>
<td>Wackestone - whole fusulinids in a grey mud matrix</td>
<td>40° 21.015'</td>
<td>111° 39.845'</td>
<td>Little Baldy ridge, north side, talus above Dry Creek</td>
<td>Beedeina</td>
</tr>
</tbody>
</table>

Figure 4. Lithology and collection locations for fusulinid-bearing samples.

Figure 5. Fusulinids from the Baldy block. 1-6, Beedeina from sample 13LB01 (1,3,5, axial; 2,4 sagittal; 6 tangential), 7-8, Wedekindellina from KNC-060707-1 (7, tangential; 8, axial) and 9-10, Fusulina from KNC-052906-9 (9, axial; 10, tangential).
Dry Canyon streambed across the canyon from the Big Baldy southwest ridge (a wackestone with over 50% volume of fusulinids). Sample KNC 052906-9 was collected from outcrop just below the Little Baldy ridge and is a wackestone with fusulinid and crinoid fragments and some quartz sand. Though three of the samples were found in talus slopes and not outcrop, they were all found on the Baldy block and the talus slopes do not appear to have any non-Baldy source of material. The fusulinids from all samples show a distinctive fusulinellid wall structure (Fig. 5), which is diagnostic of middle Pennsylvanian (Desmoinesian) age genera (Skinner and Wilde, 1954; Wilde 1990). The middle Pennsylvanian age determination matches that of the Bear Canyon Member of the Oquirrh Group (Baker 1976), the same rocks that make up the top two-thirds of Mount Timpanogos.

3. LITHOSTRATIGRAPHY
We measured two lines of section on the Baldy block (Fig. 3 and Fig. 6), one from each side of Dry Canyon, which separates the Baldy block into Big (north) and Little (south) Baldy. The section on Little Baldy traverses the northern ridge to the peak just west of the main summit. The section on Big Baldy is along its south ridge to the ridge summit southwest of the main summit (Fig. 3). Outcrop on the Big Baldy ridge is relatively poor and patchy. The Little Baldy ridge has more contiguous outcrop except for a ~90m thick zone in the middle of the section that is covered by float (Fig. 6).

Bedded units of the Baldy block consist mostly of quartz arenite sandstone or grain-rich carbonate. Both massive and cross-stratified sandstone are common, ranging in color from tan to reddish tan. Most sandstones are quartz cemented, though a few samples have calcite cement. Carbonate is mostly grey to pink laminated mudstone and wackestone/packstone (Fig. 7). Fossils in the wackestone and packstone are mostly detrital crinoid fragments with some brachiopods, with a few beds that contain bryozoan fragments and fusulinids. There are also occasional beds of massive black mudstone (Fig. 8). Ovoid bed-parallel chert nodules are common in many
laminated carbonate mudstone beds, but decrease up-section. On the Big Baldy ridge, zones of inter-bedded sandstone and carbonate that vary at centimeter to meter scales are relatively common, especially in the middle of the section (Fig. 9). The thickest zones of thin alternating units correlate to the parts of the Little Baldy section where no outcrop is visible (Fig. 6). The most striking stratigraphic features of the Baldy block are the thick arenite unit at the top of the block that covers the entire Big Baldy ridge from the saddle to the summit, which is a full third of the

Figure 6. Simplified stratigraphic columns of a) Little Baldy, b) Big Baldy, and c) Timpanogos (the Timpanogos section is adapted from Konopka 1999). Correlation in a fence diagram (d) links strata in the Baldy block to that of Mount Timpanogos. Correlation is weaker lower in the sections due to covered sections and lack of outcrop.
Fig 7. Grey wackestone from the Big Baldy south ridge. The wackestone and packstone beds in the Baldy block are often fossiliferous, and crinoid fragments are the most common fossil type.
Figure 8. Close up (a) and outcrop (b) views of a massive black mudstone unit. These units often occur directly atop sandstone units, and the contacts may represent maximum flooding surfaces. A few crinoid fragments can be seen in the close up photo, but generally these mudstones lack significant amounts of fossils.
Figure 9. Close up (a) and outcrop (b) views of a zone of interbedded sandstone and limestone from the Big Baldy south ridge. These zones correlate to the parts of the Little Baldy ridge where outcrop is missing and thus probably erode easier than the thicker monolithic beds.
Figure 10. (a) Typical breccia from near the base of the Baldy Block. Most (~70%) of the breccia seen in the field is broken quartz arenite. The breccia is made up entirely of broken and recemented native rock, with no sign of secondary breaking of the cement or hydro-fracturing, which is characteristic of faulting. (b) Highly fractured formation from ~100 m upsection from the basal arenite unit is deformed, but not to the same extent.
Figure 11. Thin sections from the breccia block in Fig. 10. Section (a) shows angular quartz arenite blocks in the matrix, which in this case is calcite. Section (b) is a close-up of the matrix, which shows no sign of secondary disruption, indicating that there was only a single phase of brecciation.
entire block (Fig. 12a), and the thick, highly brecciated arenite unit at the base of the block (Fig. 10a. Fig. 11) that forms a distinctive bench that the block sits on (Fig. 12b,c). Several talus slopes expose the red-colored arenite unit, though there are few actual outcrops.

Both sections from the Baldy block correlate well lithostratigraphically with each other and to a section measured on Mount Timpanogos by Konopka (1999) (Fig. 6), where the Desmoinesian age rocks of the Oquirrh Group are called the Butterfield Peak Formation. Their section was measured at Aspen Grove near the base of the mountain on the east side up to the summit, approximately 5 km from the sections measured on the Baldy block. Previous work on the Bridal Veil Limestone of the Oquirrh Group has shown that units in that formation can be traced 30-50 km (Shoore and Ritter, 2007), so lithostratigraphic correlation between the Timpanogos and Baldy sections should allow a good estimation of the original location of the Baldy block on Mount Timpanogos prior to any offset. The new Baldy sections described here correlate well
Figure 12. The thick quartz arenite units on either end of the Baldy block. The upper unit makes up over half of Big Baldy in photograph (a), stretching from the eastern saddle to the summit, with the same steep dip as the prominent beds marked on the left. The lower unit makes up the bench in the center of photograph (b) beneath the bulk of Big Baldy, and is highly brecciated. The cemented breccia is a strong unit that protects the underlying Manning Canyon Shale and thus the Baldy block from erosion. The line between shadow and light in (c) marks the base of the bench.
Figure 13. Looking eastward, up the Dry Canyon drainage on Timpanogos. The entirety of the Baldy Block equivalent stratigraphy can be seen, except the majority of the upper arenite unit that has eroded off the top of Timpanogos. Lighter tan units are sandstone, darker blue-grey units are limestone.

Figure 14. North face of Big Baldy. The steep face is due to incision of Battle Creek at the base. Sandstone beds form the ridges and are back tilted to near vertical attitudes. The lines drawn on indicate the 82°E dip of the beds in the Baldy block measured in outcrop and the ~15. The base of the patch of evergreen trees on the left marks the basal contact of the Baldy block. The slopes of Timpanogos are Bridal Veil member limestone, which along with the lower Manning Canyon Shale are truncated by the Baldy block.
with the very top of the Mount Timpanogos section measured by Konopka (1999) (Fig. 6). Only ~100m of the thick uppermost sandstone of the Baldy block is exposed on Mount Timpanogos, so approximately 620 m of the highest parts of the Baldy-equivalent rock have been eroded off of Mount Timpanogos (Fig. 13).

4. STRUCTURE

Structurally, the Baldy block is generally intact with single units, such as a series of sandstone beds, traceable throughout most of the block. This continuity is significant as it permits lithostratigraphic correlation of beds not only through the block, but with neighboring Mount Timpanogos as well. However, the Baldy block also manifests a high degree of structural disruption and brecciation that is rarely found in units on Mount Timpanogos. One of the most obvious manifestations of structural disruption is the steep to near vertical (50°-82°) east dip of bedding planes in the Baldy block compared to the shallow (15°) east dip of units on Mount Timpanogos (Fig. 12a, Fig. 14). Strike directions form two NW-SE domains with Big Baldy strikes generally 10° more southerly than those of Little Baldy (Fig. 3). This difference may indicate a slight vertical axis rotation of parts of the Baldy block.

Slip surfaces (localized shear) and brecciated zones (distributed shear) are common around the edges of the block, particularly near the eastern saddle detachment surface where the block abuts against Timpanogos and near the basal detachment and toe of the block. Brecciation is intense and widespread near these boundaries, but within 100 m of the detachment it transitions to a highly fractured formation (Fig. 10). 10-20 m further up section, units are nearly completely intact. The bench on which the Baldy block rests has formed atop the Manning Canyon shale and can be seen particularly well at the base of Big Baldy. We theorize that a blanket of brecciated and recemented rock (correlating to the thick basal arenite unit) protects the underlying shale layer from erosion, and slows the erosion of the Baldy block as well. The breccia lacks any veins, indicating that pressure conditions during deformation were too low for hydrofracturing.
Figure 15. Looking eastward along the summit ridge of Big Baldy (a), showing the location and orientation of sackung troughs formed by collapse of the block into the stream canyons to the north and south. A diagrammatic cross-section of Big Baldy (b) with the same orientation shows the structure of the troughs. Cross section adapted from Gutierrez-Santallola et al. 2005.
Figure 16. Looking eastward along the sackung trough on the south side of Big Baldy where the mountain is collapsing down into Dry Canyon due to oversteepening. The slope on the right is the up-slope dipping fault plane characteristic of sackung troughs.

Figure 17. Looking east up Dry Canyon at outcrops of brecciated sandstone along the basal detachment of the Baldy block. Big Baldy is on the left and the Summit ridge of Mt. Timpanogos in the background. The slope of Big Baldy has been dramatically oversteepened by the incision of the canyon, causing recent collapse of Big Baldy toward the accommodation space.
Figure 18. Looking southwest from the Little Baldy ridge (a). All the ridges and valleys on the south side of Little Baldy are due to collapse of the edge of the Baldy Block as the underlying Manning Canyon Shale as it mass wastes south toward Provo Canyon. The strata are so broken here that no outcrop is visible. Looking southwest from the base of Big Baldy across the strike valley of Manning Canyon Shale (b). The shadows are on back-rotated faces of landslide blocks (outlined), which are smaller scale examples of the what the Baldy Block represents. Note the proximity of the landslides in both photos to the urbanized valley below.
The breccia is made up entirely of cemented blocks of sandstone and limestone. The composition of the cement usually matches that of the broken blocks in the breccia, though some sandstone breccias are cemented with calcite (Fig. 11). There are no signs that the cement itself was ever broken up (Fig. 10, Fig. 11). Thus, there was probably only a single episode of movement along the detachment.

5. GEOMORPHOLOGY

The Baldy block shows signs of topographic collapse subsequent to its original emplacement. Two distinct tears in the block can be seen near the top of Big Baldy to the north and south of the main ridge (Fig. 3). These have the morphology of sackung troughs, which are linear, upslope facing scarps produced by gravitational spreading in over-steepened slopes (F. Gutierrez-Santolalla et al., 2005, Ambrosi and Crosta 2006, Li et al., 2010; Fig. 15, Fig. 16). The east-west orientation of the troughs is perpendicular to the dominant north-south orientation of features in the Wasatch Range, which is likely from local stresses caused by post-emplacement topographic development. The sackung troughs indicate the direction of collapse is towards the stream valleys on either side of Big Baldy rather than toward the main valley to the west created by Basin and Range extension. The driver of this collapse is the over-steepening of the slopes of Big Baldy by the down-cutting of Dry Creek to the south and Battle Creek to the north (Fig. 14 and Fig. 17). Numerous sackung troughs, scarps and slumps are also found on the southern slopes of Little Baldy (Fig. 3). This part of the Baldy block for the most part lacks the bench of re-cemented breccia and the buttress of Great Blue Limestone that protect Big Baldy from erosion. It sits directly on the weak Manning Canyon Shale which is collapsing toward Provo Canyon to the south (Fig. 18a). This deformation has severely disrupted stratigraphy of the southern part of the block so that it is now mostly broken up and so lacking in coherent strata that it could not be mapped (Fig. 3).
6. DISCUSSION

Previous reconnaissance mapping of the Baldy block has interpreted it as a thrust klippe or an extensional normal fault (Baker, 1964; Solomon et al., 2010). Additionally, the most recent map of the Orem quadrangle assigned the rocks of the Baldy block to the Granger Mountain Formation based on inaccurate identification of fusulinids. Careful reexamination of the fusulinid microfossils reveal that the Baldy block is middle Pennsylvanian in age, which correlates to the age of rocks found at the top of Mount Timpanogos. Lithostratigraphic analysis shows nearly identical rock types and sequences of units between the Baldy block and Mount Timpanogos. This correlation infers that the total vertical displacement of the block is around 900 m. Since the breccia in the block implies that the shear zone was very shallow and that the block was emplaced by only a single episode of deformation, the normal fault explanation for the block’s emplacement is very unlikely. On the other hand, the local structural relationships between the Baldy block and Mount Timpanogos are more consistent with a large gravity induced landslide versus a tectonically emplaced block. These relationships include: emplacement of the block onto an erosional bench of Manning Canyon Shale, back rotation of the block of up to 82° in places (Fig. 14), a basal breccia formed in a single shallow event, and subsequent internal fracturing and collapse to the north and south. The ubiquity of active landslides on the Manning Canyon Shale and on the block itself show how susceptible both large and small masses are to gravitationally induced landsliding when underlain by the Manning Canyon Shale and when unrestricted laterally by the movement on the Wasatch fault to the west and by erosion of canyons to the north and south.

The theorized development of the Baldy block is shown by the cross-sections in Figure 19. When only the Oquirrh Group rocks were exposed along the Mount Timpanogos section of the Wasatch Range the mountain front was probably a slightly eroded planar surface that reflected the plane of the Wasatch Fault, much like present-day Spanish Fork Peak to the south (Fig. 20a
and Fig. 1). When the Manning Canyon Shale was eventually exposed in the footwall by exhumation along the fault, the mountain front experience much more rapid cliff retreat through erosional excavation of weak shale from underneath the massive section of Oquirrh Group limestone and sandstone. A similar situation to the pre-emplacement stage of the Baldy block exists to the south of Provo Canyon where Cascade Mountain forms an oversteepened cliff face towering over a gently sloping bench of Manning Canyon Shale (Fig. 20b and Fig. 1). We envision that oversteepening of the massive Oquirrh Group cliffs of Cascade Mountain is creating a
Figure 20. Analogs along the Wasatch Front for different periods in the Baldy Block’s development. Photograph (a) is Spanish Fork Peak in the Wasatch Range, 30 km south of Baldy (Fig. 1). The mountain front is a planar surface reflecting the plane of the Wasatch Fault, modified by erosion (compare Fig. 17a). Photograph (b) is a view southward from Big Baldy along the Wasatch Front across the Provo River drainage. The cliffs of Cascade Mountain tower over the Manning Canyon Shale strike valley. The strike valley forms as the Manning Canyon Shale undercuts the sandstone and limestone of the Oquirrh Group (compare Fig. 17b), making Cascade Mountain more susceptible to landsliding in a similar way to the Baldy block.
similar gravitational instability to what existed at Mount Timpanogos, and that a large earthquake could induce a similar massive landslide there or other places along Mount Timpanogos. The landslide would use the Manning Canyon Shale as it basal detachment and slide gigantic blocks of Oquirrh Group on to the eroded bench.

Present day Little and Big Baldy are the remnants of such a landslide, now partially separated by the erosional incision of Dry Canyon. The basal detachment is visible in places where the steeply dipping beds of the Baldy block truncate against the shallower dipping beds of the Bridal Veil Limestone and Manning Canyon Shale (Fig 14).

The timing of the gigantic slide is possible to infer by applying slip rates along the Wasatch Fault coupled with average erosion rates of similar rocks in American Fork Canyon to the north (Fig. 1). Down-cutting rates of 0.46-1.02 mm/a are estimated for American Fork Canyon near Timpanogos Cave by Mayo et al. (2009). Dry Canyon has cut down at least 600 m through the Baldy block. Assuming that this incision is post-emplacement yields an age of emplacement of the Baldy block between 1300-600 ka, though this estimate may be low since the average streamflow of Dry Creek is lower than that of the American Fork River. The difference in elevation between the current headwall of the Wasatch fault and the base of the Baldy block is ~500 m. The slip rate along the Wasatch fault has changed over time (Nelson et al., 2009), particularly at the beginning of the Holocene, in part due to isostatic rebound from the disappearance of Lake Bonneville (Karow and Hampel, 2010). The average slip rate since the mid-Pleistocene is 0.6-1.2 mm/a (Mayo et al., 2009; Nelson et al., 2009; Karow and Hampel, 2010; Jewell and Bruhn, 2013), and based on these rates the maximum age of the Baldy block would be 800-400 ka, if the landslide occurred as soon as its current base was exposed by the fault.

The amount of erosional incision of the Baldy block itself also infers that the footwall scarp for the slide would also be highly incised and difficult to recognize. However, directly upslope from
the Baldy block are found faceted spurs typical of headwall scarps (Fig. 21). There is also a 1.5 km semi-circular eastern indentation of the main northwest-southeast trending ridge of Mount Timpanogos that may correlate with the original, but highly eroded headwall scarp of the slide (Fig 21).

Large landslide deposits composed of megabreccia have been widely documented in the Basin and Range, where normal faulting creates high relief (Longwell 1951; Cook 1960; Burchfiel 1966; Krieger 1977; Schmitt and Brown, 1991; Morris and Hebertson, 1996; Bishop 2010). Many of these landslides have been described with the same structural features and internal stratigraphic cohesion as the Baldy block. Cook (1960), in a study of megabreccia blocks in the Beaver Dam Mountains of Utah, noted the rotation of the blocks and their stratigraphic relationships to unbrecciated outcrops of the same rock on nearby steep hillsides. Krieger (1977) noted the normal stratigraphic sequence in megabreccia blocks in the Kearny and El Capitan Mountain
quadrangles of Arizona, indicating that they slid as a coherent mass. Schmitt and Brown (1991), noted the same thing in megabreccia blocks in the Horse Camp Formation of Nevada. Morris and Hebertson (1996) identified several generations of similar megabreccia deposits in the Canyon Mountains of central Utah. These studies show that landslides that emplace large blocks like the Baldy block are common in the Basin and Range. The only major differences between the Baldy block and the similar landslides described are the Baldy block’s thickness (>1 km versus several hundred meters) and its topographic and geomorphological prominence. The latter is probably due to the Baldy block’s relatively young Pleistocene age compared to the Miocene to Pliocene age of the other landslides (Cook 1960; Krieger 1977; Schmitt and Brown, 1991; Morris and Hebertson, 1996), limiting the relative amount of erosion and modification the Baldy block has experienced. The Baldy block’s relative thickness may be due to a preexisting structural weakness that, in conjunction with the weak underlying Manning Canyon Shale, made it possible for
a very thick package of rock to fail. There are many west-dipping faults in the footwall of the landslide that are exposed in Provo Canyon (Solomon et al., 2010 and Constenius et al., 2011), and a similar north-south fault running through Mount Timpanogos previous to the emplacement of the Baldy block would have provided such a weakness.

Another possible example of a Baldy-type landslide in the Wasatch Range itself is Maple Mountain north of Slate Canyon, 15 miles south of Baldy (Fig. 22). As much as 1 km of strata have been offset by several hundred meters, forming Maple Flat and a distinctive planar slope offset from the slope created by the Wasatch fault. The discontinuity was mapped by Constenius et al. (2011) as a west-verging thrust with increasing displacement to the south of up to 2000 m. However, much like previous interpretations of the Baldy block, the fault (?) is not traceable laterally for more than a few hundred meters. The fault plane actually dips west but lacks a soft layer like the Manning Canyon Shale to slide upon. Therefore, the Maple Mountain block did not develop to the same magnitude as the Baldy block, but still shows significant vertical movement.

7. CONCLUSIONS
Structural, litho- and bio-stratigraphic evidence from the Baldy block indicate that the normal fault model for the block’s emplacement is very unlikely, and that a landslide model is much more realistic. Litho- and bio-stratigraphic data ties the Baldy rocks to those of adjacent Mount Timpanogos, and the block’s structure and brecciation indicate a single, perhaps catastrophic deformational event that led to its emplacement.

The processes that affected and still affect the Baldy block remain active all along the Wasatch Front, and thus must be understood to make predictions about how it will develop. In particular, landslides are still very much a danger along the densely populated Wasatch Front, and below the Baldy block in particular. The cracks at the top of Big Baldy represent the further collapse of the block into the stream canyons on either side, and as those canyons continue to deepen and
the Manning Canyon shale continues to erode, further earthquake- or precipitation-induced mass wasting of the Baldy block into the densely populated valley is likely.

8. REFERENCES


Reinert, E. and Armstrong, P. A., 2000, Tectonic geomorphology of the Wasatch mountains (Utah); indicators of spatial and temporal variations in tectonic activity: Geological Society of


APPENDIX 1. UNIT DESCRIPTIONS

i. Little Baldy Section

Unit 1. 2 m thick dark grey to black massive carbonate mudstone with no bedding or fossil fragments transitioning to 9 m thick slightly laminated, lighter grey mudstone with a few crinoid fragments and elongated, bed-parallel chert nodules. Above the mudstone is a 2 m thick zone of grey crinoidal packstone interbedded (cm- to dm-scale) with white quartz arenite.

Unit 2. White, clean, supermature massive quartz arenite. No bedding visible in outcrop. Thickness 26 m. Transitions in top 2 m to laminated siltstone ranging in color from purple to red to brown.

Unit 3. Thin (<1 m) black massive carbonate mudstone at base, then pink or reddish grey laminated mudstone with a few crinoid fragments. There are some zones of wavy lamination and some thin brecciated zones. No chert nodules. Thickness 30 m.

Unit 4. White, clean, supermature massive quartz arenite. No bedding visible except at the top of the unit where some crossbedding can be seen. This unit is a very good cliff former and can be seen outcropping on Big Baldy across Dry Canyon. Thickness 15 m.

Unit 5. Thin (<1 m) black massive carbonate mudstone at base, then grey laminated mudstone with few crinoid fragments and many bed-parallel elongate chert nodules. Fossil density increases upward to a crinoid wackestone/packstone 32-36 m above the base of the unit. Above that is 8 m of interbedded grey mudstone and wackestone, then a further 8 m with siliciclastic siltstone interbeds. Total thickness 50 m.
Unit 6. White, clean, supermature massive quartz arenite with a ~1 m zone of brecciation. Thickness 9 m.

Unit 7. 4 m-thick black massive carbonate mudstone at base, then a 30 m-thick zone of grey, laminated carbonate mudstone with occasional interbedded layers of darker crinoid wackestone.

Unit 8. White, clean supermature quartz arenite. Generally massive, but with bedding visible near the base and occasional laminated zones. Highly fractured zone (1-2 m thick) 9 m above the base. Total thickness 46 m.

Unit 9. Grey, laminated carbonate mudstone with abundant bed-parallel elongated chert nodules but lacking in even the few crinoid fragments seen in most laminated carbonate mudstone units. This unit is a slope former and only outcrops on the south face of the Little Baldy ridge. It is approximately 40 m thick, though there are areas where only float is present. At the top of this unit there are dm- to m-scale interbeds of white quartz arenite.

Unit 10 & 11. On the Little Baldy ridge, these units do not appear in outcrop, and their lithology is inferred from float. The float in the lower 47 m (unit 10) is almost exclusively clean, white supermature quartz arenite and correlates to a quartz arenite unit on Big Baldy. The float in the upper 45 m (unit 11) is a mix of quartz arenite and grey laminated carbonate mudstone. This zone correlates to unit 6 on Big Baldy, which contains cm- to m-scale interbeds of quartz arenite and laminated carbonate mudstone.

Unit 12. White, clean, supermature, massive quartz arenite. Thickness 18 m.

Unit 13. Grey laminated carbonate mudstone with few chert nodules and few crinoid fragments for 38 m, then 5 m of transitional interbeds to 15 m of crinoid wackestone/packstone. Total thick-
ness 58 m.

Unit 14. White, clean, supermature, massive quartz arenite. Thickness 9 m.

Unit 15. Grey, laminated carbonate mudstone, lacking chert nodules and lacking fossils. Thickness 27 m.

Unit 16. White to pink, clean, supermature quartz arenite, mostly massive. ~2 m thick interbed of grey crinoid wackestone at 45 m from base and ~2 m thick interbed of laminated carbonate mudstone at 53 m from base. Total thickness 67 m.

Unit 17. Grey crinoid-rich wackestone with packstone beds. Thickness 39 m.

Unit 18. White to pink, clean, supermature, massive quartz arenite. ~1 m interbeds of wackestone at 15 m and 81 m from base. Total thickness to end of measured section is 85 m, but this is the thick upper unit of the Baldy block so its total thickness is much greater.

ii. Big Baldy Section

Unit 1. Black massive carbonate mudstone with a few sparse crinoids, approximately 1.5 m thick, with 0.5 m of brecciated white, massive quartz arenite beneath before outcrop disappears. Outcrop is sparse above the mudstone but float is grey, laminated carbonate mudstone.

Unit 2. White, clean, supermature, massive quartz arenite above grey, laminated carbonate mudstone. Thickness is uncertain but carbonate outcrops again 29 m above the lower contact of this unit.
Unit 3. 1-2 m thick bed of black, massive carbonate mudstone then 10-15 m of interbedded white, massive quartz arenite and laminated grey carbonate mudstone with bed-parallel chert nodules. One of the carbonate interbeds is a packstone with large, abundant bryozoan fragments. Top of outcrop is black, massive carbonate mudstone before outcrop ends.

*Here there is ~66 m of section where no outcrop is visible except for a thin quartz arenite layer.*

Unit 4. Grey, laminated carbonate mudstone to wackestone with crinoid debris and bed-parallel chert nodules. Thickness ~15 m.

Unit 5. White, clean, supermature, massive quartz arenite. 5m above the base is a brecciated layer. Outcrop disappears after 9 m.

*Here there is ~60 m of section where no outcrop is visible.*

Unit 6. Grey, laminated carbonate mudstone with bed-parallel chert nodules for ~10 m, then a ~50 m thick zone of cm- to m-scale interbeds of laminated carbonate mudstone and white, massive quartz arenite.

Unit 7. White, clean, supermature, massive quartz arenite. Unit thickness is approximately 11 m, but due to the patchy nature of outcrop on this part of the ridge units 7 and 8 may simply be thick interbeds, and thicknesses are uncertain.

Units 8 - 10. Grey, laminated carbonate mudstone with a few crinoid fragments and lacking in chert. Due to the patchy nature of outcrop on this part of the ridge units 7 and 8 may simply by thick interbeds, and thicknesses are uncertain. There are some thin quartz arenite beds in this sec-
tion.

Unit 11. White, clean, supermature, massive quartz arenite. Thickness 63 m.

Unit 12. Grey, laminated carbonate mudstone with a few crinoid fragments and lacking in chert. Thickness is 13 m to the top of the southwest subpeak of Big Baldy.