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Discovery of the Baldy toreva near urban areas along the southern Wasatch Range, Utah

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ABSTRACT

Structural and geomorphic studies, and lithostratigraphic and biostratigraphic mapping reveal that a giant toreva block (6.125 km^3) slid off Mount Timpanogos toward what are now densely populated urban areas along the Wasatch Front of Utah. The block forms a prominent peak known as Big Baldy, which consists of steeply dipping and locally brecciated limestone and quartzarenite over nearly horizontal shale. Preferential erosion of this shale below overlying limestone and quartzarenite cliffs is most likely the cause of this particular landslide and potential future slides along the Wasatch Front. The low-angle contact at the base of the giant toreva block was initially mapped as a thrust, then as a low-angle normal fault. In both cases, these faults were inferred to have large amounts of displacement (900 meters), but no traces of such faults are found in adjacent canyons. The Baldy slide is associated with geomorphologic features, such as faceted spurs, landslide scarps, sackungen, and hummocky terrain. Limestone and quartzarenite beds in the block are back-rotated up to 80° and are locally broken and brecciated. No evidence of hydro-fracturing is found in the breccia or of multiple brecciation episodes, which indicates surficial rather than deep-crustal processes and perhaps a single event of slip. We speculate based on structural reconstructions of the slide block, and interpolation of maximum downcutting rates on nearby streams, that the slide initiated between 700 and 500 ka. Discovery of the Baldy slide attests to the importance of recognizing the influence of surficial processes in mountain front development and demonstrate the ongoing geologic hazard of mass wasting to communities along the seismically active Wasatch Front and similar horst blocks.

KEY WORDS: geologic hazards, landslide, sackungen, toreva block, Wasatch fault, Wasatch Range, Utah.

INTRODUCTION

The Wasatch Range of Utah is a natural laboratory for recognizing how the interplay between tectonic and surficial processes shapes mountain front landscapes and contributes to geologic hazards. The steep mountain front of the Wasatch Range, which locally averages 46°, is a result of active normal faulting of mostly Paleozoic rocks resistant to erosion. Strain rates are high enough at ~2 mm/yr (Chang et al., 2006) that steep-faced faceted spurs are common. The Paleozoic stratigraphy of the footwall consists mostly of cliff-forming limestone and quartzarenite with the exception of the Mississippian Manning Canyon Formation. This 300-m-thick, mostly shale unit forms a distinct erosional strike valley across much of the southern Wasatch Range adjacent to the densely populated Utah Valley (Fig. 1). Two peaks occupy the strike valley on the west face of Mount Timpanogos, a prominent peak known as Big Baldy and a smaller peak to the south across Dry Creek known as Little Baldy. The Baldy block (Figs. 1A–B) consists of a large, resistant massif (6.125 km^3) of steeply dipping limestone and quartzarenite that structurally overlies the near horizontal shale. The block was interpreted initially as a thrust klippe (Baker, 1964), and later as a klippe above a low-angle normal fault (Armstrong, 1972; Wernicke and Spencer, 1999; Solomon et al., 2010; Constenius et al., 2011). Olsen (1955) briefly raised the possibility of a landslide origin for the block, but ultimately decided against it, citing Morrowan units on Mount Timpanogos that are not found in the Baldy block (Fig. 2).

The thrust klippe interpretation (Baker, 1964) was based on the occurrence of (1) breccia along a horizontal fault trace; (2) contortions in structurally underlying units; (3) proximity to a large fold; and (4) the absence of Pennsylvanian units below Big Baldy. The structural relationship of younger Pennsylvanian limestone and quartzarenite over older Mississippian shale makes this interpretation problematic. This issue was pointed out by Armstrong (1972), who argued that many features in the Basin and Range Province mapped as thrust faults can be interpreted as 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 listric normal fault. Subsequent mapping by Solomon et al. (2010) used Armstrong's interpretation

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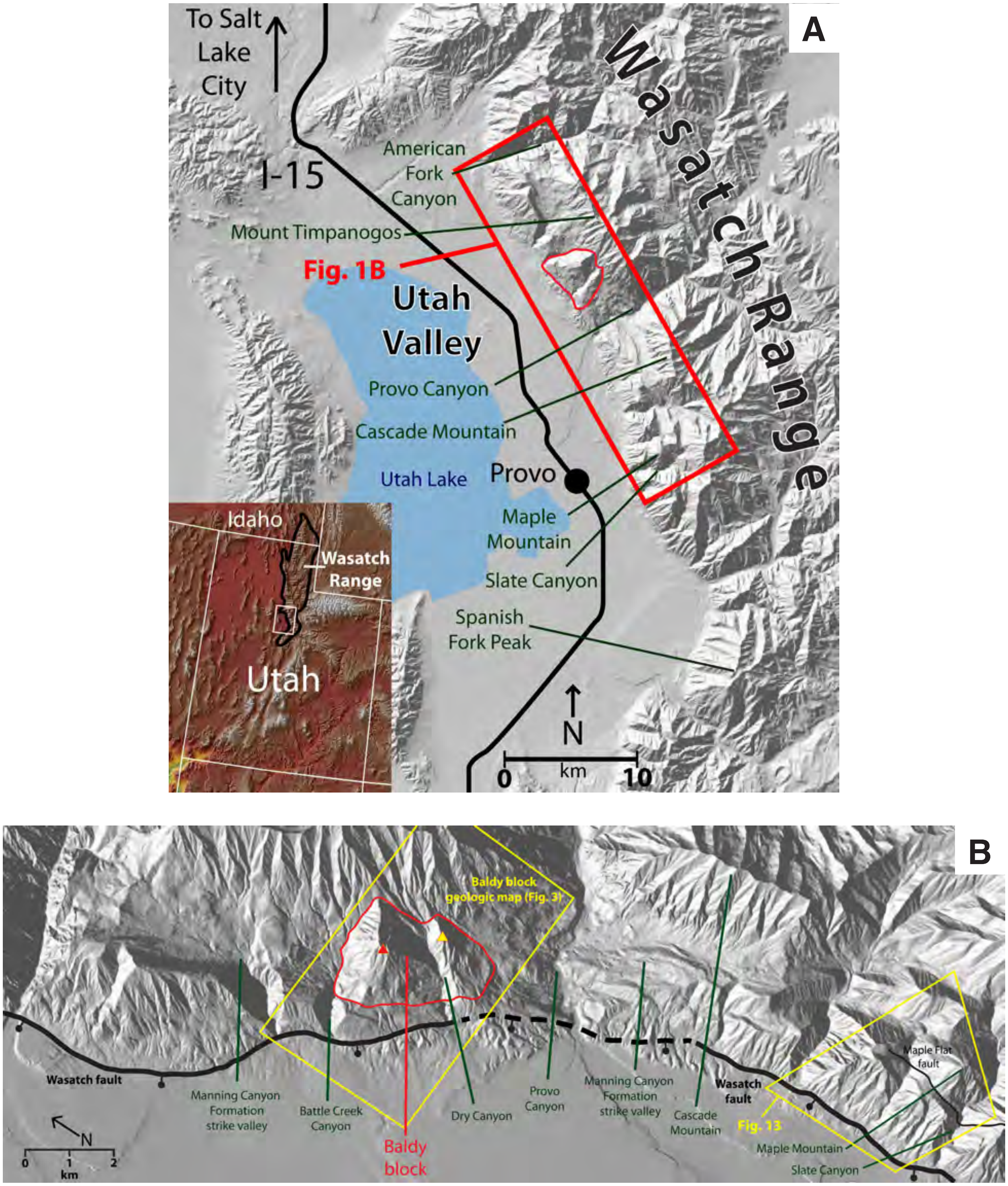

Figure 1. A, Location map of the southern Wasatch Range area around the Baldy block, which is outlined in red. The entirety of Utah Valley north of Provo city, including the areas directly beneath the Baldy block, are urbanized. Spanish Fork Peak in the south is sometimes incorrectly called 'Maple Mountain,' whereas the peak labeled 'Maple Mountain' in this figure (and referred to as such in the paper) has no official name, but is locally known as 'Maple Mountain.' **B,** Zoomed in view of the area around the Baldy block. The block sits anomalously in the strike valley of the Manning Canyon Formation. Big Baldy peak is marked with a red triangle, Little Baldy peak with a yellow one.

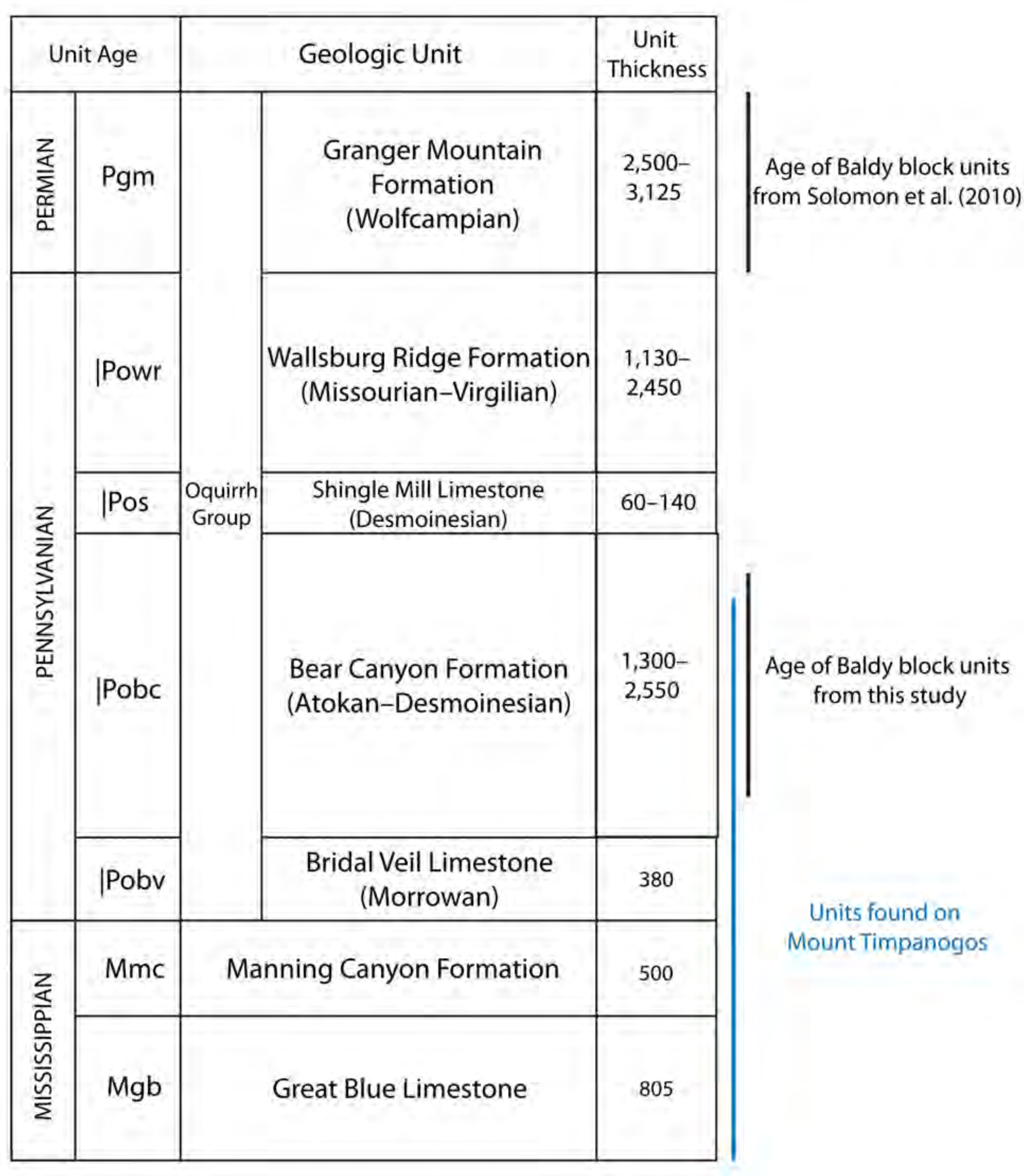

Figure 2. Stratigraphic column of the relevant rock units in the environs of the Baldy block. Thicknesses are in meters. Adapted from Hintze and Kowallis, 2009.

of the Baldy block as an extensional klippe lying on a low-angle normal fault.

Although the low-angle normal fault interpretation avoids the need for complex fault geometries required by the thrust fault interpretation to explain younger-on-older structural relations, it introduced inconsistencies with what is observed in the area. For example, Solomon et al. (2010) correlated the Baldy block with the early Permian Granger Mountain Formation based on what we now know to be misidentified fusulinids (Fig. 2). What was not addressed, however, is how a part of the Granger Mountain Formation was down-faulted along a low-angle normal fault to rest on top the Mississippian Manning Canyon Formation, which is nearly 2,000 m stratigraphically below it. A fault with 2,000 m of vertical displacement would be at least 200 km long according to length-to-throw ratios from fault databases (Kim and Sanderson, 2005). The low-angle nature of the fault would also require many times more horizontal than vertical displacement. Lack of evidence for a fault of this magnitude raises questions about the correlation between strata comprising the Baldy block and the Granger Mountain Formation, and the origin of the Baldy block in general.

To resolve these issues, we (1) conducted lithostratigraphic and biostratigraphic analyses of the limestone and quartzarenite units of the Baldy block; (2) conducted geometric and kinematic structural analyses; and (3) documented the Baldy block's geomorphic features.

GEOLOGIC SETTING

Mississippian to Permian limestone, quartzarenite, and shale units of north-central Utah were deposited in a rapidly subsiding intracratonic depocenter known as the Oquirrh Basin (Jordan and Douglass 1980). The units of Pennsylvanian to early Permian age are known collectively as the Oquirrh Group. With some exceptions, such as the Bridal Veil Limestone, the Oquirrh Group has few distinctive horizons, which makes lithostratigraphic correlations difficult.

The Oquirrh Group is also incorporated into the Cretaceous Sevier fold-and-thrust belt (Yingling and Heller, 1992), which further complicates lithostratigraphic correlations. In the southern Wasatch Range near Mount Timpanogos, the Oquirrh Group forms part of the Charleston-Nebo thrust sheet. Basin and Range extension has also structurally modified the Oquirrh Group (Constenius, 1996). The Wasatch normal fault, which forms the eastern edge of the Basin and Range Province, is responsible for the present relief of the Wasatch Range. Differential erosion has contributed to the range's landforms, in particular the strike valley of the Manning Canyon Formation upon which the Baldy block sits. (Fig. 3).

LITHOSTRATIGRAPHY

We measured two lines of section on the Baldy block (indicated by the two red lines on Fig. 3), one from each side of Dry Canyon, which separates the block into Big Baldy (north) and Little Baldy (south). The section on Little Baldy traverses its northern ridge to the peak just west of the main summit. The section on Big Baldy traverses its south ridge to just southwest of the main summit (Fig. 3). Outcrop on the Big Baldy ridge is relatively poor and patchy. The Little Baldy ridge has more continuous outcrop except for an ~90-m-thick zone in the middle of the section that is covered by float (Fig. 4).

The Baldy block consists mostly of quartzarenite and grain-rich carbonate. Both massive and cross-stratified sandstone are common, ranging in color from tan to reddish tan. Most sandstone is quartz-cemented, although a few samples have calcite cement. Carbonate is mostly gray- to pink-laminated mudstone and wackestone/packstone. 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 local beds of massive dark gray mudstone. Ovoid bed-parallel chert nodules are common in many laminated carbonate mudstone beds, but decrease up-section. On the Big Baldy ridge, zones of interbedded sandstone and carbonate that vary at centimeter to meter scales are relatively common, especially in the middle of the section. The thickest zones of thin alternating units correlate to the parts of the Little Baldy section where no outcrop is visible (Fig. 4B). See the appendix for a more complete list of the units and unit descriptions from the two measured sections.

The most striking stratigraphic features of the Baldy block are (1) a thick quartzarenite unit at the top of the block that covers the entire Big Baldy ridge from the saddle to the summit, a full third of the entire block—signified by 'A' on Fig. 5; and (2) the thick, highly brecciated quartzarenite unit at the base of the block, which forms a distinctive bench at the base of the block—signified by 'B' on Fig 5.

Both measured sections from the Baldy block correlate well lithostratigraphically with each other and with a section measured on Mount Timpanogos by Konopka (1999) (Fig. 4). In the Konopka (1999) section, Desmoinesian rocks of the Oquirrh Group are called the Butterfield Peaks Formation. The section was measured at the community of 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 westward (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 Tim-

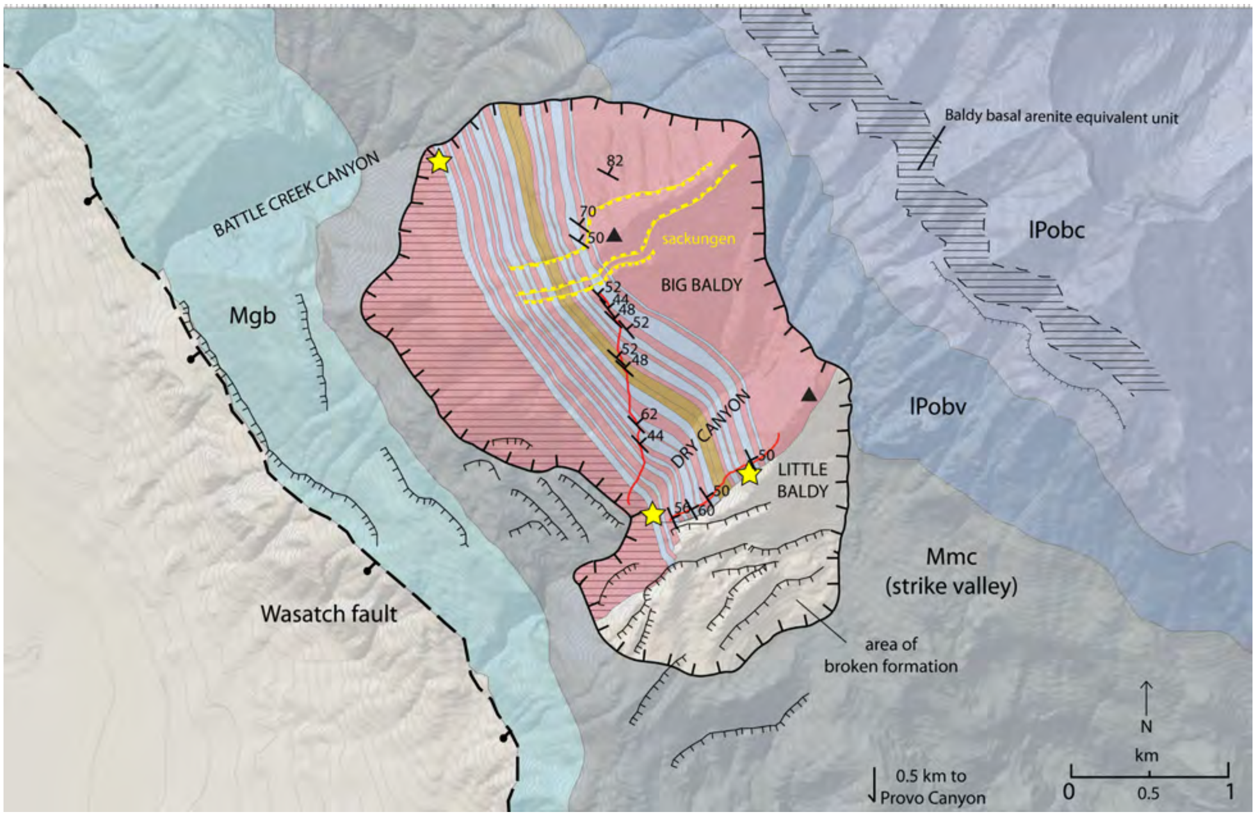

Figure 3. Map of the Baldy block on the western flank of Mount Timpanogos at 1:24,000-scale. The summits of Big and Little Baldy mountains are marked with black triangles. In our study, the unit making up the Baldy block is the Bear Canyon Formation of the Oquirrh Group (|Pobc), which is the same unit comprising the upper part of Mount Timpanogos. Pink layers are sandstone, blue are limestone, and tan are alternating thin layers of each. The basal quartzarenite unit on the Baldy block and the corresponding layer on Mount Timpanogos have a line pattern. Light gray area on the south side of the block is undifferentiated units involved in modern landslides. The block is surrounded by a detachment fault with tic marks on the hanging wall. Thinner black lines are landslide scarps with tic marks on the hanging wall. The two red lines denote ridges where stratigraphic sections were measured, and the yellow stars indicate fusulinid sample locations. The Manning Canyon Formation (the area in gray, identified by 'Mmc') is a weak layer that contributes to many landslides in the area. The Baldy block has already begun to break apart on top of it, particularly on the southern end below Little Baldy. Sackungen (yellow lines) on Big Baldy show where it has begun to collapse into stream canyons to the north and south. The unit below the Baldy block, marked 'Mgb,' is the Mississippian Great Blue Limestone.

panogos prior to any offset. The new Baldy sections described here correlate well with the uppermost Mount Timpanogos section measured by Konopka (1999) (Fig. 4). Only ~100 m of the thick uppermost sandstone of the Baldy block is exposed on Mount Timpanogos, so ~620 m of the highest parts of the Baldy-equivalent rock have been eroded off of Mount Timpanogos—signified by 'C' on Fig. 5.

STRUCTURAL GEOLOGY

Structurally, the Baldy block is generally intact with individual units traceable throughout most of the block. This continuity is significant as it permits lithostratigraphic correlation of beds not only through the block, but also with neighboring Mount Timpanogos. The intact units are highly rotated, with steep to very steep (50–82°) east dip of bedding planes in the Baldy block compared to the shallow (15°) east dip of units on Mount Timpanogos (Fig. 6). Strike directions form two NW–SE domains, with Big Baldy strikes generally 10° more northwesterly than those of Little Baldy (Fig. 3). This difference may indicate a slight vertical axis rotation of parts of the Baldy block.

Slip surfaces (indicating localized shear) and brecciated zones (indicating distributed shear) are common around the

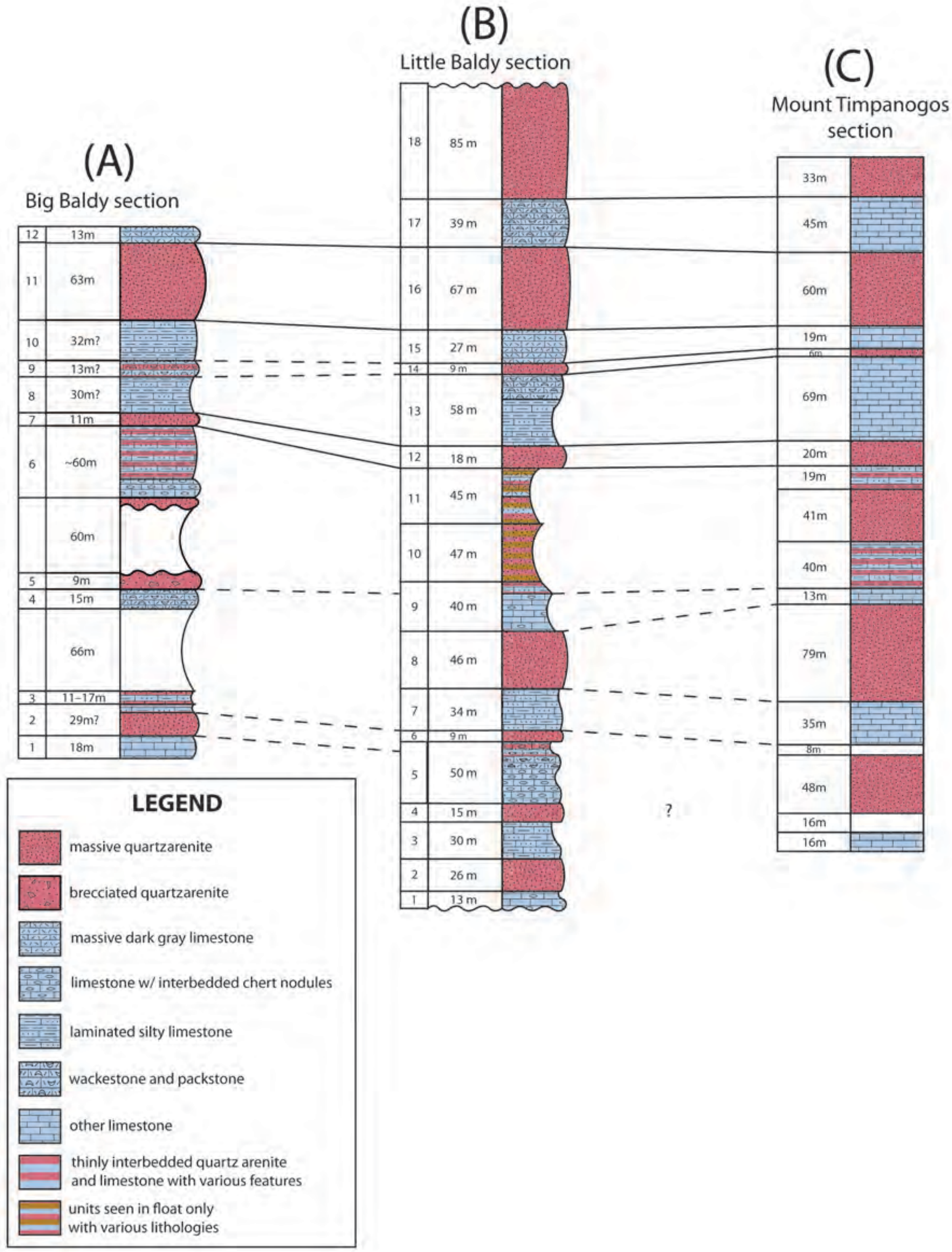

Figure 4. Simplified stratigraphic columns of **A,** Big Baldy mountain; **B,** Little Baldy mountain; and **C,** Mount Timpanogos (the Timpanogos section is adapted from Konopka, 1999). Correlation in a fence diagram links strata in the Baldy block to that of Mount Timpanogos. Correlation is weaker lower in the sections due to covered sections and lack of outcrop.

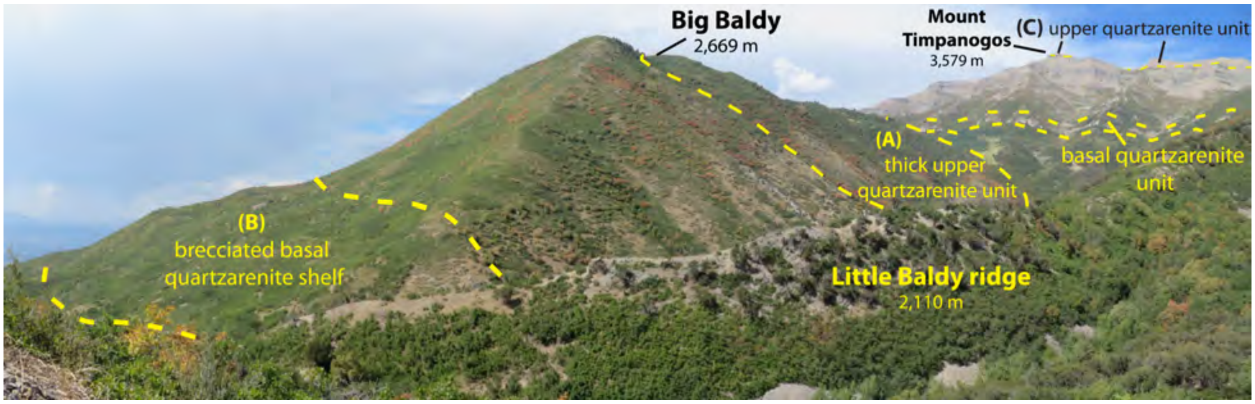

Figure 5. View northward from the south side of Little Baldy at the thick quartzarenite units on either end of the Baldy block. The upper unit (signified by 'A') makes up one third of Big Baldy, stretching from the eastern saddle to the summit. The lower unit (signified by 'B') makes up the bench beneath Big Baldy, and is highly brecciated. The cemented breccia is a strong unit that protects the underlying Manning Canyon Formation and, thus, the Baldy block from erosion. In the background, the entirety of the Baldy block equivalent stratigraphy on Mount Timpanogos can be seen, except the majority of the upper quartzarenite unit that has eroded off the summit ridge (signified by 'C'). The toe of the Baldy block has been truncated by the Wasatch fault.

edges of the block, particularly near the eastern saddle detachment surface where the block abuts against Mount Timpanogos and near the basal detachment and toe of the block. Brecciation is pervasive near these boundaries (Fig. 7A), but within 100 m up-section of the detachment it transitions to a highly fractured broken formation (Fig. 7B). Ten to 20 m farther up-section, units are nearly completely intact.

The bench on which the Baldy block rests (signified by 'B' on Fig. 5) formed atop shale of the Manning Canyon Formation and is well distinguished at the base of Big Baldy. Exposures of the bench in stream cuts reveal it is a blanket of brecciated and recemented rock correlating to the thick basal quartzarenite unit. The indurated unit armors the underlying shale layer from erosion, slowing the erosion of the Baldy block. The breccia unit lacks any veins, indicating that stress conditions during deformation were too low for hydro-fracturing. Rock fragments that make up the breccia consist entirely of quartzarenite and limestone. The composition of the cement commonly matches that of the broken blocks in the breccia, though some quartzarenite breccia is cemented with calcite. There are no signs that the cement itself was ever broken up (Fig. 7A), which is consistent with a single episode of movement along the slide detachment.

GEOMORPHOLOGY

The headwall of the Baldy block landslide is mostly eroded away; however, directly upslope from it are eroded features that match the morphology of modern headwall scarps (Fig. 8). There is no landslide toe at the base of the Baldy block. The basal quartzarenite unit abruptly ends at a steep, 100-m-tall slope that roughly parallels the Wasatch fault (Fig. 5). This suggests that the landslide did originally spill over the fault into the rift valley to the west, but was truncated by subsequent movement along the fault. The toe of the landslide, including the missing Bridal Veil Limestone that Olsen (1955) noted, should therefore be buried beneath Quaternary deposits filling Utah Valley.

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. These features are typical sackungen (Fig. 3), which are linear, up-slope facing scarps produced by gravitational spreading in over-steepened slopes (Gutiérrez-Santolalla et al., 2005; Ambrosi and Crosta, 2006; Li et al., 2010). The east–west orientation of the troughs is perpendicular to the dominant north–south orientation of features in the Wasatch Range; thus, the orientation of the troughs is likely determined by local extensional stresses caused by post-emplacement topographic development of the Baldy block. The sackungen indicate that the direction of collapse is toward the stream valleys on either side of Big Baldy rather than toward the main rift valley to the west created by Basin and Range extension. Numerous sackungen, scarps, and slumps are also found on the southern slopes of Little Baldy (Fig. 3). This part of the

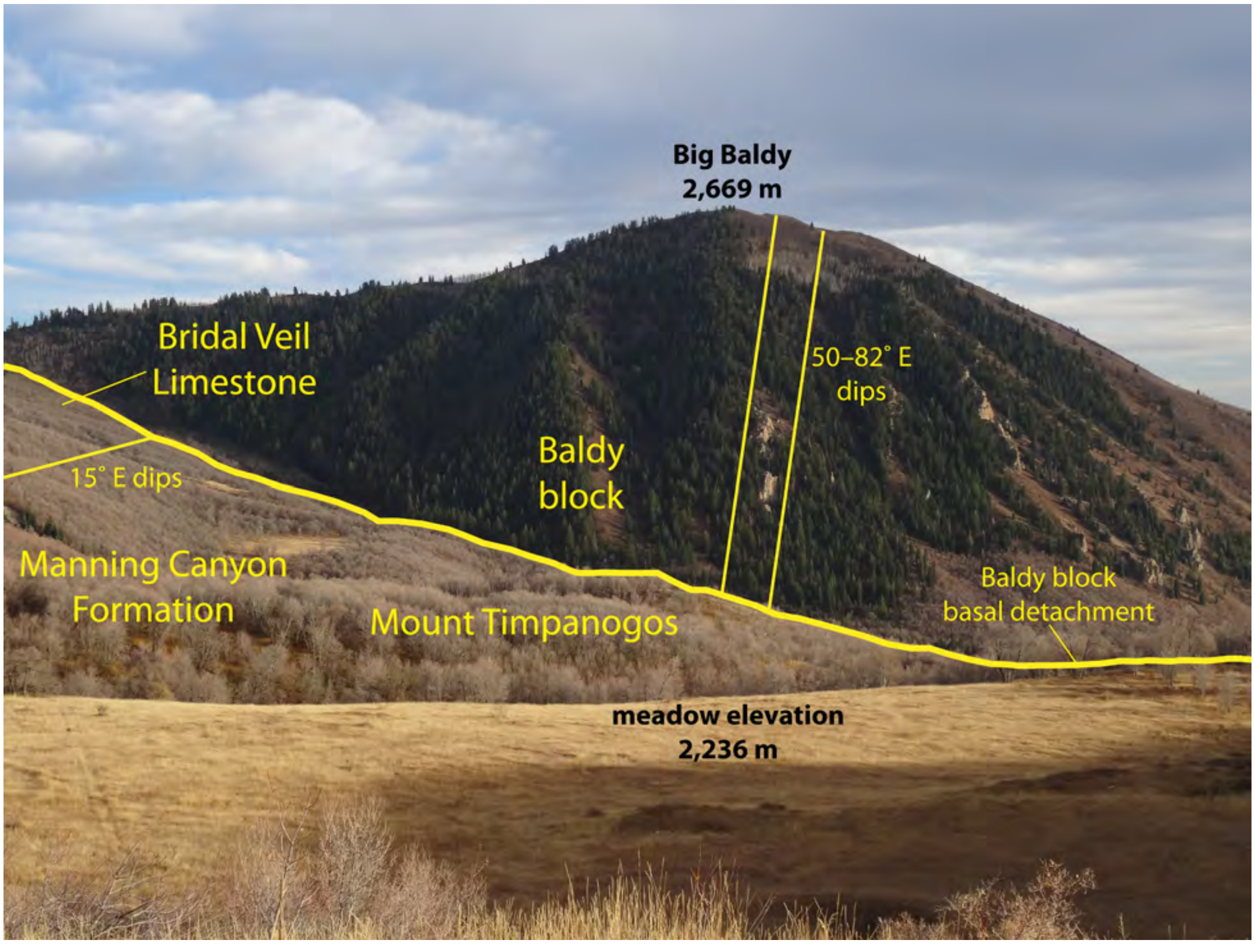

Figure 6. North face of Big Baldy. The steep face is due to incision of Battle Creek at the base. Sandstone beds form the ridges and are back-tilted to near vertical attitudes. The two nearly vertical, thin yellow lines indicate the ~50–82° E dip of the beds in the Baldy block measured in outcrop, whereas the one thin yellow line on the far left indicates the ~15° E dip of the beds beneath the Baldy block. The thick yellow line marks the basal contact of the Baldy block.

Baldy block mostly lacks the bench of recemented breccia and the buttress of the Great Blue Limestone that protect Big Baldy from erosion. It sits directly on weak shale of the Manning Canyon Formation, which is mass wasting toward Provo Canyon to the south (Fig. 9). This deformation has severely disrupted stratigraphy of the southern part of the block so that it and adjacent areas are now part of a modern landslide complex (Fig. 3).

BIOSTRATIGRAPHY

The mapping of the Baldy block as shale and other rocks as in the 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 reexamined 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 collected an additional sample from another location (13LB01). Samples KNC 060707-1, KNC 060707-1(2), and 13LB01 (indicated by the three stars on Fig. 3) were found as float in talus slopes directly below outcrops on the Baldy block. The former two are from the northwest flank of Big Baldy (a sandstone and a carbonate grainstone, both with detrital crinoid, bryozoan, and fusulinid fragments), and the latter from above Dry Canyon streambed across the canyon from the Big Baldy southwest ridge (a wackestone with more than 50% volume of fusulinids). Sample KNC 052906-9 was collected from an outcrop just below the Little Baldy ridge and is a wacke-

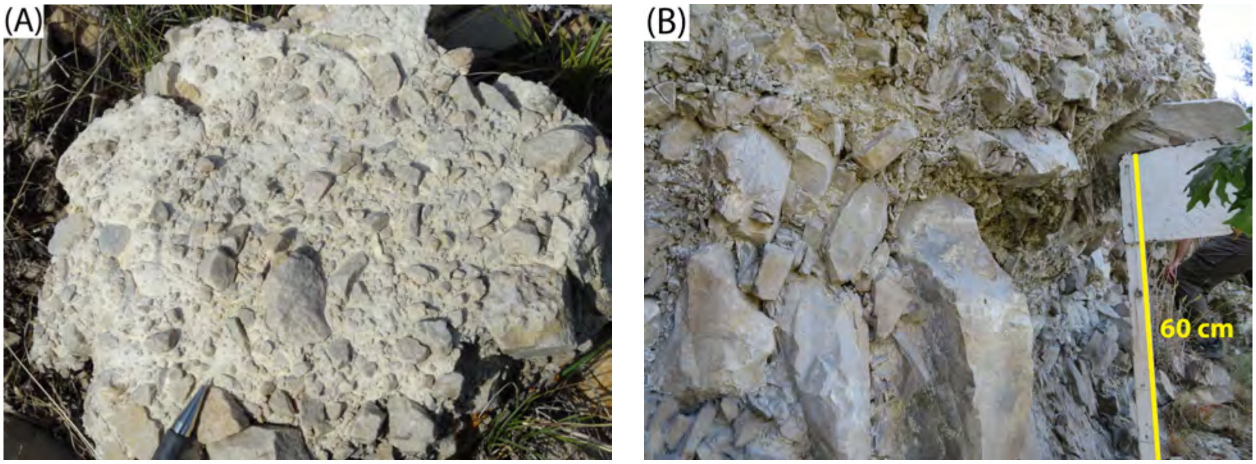

Figure 7. A, Typical breccia from near the base of the Baldy block. Most (~70%) of the breccia seen in the field is broken quartzarenite. This breccia sample is composed entirely of broken and recemented quartzarenite, with no sign of secondary breaking of the cement or hydro-fracturing, which is characteristic of faulting. All the breccia seen on the block fits this pattern. **B,** Highly fractured formation from ~100 m up-section from the basal quartzarenite unit is deformed, but not to the same extent. Measuring staff on right side is 60 cm long.

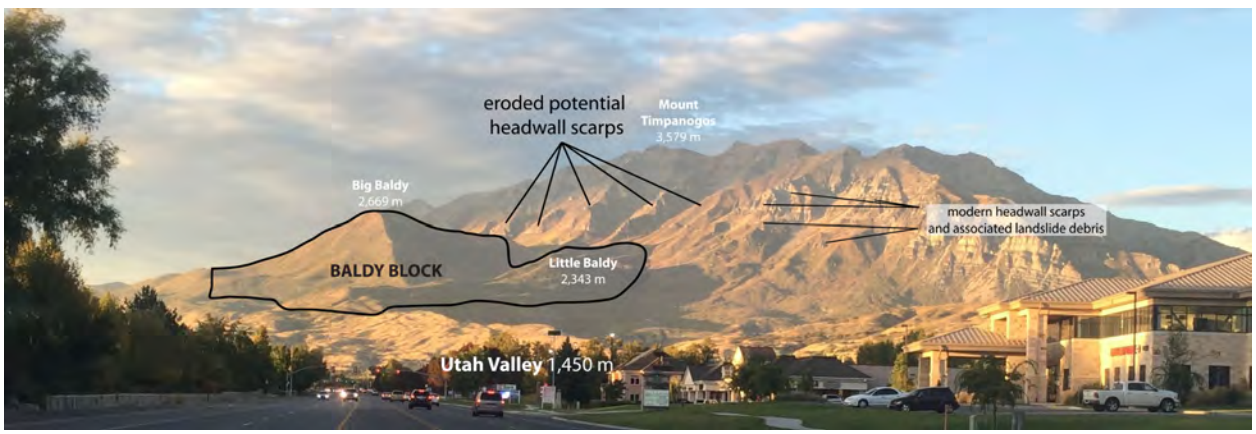

Figure 8. Potential remnants of the headwall scarp of the Baldy slide on Mount Timpanogos. Directly above the Baldy block are highly eroded possible landslide scarps (as indicated by the pyramid-shaped group of lines on the left), adjacent to modern scarps caused by more recent slope failures (indicated by the horizontal lines on the right).

stone with fusulinid and crinoid fragments and some quartz sand.

The fusulinids show a distinctive four-layer wall structure (Fig. 10), 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 Formation of the Oquirrh Group (Baker 1976), the same rocks that comprise the top two-thirds of Mount Timpanogos.

SUMMARY OF OBSERVATIONS

The Baldy block was previously interpreted as a thrust klippe (Baker, 1964) and as a fault block bounded by a low-angle normal fault (Armstrong, 1972; Wernick and Spencer, 1999; Solomon et al., 2010; Constenius et al., 2011). Additionally, the latter two authors reassigned the rocks of the Baldy block to the Granger Mountain Formation based on misidentification of fusulinids. Careful reex-

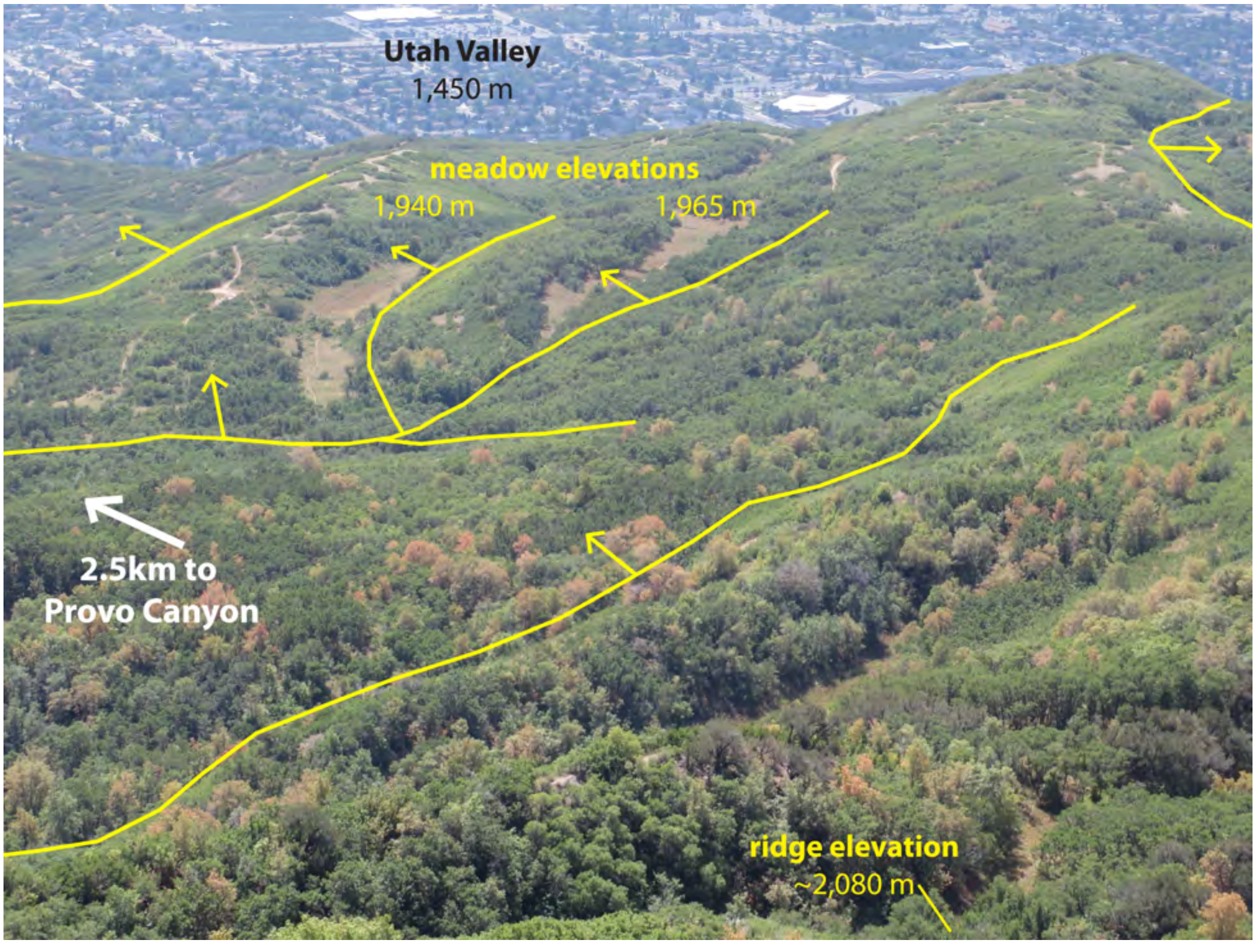

Figure 9. Looking southwest from a ridge on the south side of Little Baldy. All the ridges and valleys on the south side of Little Baldy are due to present-day collapse of the edge of the Baldy block. The yellow lines show the headwall scarps of some of these slides, and the yellow arrows the direction of mass movement for each. The collapse is caused by the underlying Manning Canyon Formation failing south toward Provo Canyon. The strata are so broken here that no outcrop is visible. The distance from the ridge at the very bottom right of the photo to the valley below is ~4 km.

amination of fusulinid microfossils reveals that strata of the Baldy block is middle Pennsylvanian, which correlates to the age of rocks found in the top two-thirds 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 about 900 m, rather than the 2,000 m required if the Baldy block was composed of Granger Mountain Formation rocks. The lack of any fault with at least 900 m of slip on either side of the Baldy block argues against a tectonic origin. This conclusion is also supported by lack of evidence of hydro-fracturing and secondary fracturing in breccia. These relationships indicate breccia formed at shallow depths during one single episode of fracturing, which is inconsistent with a fault interpretation.

Structural relationships between the Baldy block and Mount Timpanogos are consistent with a gravity-induced landslide origin versus tectonic emplacement of the block; it is a classic toreva block. Toreva characteristics of the Baldy block include: (1) emplacement of the block onto an erosional bench of the Manning Canyon Formation; (2) back-rotation of the block of up to 67° to the NE, due to the fact that the bedding planes on the face of Mount Timpanogos have an initial dip of 15° to the NE, and the steepest dips in the Baldy Block are 82° (Fig. 6); and (3) a basal breccia formed in a single shallow event. The basal detachment is visible in places where the steeply dipping beds of the Baldy

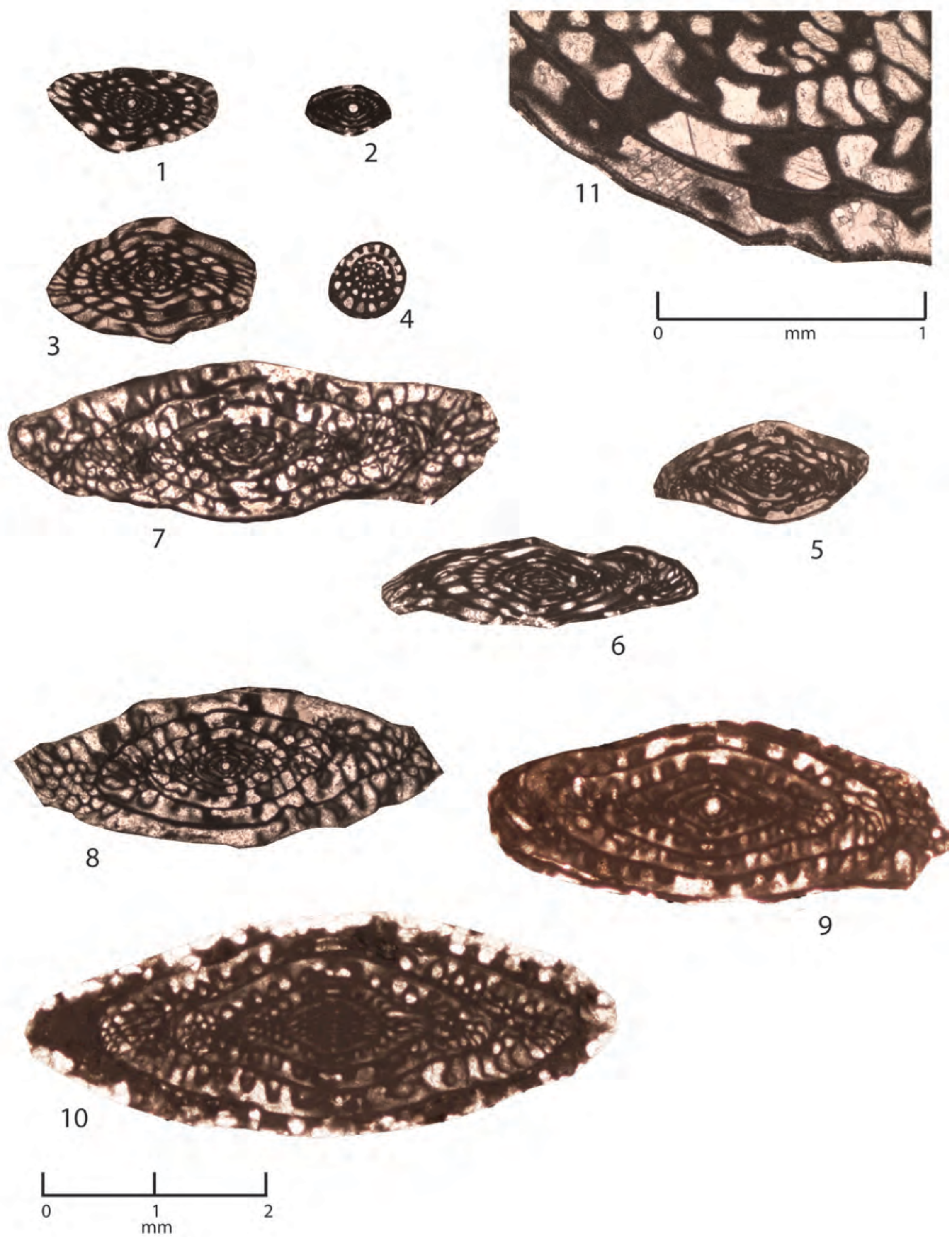

Figure 10. Fusulinids from the Baldy block. 1–6, *Beedeina* from sample 13LB01 (1,3,5, axial; 2,4 sagittal; 6 tangential); 7–8, *Wedekindellina* from KNC-060707-1 (7, tangential; 8, axial), and 9–10, *Fusulina* from KNC-052906-9 (9, axial; 10, tangential); 11, close-up of *Beedeina* from sample 13LB01 showing four-layer wall structure and chomata typical of *Beedeina*.

block truncate into shallower dipping beds of the Bridal Veil Limestone and the Manning Canyon Formation (Fig. 6). The ubiquity of active landslides on the Manning Canyon Formation and on the block itself show how susceptible both large and small masses are to gravitationally induced landsliding when underlain by the Manning Canyon Formation.

EMPLACEMENT OF THE BALDY BLOCK

Our model for the origin and progressive development of the Baldy block is shown by the cross sections in Figure 11. Before the Manning Canyon Formation was exhumed in the footwall of the Wasatch fault, only cliff-forming Oquirrh Group rocks formed the west face of paleo-Mount Timpanogos. Other sections of the Wasatch Range that are currently at this level of extensional exhumation—such as the Spanish Fork Peak area to the south (Figs. 1 and 12A)—have a steep, continuous slope at an angle only slightly less than the dip of the Wasatch fault itself. However, when the Manning Canyon Formation was eventually exposed in the footwall, as along the present Wasatch front from Provo to American Fork cities, weak shale of the Manning Canyon Formation was excavated by erosion from underneath resistant Oquirrh Group limestone, and sandstone and the mountain front experienced a phase of rapid cliff retreat.

A modern analog of the pre-failure stage of the Baldy block exists on the west face of Cascade Mountain, which is across Provo Canyon from Mount Timpanogos (Fig. 1). Cascade Mountain, which is ~1,500 m high and nearly vertical in places, towers over a gently sloping bench of Manning Canyon Formation (Figs. 1 and 12B). We envision that over-steepening of the massive Oquirrh Group cliffs of Cascade Mountain is creating a similar gravitational instability to what existed at Mount Timpanogos, and that an extremely wet year or large earthquake could trigger a similar massive landslide there or other places where similar stratigraphic relations exist along the Wasatch Front. Such a landslide would likely break into and follow the Manning Canyon Formation as its basal detachment and slide gigantic blocks of Oquirrh Group rocks on to the erosional bench of shale. Recent evidence of mass wasting activity along the cliff face involves a rock avalanche from a block of limestone (60 × 10 × 8 m) that fell from the undercut Bridal Veil Limestone. The rock avalanche formed a fresh scar on the cliff face, and a wide trail of debris through vegetation at the base of the cliff.

AGE CONSTRAINTS FOR THE LANDSLIDE

The timing of the Baldy block emplacement can be inferred 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). Downcutting rates of 0.46–1.02 mm/yr are estimated for American Fork Canyon near Timpanogos Cave on the north flank of Mount Timpanogos (Mayo et al., 2009). The stream in Dry Canyon is ~500 m below the summit of Big Baldy and 200 m below the summit of Little Baldy. If the original surface of the toreva block was a smooth incline from the top of Big Baldy to the top of Little Baldy, the stream has cut down 300–350 m since emplacement of the block. Applying the American Fork river incision rate with the assumption that the downcutting is all post-block emplacement yields a landslide age of from 750 to 300 ka. Since the average streamflow of Dry Creek through Dry Canyon is lower than that of the American Fork river, ages on the high end of the estimate are more likely.

Slip along the Wasatch fault can also constrain when the Big Baldy landslide occurred. The maximum age may be constrained by assuming that the slide postdates exhumation of the Manning Canyon Formation in the footwall of fault. The current difference in elevation between Holocene scarps of the Wasatch fault and the base of the Baldy block is ~500 m. The estimated vertical slip rate of the Wasatch fault since the mid-Pleistocene varies from 0.6 to 1.2 mm/yr (Mayo et al., 2009; Nelson et al., 2009; Karow and Hampel, 2010; Jewell and Bruhn, 2013). At these rates, the Manning Canyon Formation would have first appeared at the surface between 800 and 400 ka. If the mountain front at Mount Timpanogos evolved similarly to present-day Cascade Mountain (Fig. 12B), the landslide would not have occurred when the Manning Canyon Formation was first exposed, so ages on the high end of this estimate are less likely. These two rough estimates overlap, and may suggest that the Baldy block was emplaced about 700–500 ka.

OTHER EXAMPLES OF LARGE LANDSLIDES IN THE BASIN AND RANGE PROVINCE

Landslide deposits composed of large, intact blocks are widely documented in the Basin and Range Province where normal faulting creates slope instabilities of a steep mountain front susceptible to over-steepening by differential erosion of cliff and slope forming units, and to earthquake trigger mechanisms (Longwell, 1951; Burchfiel, 1966; Krieger, 1977; Schmitt and Brown, 1991; Morris and Hebertson, 1996; Bishop, 2010). Landslides that emplace large toreva blocks are also common in the Basin and Range Province and the Colorado Plateau. Toreva blocks were first defined by Reiche (1937), who described their internal stratigraphic coherence, back-rotation, and the fact that broken and brecciated rock is limited to it base nearest the detachment. He noted multiple toreva blocks in the Grand Canyon of Arizona and along the Rio San Jose valley in New Mexico, one of which emplaced a single block ~1.2 km long. Huntoon and Billingsley (1978) mapped several toreva blocks at Surprise Valley in the Grand Canyon, noting their

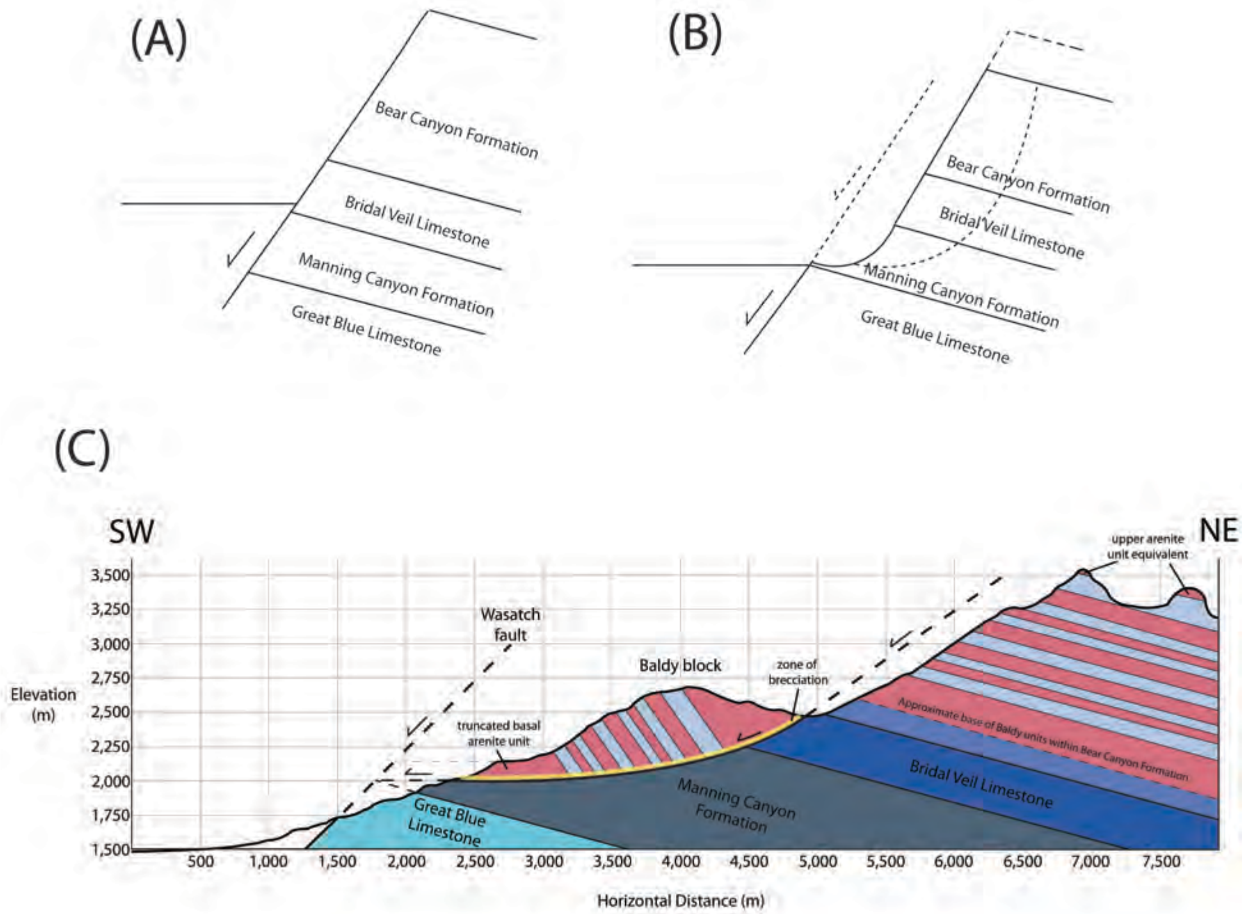

Figure 11. Diagram of the evolution and emplacement of the Baldy block. **A,** Before the Manning Canyon Formation was exhumed in the footwall of the Wasatch fault, the relatively resistant rocks of the Bear Canyon Formation and Bridal Veil Limestone would have formed a planar mountain front. **B,** After the shale was exposed, it eroded faster than the overlying resistant units, which undercut the cliffs. This, in turn, caused accelerated cliff retreat. **C,** Perhaps along a pre-existing weakness, a large mass of Mount Timpanogos slid along a detachment in the Manning Canyon Formation. Currently, only the Bear Canyon Formation is present in the Baldy block. Lower units of the block have either eroded away or were carried over the Wasatch fault onto the hanging wall, and are now buried beneath the Utah Valley. The zone of brecciated rock at the base of the block is highlighted in yellow.

stratigraphic coherence and back-rotation. The only major differences between the Baldy block and the landslides described above are its thickness (> 1 km), topographic and geomorphological prominence, and occurrence along an active fault. The Baldy block's relative thickness may be due to a preexisting structural weakness that, in conjunction with underlying shale of the Manning Canyon Formation, made it possible for a very thick package of well indurated layers of mostly limestone and sandstone to fail. A west-dipping normal fault with < 100 m of displacement is mapped near where the Baldy block broke away from the west face of Mount Timpanogos (Solomon et al., 2010; Constenius et al., 2011). However, bedding planes on this face of Timpanogos dip gently (15°) to the NE—away from the slide.

Another possible example of a Baldy-type landslide in the Wasatch Range only 20 km south of Big Baldy is observed in Slate Canyon (Fig. 13). As much as 1 km^3 of strata is offset by several hundred meters along a distinctive planar slope. The discontinuity was initially designated as the Maple Mountain fault (Baker, 1968) with normal displacement. It was reinterpreted by Constenius et al. (2011) as a west-verging thrust (Maple Flat thrust) with increasing displacement to

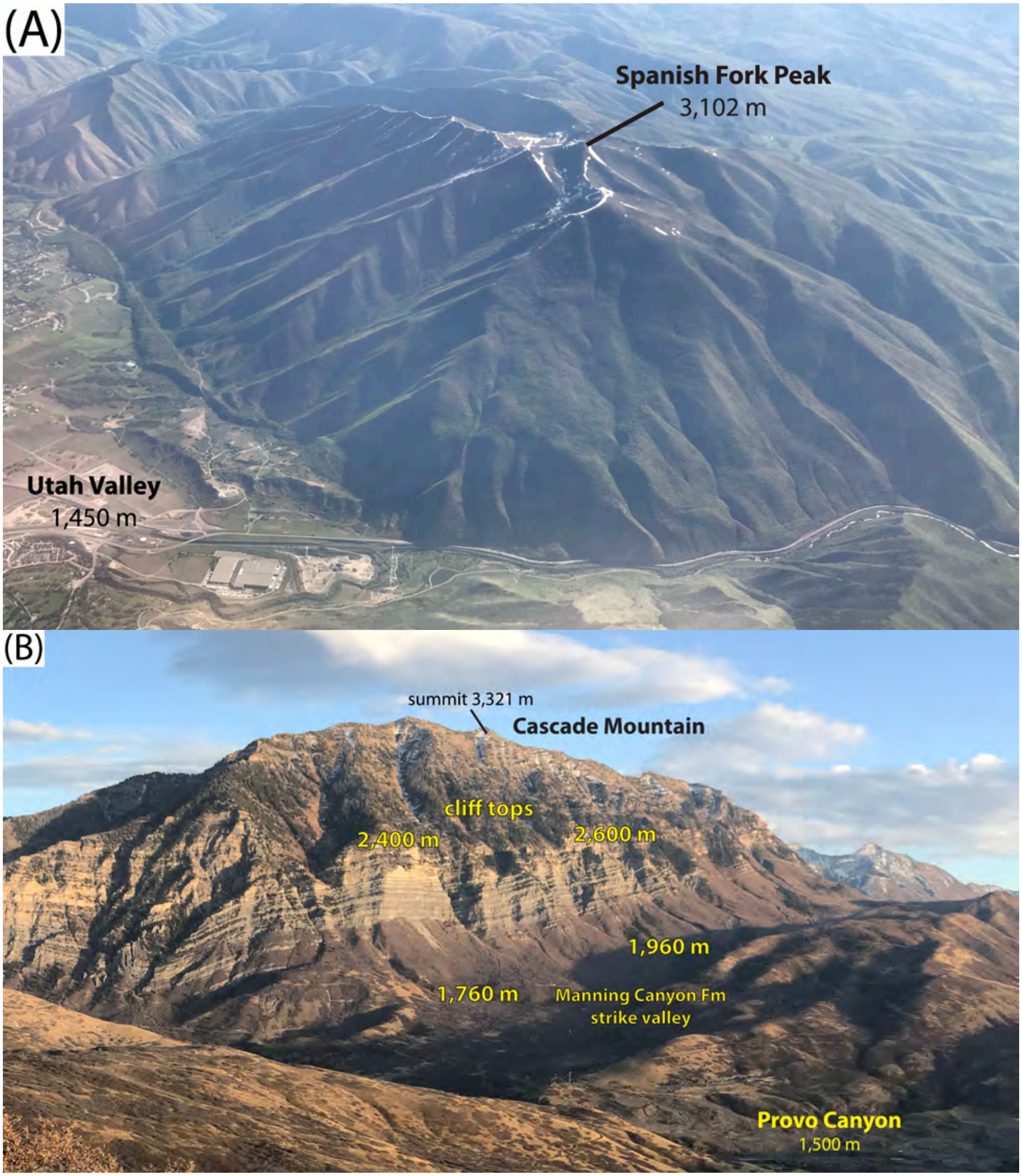

Figure 12. Analogs along the Wasatch Front for different periods in the Baldy block's development. **A,** Spanish Fork Peak in the Wasatch Range, 33 km south of Big Baldy (Fig. 1), looking northeast. The mountain front on the left side is a planar surface reflecting the plane of the Wasatch fault modified by erosion (compare Fig. 11A). **B,** View southeast from Little Baldy along the Wasatch Front across the Provo River drainage. The cliffs of Cascade Mountain tower over the Manning Canyon Formation strike valley. The strike valley forms as erosion of the Manning Canyon Formation undercuts sandstone and limestone of the Oquirrh Group (compare Fig. 11B). This has made the face of Cascade Mountain more susceptible to landsliding in a similar way to the Baldy block.

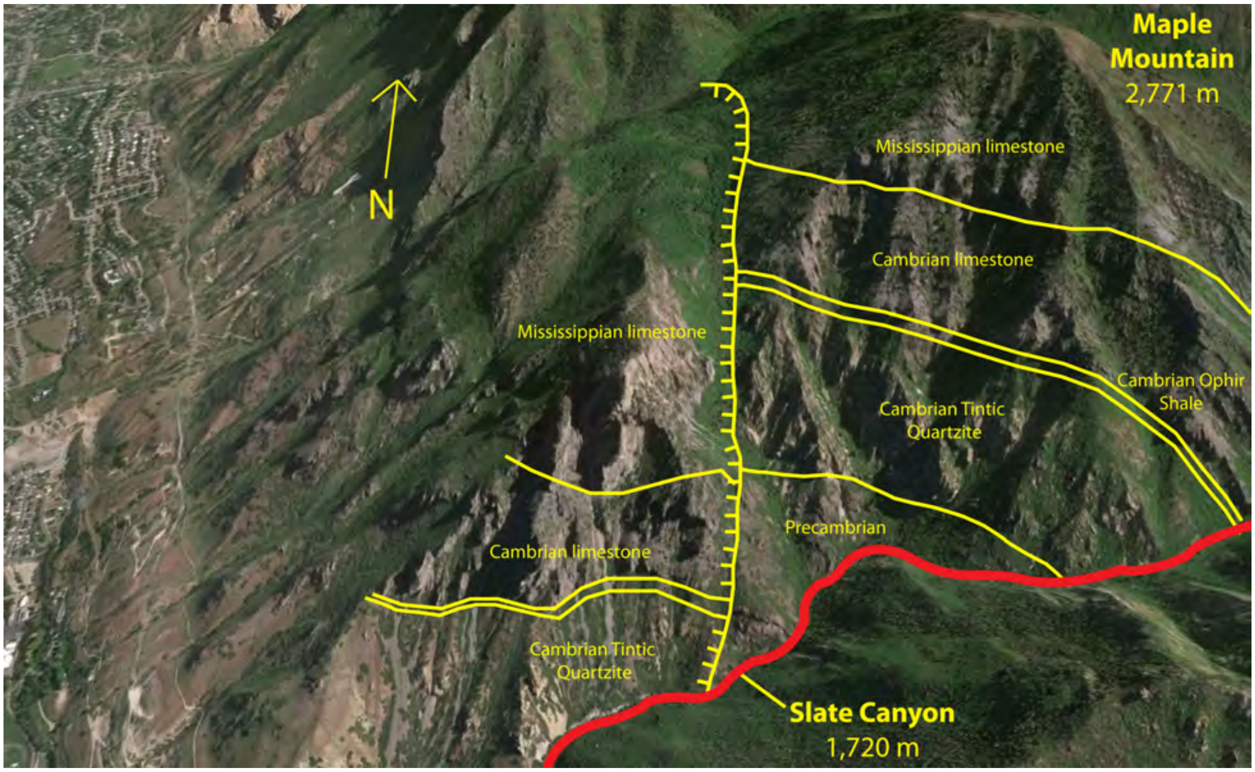

Figure 13. Google Earth image of the south face of Maple Mountain above Slate Canyon, showing offset along the Maple Flat thrust fault as named by Constenius et al., 2011. Slate Canyon is traced in red. Constenius et al., 2011, mapped it as a west-verging thrust fault. The fault, however, is traceable for less than 7 km, despite having offset of 400 m. This feature may be another example of a large landslide block along the Wasatch Front. (Satellite images are from the NASA/U.S. Geological Survey Landsat Science program.)

the south of up to 400 m over a distance of only 3 km. Much like previous interpretations of the Baldy block, however, this fault (?) is not traceable laterally for more than a few hundred meters. Our field inspection of the proposed thrust reveals that it is a west-dipping discontinuity, much like the detachment surface associated with the Baldy slide; thus, it is unlikely to be a west-verging thrust. The short length, but large displacement of the discontinuity, is not consistent with a normal fault. We instead refer to the discontinuity as the Maple Flat slide and Maple Mountain block. One difference between the Maple Flat slide and the Baldy block is that the former does not have a shale layer like the Manning Canyon Formation 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.

CONCLUSIONS

Structural, lithostratigraphic, and biostratigraphic evidence from the Baldy block indicate that the thrust and normal fault models for the block's emplacement are incorrect, and that it is actually a large toreva block landslide, parts of which are actively deforming. Lithostratigraphic and biostratigraphic correlations tie the Baldy rocks to those of adjacent Mount Timpanogos, and the block's structure and brecciation indicate a single, perhaps catastrophic slide event that led to its emplacement.

The landslide conditions that formed the toreva of the Baldy Block remain active all along the Wasatch Front; thus, these mass movement features should be closely monitored to determine if the Baldy slide is still active and poses a threat to nearby urban areas. For example, are the sackungen at the top of Big Baldy actively widening toward the increasingly incised canyons on either side? How does further erosion and landsliding of the Manning Canyon Formation beneath the Baldy slide block or adjacent cliffs of Cascade Mountain compromise the stability of these features? Are there daylighting fractures on the over-steepened cliff faces of Cascade Mountain or other parts of Mount Timpanogos that indicate existing instabilities that also should be monitored? What are the possible consequences of these instabilities causing a Baldy-like landslide during the next large earthquake or extreme weather event along the Wasatch Front?

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Appendix 1. Descriptions of Rock Units Measured on Little and Big Baldy Mountains.

LITTLE BALDY SECTION

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

Unit 2. White, clean, supermature massive quartzarenite. 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 gray 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 quartzarenite. 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 also be seen outcropping on Big Baldy on the other side of Dry Canyon. Thickness 15 m.

Unit 5. Thin (< 1 m) black massive carbonate mudstone at base, then gray 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 gray mudstone and wackestone, and then 8 m with siliciclastic siltstone interbeds. Total thickness 50 m.

Unit 6. White, clean, supermature massive quartzarenite with an ~1-m zone of brecciation. Thickness 9 m.

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

Unit 8. White, clean, supermature quartzarenite. 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. Gray, 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 it only outcrops on the south face of the Little Baldy ridge. It is ~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 quartzarenite.

Units 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 quartzarenite and correlates to a quartzarenite unit on Big Baldy. The float in the upper 45 m (unit 11) is a mix of quartzarenite and gray laminated carbonate mudstone. This upper zone correlates to unit 6 on Big Baldy, which contains cm- to m-scale interbeds of quartzarenite and laminated carbonate mudstone.

Unit 12. White, clean, supermature, massive quartzarenite. Thickness 18 m.

Unit 13. Gray 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 thickness 58 m.

Unit 14. White, clean, supermature, massive quartzarenite. Thickness 9 m.

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

Unit 16. White to pink, clean, supermature quartzarenite, mostly massive. Approximately 2-m-thick interbed of gray 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. Gray crinoid-rich wackestone with packstone beds. Thickness 39 m.

Unit 18. White to pink, clean, supermature, massive quartzarenite. Approximately 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.

BIG BALDY SECTION

Unit 1. Black massive carbonate mudstone with a few sparse crinoids, ~1.5 m thick, with 0.5 m of brecciated white, massive quartzarenite beneath before outcrop disappears. Outcrop is sparse above the mudstone, but float is gray, laminated carbonate mudstone. Float continues for 16 m, for a total thickness of 18 m.

Unit 2. White, clean, supermature, massive quartzarenite above gray, laminated carbonate mudstone. Thickness is uncertain, but carbonate outcrops again 29 m above the lower contact of this unit.

Unit 3. One- to 2-meter-thick bed of black, massive carbonate mudstone then 10–15 m of interbedded white, massive quartzarenite and laminated gray 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 quartzarenite layer.

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

Unit 5. White, clean, supermature, massive quartzarenite. Five meters 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. Gray, laminated carbonate mudstone with bed-parallel chert nodules for ~10 m, then an ~50-m-thick zone of cm- to m-scale interbeds of laminated carbonate mudstone and white, massive quartzarenite.

Unit 7. White, clean, supermature, massive quartzarenite. Unit thickness is ~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. Gray, 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 be thick interbeds, and thicknesses are uncertain. There are some thin quartzarenite beds in this section.

Unit 11. White, clean, supermature, massive quartzarenite. Thickness 63 m.

Unit 12. Gray, 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.