UNDIFFERENTIATED ALLUVIUM VERSUS COLLAPSE BRECCIAS

Undifferentiated alluvial deposits occur in the southeastern end of Spanish Valley (Fig. 1). These are small oval-shaped remnants of terrace and pediment deposits 1–10 m thick. Pediment deposits derive from the reworking of terrace T1 and consist of angular to subrounded clasts of Jurassic and Cretaceous limestone (Morrison and Burro Canyon Formations), Jurassic sandstone and pebble- to boulder-sized gravel of Tertiary igneous rocks from the La Sal Mountains. Terrace deposits are composed of well-sorted and rounded gravels with a predominance of igneous rocks in a white sandy matrix. Occasionally, pediment deposits unconformably overlie deformed floodplain sediments consisting of horizontally laminated silts and marls with abundant vegetation remains, which may be attributed to the infill of paleo-collapse sinkholes (Fig. DR1). They are difficult to correlate with other terrace or pediment deposits because their relative height has changed from the original position due to salt dissolution subsidence. This alluvium capped mounds were previously interpreted as collapse breccias by Weir et al. (1961), Sugiura and Kitcho (1981), Doelling (1988, 2004), and Harden et al. (1985).

MILL CREEK AND PACK CREEK TERRACES

The alluvium located at the confluence of Mill Creek and Pack Creek thickens to more than 30 m (Figs. 1 and DR2A). Although clast imbrication suggests that most of the alluvial deposit belongs to Pack Creek, the existence of gravel channels oriented perpendicularly to Spanish Valley indicates that the deposit was partially sedimented by Mill Creek. This detrital fill is altitudinally correlated with Pack Creek T4 Terrace. The terrace is restricted to the hanging-wall of the innermost normal fault of the northeastern flank of the valley (Fig. 1). The fault, with a minimum throw of 30 m, juxtaposes Kayenta Fm. against and Navajo Sandstone.

The alluvial fill is offset by abundant secondary faults with throws of up to several meters. Faulting is also accompanied by a general tilting of around 10° to the SW. The 18 m difference in height of the terrace surface between the flanks and center of the graben represents the vertical displacement attributable to post-sedimentary subsidence. A gravel pit excavated in this thickened terrace at the left margin of Mill Creek exposes a 4 m wide graben structure bounded by secondary normal faults (Fig. DR2B and C). The antithetic fault, with a minimum throw of 2.2 m, shows a shear zone composed of reoriented pebbles and cobbles. The following units were mapped in the pit wall: (1) Deposit of terrace T4: Well-sorted, clast-supported gravel with clasts up to 30 cm long in a silty orange matrix. (2) Pediment deposits: Poorly-sorted, matrix-supported, angular pebble and cobble gravel with angular clasts up to 20 cm long. (3) Buried soil: Red silt with scattered pebbles completely coated by a thin calcite layer and scattered millimeter-scale calcite nodules. (4) Sheet-wash deposit: Parallel-laminated orange silt with scattered pebbles up to 3 cm long. (5) Colluvial wedge: 1.20 m thick, calcite-cemented, poorly sorted, matrix-supported gravel with oriented pebbles, cobbles and boulders as much as 80 cm long. (6) Colluvium: Massive orange silt with embedded clasts between 3–10 cm in size. (7) Sheet-wash deposit: Parallel-laminated red fine sand partly distorted by pedogenic processes. (8) Colluvium similar to unit 6.
The geometrical relationships of the different units of the downthrown block of the graben structure record two discrete displacement events suggesting that the faults have an episodic behavior. The older event is recorded by F2, which offset units 1–3 and is truncated by unit 4. Using the base of unit 2 we estimate a minimum vertical throw of 46 cm because unit 2 has been removed by erosion from the footwall. The buried and faulted paleosol (unit 3) suggests that the development of the surface rupture event took place when the terrace was already a relatively stable relict surface affected by soil development. The most recent event is recorded by displacement on fault F1 that ruptured units 1–4 and created the scarp that led to the formation of a colluvial wedge (unit 5). Considering the thickness of the colluvial wedge thickness (1.2 m), we roughly estimate a vertical throw of 2.4 m for this event.

The correlation of Mill Creek terraces with Pack Creek terraces is not feasible without dates, since the thickened terrace fill located at the hanging wall has been offset and terraces in the footwall do not show a persistent lateral continuity. Rather, they form isolated remains that prevent their correlation.

STRATIGRAPHY AND STRUCTURE OF TRENCH 1

This trench exposed an upper graben and a downthrown block separated by an intermediate horst. The older Quaternary stratigraphic units are faulted and confined to the downthrown block, while the youngest units were deposited across the horst (Fig. 6). The depression fill consists of Pack Creek Terrace T5 sediments (floodplain facies and beds of pebble-gravel derived from the La Sal Mountains) that grade horizontally and vertically into colluvial and sheet-wash deposits including locally-derived cobbles and pebbles of the Navajo and Kayenta sandstone. The correlation of the upper units within the downthrown block and the upper graben was based on facies resemblance, the occurrence of three black-dark gray, calcite-cemented siltstone units with abundant charcoal (units 8, 10 and 12). The correlation of the lower units with datable material has been supported by radiocarbon numerical dates (Table 1) with the exception of unit 2 that was correlated by facies resemblance.

The following units were logged in the trench (Fig. 6): (1) Bedrock: Well-bedded yellow Navajo Sandstone. (2) Colluvium: Matrix-supported subangular gravel with cobbles up to 30 cm long. An age range of 4500–4490 cal BP at (error margin at 2 sigma here and elsewhere) was obtained from charcoal collected 3 cm below the top of the unit in the downthrown block. (3) Colluvial wedge: Clast-supported subangular gravel with sandstone clasts of up to 10 cm in size in a coarse white sand matrix. (4) Pack Creek floodplain deposits and interbedded organic horizons: Horizontally-laminated, well-sorted, white, coarse-medium sand with scattered rounded pebbles of 0.5–1 cm of diorite, sandstone and limestone, interbedded with 2–4 cm thick black organic peat beds. The peat layers in the downthrown block fill were deposited in ephemeral palustrine environments. East of fault F3, two peat layers located above and beneath unit 5 provided radiocarbon ages of 3400–3330 and 4340–4290 cal BP, respectively. Conversely, plant remains collected from a peat layer to the west of fault F3 yielded an inconsistent age of 1320–1270 cal BP. The sample seems to have been contaminated by living plant roots. As a result, we have been unable to correlate the peat layers on both sides of fault F3. (5) Colluvial wedge: Clast-supported subangular gravel with cobbles up to 15 cm long in a coarse white sand matrix. (6) Sheet-wash deposits: Horizontally-laminated gray silt with scattered subangular sandstone clasts up to 5 cm long. A piece of charcoal extracted 3 cm above the base of this unit was dated at 2680–2640 cal BP. (7) Sheet-wash deposits: Massive brown silt with angular
sandstone clasts up to 3 cm long that grades away from the scarp into unit 7'. An identical age of 2460–2340 cal BP was obtained from a charcoal sample collected 4.5 cm above the base of this unit in the graben fill and from an interbedded peat layer 7 cm from the base of unit 7 in the downthrown block. (7') Idem to unit 4. (8). Sheet-wash deposits: Black medium sand with sandstone clasts up to 5 cm and abundant detrital charcoal at the base of the unit that provide a radiocarbon age of 2360–2340 cal BP. (9) Pack Creek floodplain deposits: Calcite-cemented, light-gray, horizontally-laminated silt with orange oxidation lenses and pebbles 0.5–2 cm long of diorite, sandstone and limestone. (10). Sheet-wash deposit: Dark gray medium sand with sandstone clasts up to 5 cm with scattered detrital charcoal. (11) Idem to unit 10. (12) Idem to unit 11. A charcoal piece collected at 1.5 cm above the base of the unit yielded a radiocarbon age of 2330–2140 cal BP. (13) Sheet-wash deposit: Orange massive silt with angular sandstone clasts of up to 2 cm. (14) Sheet-wash deposit: Red-orange horizontally-laminated silt with angular sandstone clasts of up to 2 cm. (15) Man-made fill: Breccia made up of reworked units 8–14, vegetable fragments, charcoal and artifacts (glass, rubber, plastic and pottery). (16) Sheet-wash deposit: Red massive silt with scattered angular sandstone clasts up to 6 cm long. (17) Fissure fill: Massive coarse white sand with sandstone cobbles up to 15 cm.

The eastern margin of the upper-graben shows a swarm of subvertical west-dipping synthetic faults that dip west (F11 to F17). Lateral separation along fault F11 created a tapering downward fissure that is 42 cm at top (unit 18 in Fig. 6). The fissure cuts through units 2 and 6 but is truncated by unit 7 (Fig. 7A). From the base of unit 6 we measure a cumulative vertical offset of just 17 cm on the fissure. On the other hand, shearing during normal displacement along faults F12 to F17 reoriented clasts next to the fault plane. With the exception of F12, which is truncated by unit 7, the other faults offset units 2 and 6–11 and are truncated by unit 12. Unit 12 bends toward the graben, increasing its dip from 5º in the footwall of F17, to 32º in the hanging wall. The dip of the overlying units decreases progressively upwards, suggesting sedimentation during subsidence. The flexure of unit 12 may correspond to a drape fold controlled by motion on F17. Using the base of unit 7 we estimate a total throw of 1.13 m by summing the displacement from F13 to F17. However, this is minimum value because unit 7 has been eroded from the footwall of F17. The southwestern edge of the upper-graben is controlled by the antithetic fault F10. The fault shows a maximum 2.30 m wide shear zone of reoriented brecciated sandstone cobbles (Fig. 7B) that extends through units 2–10 and is unconformably overlapped by unit 11. The vertical distance between the floor of the trench, where unit 2 crops out, and the top of the shear zone is 2.27 m. This is a minimum vertical displacement on fault F10, because unit 2 was eroded from the footwall. The strata is flexed toward the graben forming a superimposed drag fold over fault F10 in the downthrown block, where unit 11 abruptly reaches a dip of more than 50º.

The SW sector of the trench exposed a downthrown block bounded by the synthetic master fault F7 dipping 50º, with an associated shear zone 5 cm wide and a swarm of subvertical secondary synthetic faults (F1 to F6, F8 and F9). We distinguish three sedimentary packages: (1) the undeformed upper package made up of the youngest units 15 and 16, unconformably overlying all the deformational structures. (2) The intermediate package, which includes units 8–13, shows ductile deformation and truncates all the faults with the exception of F5, F6, F8 and F9. Using the base of unit 8 we measure a minimum cumulative vertical throw of 32 cm along faults F5 and F6. The strata are bent toward the downthrown block in the hanging wall of F7, with upward dip attenuation from 27º to 5º. The flexure that accommodated a vertical displacement of 2.36 m is a drag fold created by movement on fault F7. Dragging also affected
the underlying units of the lower package to the west of F1. (3) The lower package includes units 2–7. Unit 4 was affected by plastic deformation presumably occurred when the sediment was unconsolidated and in a water-saturated state (Fig. 6). The interbedded peat layers are split into patches that show disharmonic folds and the associated sands display broken or contorted lamination. The lower package is affected by faults F1 to F5 and F7. F1, F2 and F5 account for most of the deformation affecting the lowermost strata, whereas F3 and F4 are responsible for centimeter-scale throws with associated shear zones in unit 4. Fault F1 cuts units 2 and 4 and is truncated by unit 7. F1 steepens upward, reversing its dip direction in the upper part. From the exposed thickness of unit 2 in the footwall we measure a minimum throw of 45.1 cm on fault F1 because the trench was not deep enough to expose unit 2 in the hanging wall. F2 splays from F1 to form an overhanging fault plane cutting unit 7, but the fault is truncated by unit 8. There is 50 cm of displacement on F2 using the base of unit 7 as a marker. Two colluvial wedges (units 3 and 5) 77 cm and 48 cm thick are intercalated within unit 4 in the downthrown block of fault F5 (Fig. 7C and D). The two colluvial wedges along with units 4 and 7 are deformed into a conspicuous drag fold in the hanging wall of fault F5. Using the base of upper colluvial wedge (unit 5) we estimate a minimum vertical throw of 56 cm due to dragging along F5. Both colluvial wedges along with units 4 and 7 are offset 3.5 cm by faults F3 and F4.

**TRENCH 2**

This trench is located in a marginal secondary graben 145 m long and 82 m wide on the southwestern margin of Spanish Valley. It was excavated across an antislope scarp associated with the SW-dipping antithetic fault that controls the depression (Fig. 1 and 4C). The throw of the master fault of the marginal upper keystone graben is estimated to be 120 m, expressed as a prominent scarp more than 90 m high with thick colluvial debris cones at its foot that overlap the trough fill. The antithetic fault is 350 m long, strikes N142E, and shows a 6 m high uphill-facing scarp (Fig. 4C). The trench was 7 m long and up to 2.5 m deep showing faulted Quaternary deposits (Fig. DR3).

The trench exposed a fault plane with a 84SW dip with no slickensides. Two overlapping, tapering-downward fissure fills 35 and 42 cm wide (units 3 and 5) next to the fault plane record two faulting events in which vertical displacement is accompanied by significant lateral extension probably related to the outward toppling of the footwall toward Spanish Valley (Fig. DR3). Oriented fabrics in the clasts of both fissure fills may be attributed to a syndepositional orientation and/or shearing. The fissures corresponding to units 3 and 5 are overlapped by the younger units 4 and 6, respectively. This is, unit 4 postdates and predates the older surface rupture event, whereas unit 6 postdates the most recent event. The following units are mapped in the trench log: (1) Bedrock: Well-bedded sandstone of the Kayenta Formation. (2) Loess: Pale orange massive silt. (3) Fissure fill: Clast-supported breccia consisting of pebbles up to 5 cm long with oriented fabrics in a pale orange silty matrix. (4) Colluvium: Light red massive silt with embedded pebbles up to 2 cm long and scattered clasts up to 10 cm in size at the top. (5) Fissure fill: Mud-supported breccia made up of pebbles up to 7 cm long and some boulders up to 40 cm with oriented fabrics. (6) Loess: Massive red silt with embedded scattered clasts up to 5 cm long next to the face of the fault scarp.

The structural and stratigraphic relationships observed in the trench can be explained by three discrete faulting events involving the development of two fissure fills and the folding of units 2 and 4. This implies episodic rather than continuous slow displacement over time.
Unfortunately, no charcoal was found in the exposed sediments. The first event created the depression in which unit 2 was deposited. The second one caused the opening of the tension crack filled by unit 3. The exposed thickness of unit 2 indicates a minimum vertical displacement of 49 cm, because unit 2 is absent in the footwall. The MRE formed the western fissure filled by unit 5. The opening of the tension crack caused lateral shortening and folding of units 3 and 4. The thickness of unit 4 indicates a minimum displacement of 25 cm.

REFERENCES CITED


Figure DR1. (A) Remains of a pediment deposit derived from terrace T1 on the northeastern flank Spanish Valley, unconformably overlying deformed parallel-laminated floodplain sediments, probably related to the infill of a dissolution-induced subsidence basin. (B) Pediment deposit capping a hill, consisting of massive subrounded pebble cobble gravel including sandstone, limestone and igneous rocks. (C) Deformed underlying unit made up of parallel-laminated gray marls and brown silts dipping 20SW. Photograph taken at 38º 32’ 04.41N, 109º 28’ 39.35’’W

Figure DR2. (A) Fault-controlled sedimentation of Pack Creek terrace T4. The alluvial fill, restricted to the downthrown block, exceeds 30 m in thickness. (B) Exposure of a graben structure with a minimum late Quaternary throw of 2.2 m in the deposit of Mill Creek terrace T4. Photo taken from 38º 33’ 31.66’’N, 109º 31’ 23.15’’W. (C) Interpretative diagram of B. F1 is the antithetic fault and F2 is the synthetic fault.

Figure DR3. Log of trench 2. A description of the units is included in the text.
1. Clast-supported gravel with clasts up to 30 cm long in a silty orange matrix.
2. Matrix-supported gravel with clasts 1-5 cm long in a silty orange matrix.
3. Red soil with pebbles completely coated by calcite cement.
4. Parallel-laminated red silt.
5. Calcite cemented, matrix-supported gravel with cobbles as much as 80 cm long.
6. Massive orange silt with embedded clasts 3-8 cm long.
7. Laminated red sand. Lamination is partly distorted by pedogenic processes.
8. Massive orange silt with embedded clasts 3-8 cm long.