THE BEAR RIVER LANDSLIDE COMPLEX, PRESTON, IDAHO: GEOLOGIC CONSIDERATIONS AND HISTORICAL PERSPECTIVES

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ABSTRACT

The Bear River Landslide Complex is a series of earth movements in northern Cache Valley, north of Preston, Idaho. The landslides occur in unconsolidated sediments of the Pleistocene Bear River Delta which formed where the river entered Lakes Bonneville and Provo. The Lake Bonneville delta deposits are up to 490 feet (150 m) thick and consist of a lower alluvial coarse sand and gravel unit, a middle delta front fine sand and silt unit, and an upper pro-delta clay up to 50 feet (15 m) thick. The interbedded character of the fine sands, silts, and clays, together with abrupt lateral facies changes, produce numerous confined and perched aquifers.

The complex exhibits widely variable types of failure, movement rates and magnitudes. The majority of movements are properly classified as complex, and are slump-earth flows. Earth falls, slumps, rotational slides, and earth flows are also common. The laterally variable nature of the deltaic sediments and resultant inhomogeneous groundwater flow patterns produce the variability of movements within the complex.

The first order cause of the earth movements is the incision of the unconsolidated deltaic sediments by the Bear River, which has created steep unstable slopes along the margins of the river valley. The second order cause of the landslides is high groundwater levels created by a combination of normal infiltration and artificially-created recharge due to irrigation of farmland on the delta surface. Periods of abnormally high precipitation serve to further increase the saturation level of the sediments, and decrease stability in the area of the landslide complex. The period of high precipitation in 1980-1983 resulted in extensive landslide activity in 1981-1984, which seriously threatens the route of U. S. Highway 91 north of Preston.

INTRODUCTION

The Bear River Landslide Complex is a series of active earth movements located along the Bear River drainage, northwest of Preston, Idaho (Figure 1). Earth failures of variable sizes, types, and rates of movement are occurring in unconsolidated fine sands, silts, and clays of the Pleistocene Bear River delta. Rapid downcutting by Bear River through these heterogeneous deltaic sediments has resulted in slope instability along the incised river and its tributaries, Battle and Deep Creeks. Although the landslide complex apparently has been intermittently active for several thousand years, historical reports indicate a marked increase in activity within the last 60 years.

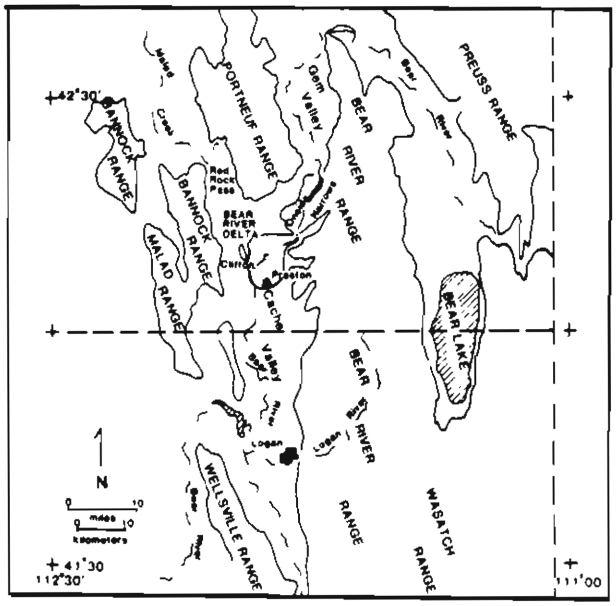


FIGURE 1: Location map for southeastern Idaho and northern Utah, showing Cache Valley and Bear River Delta (stippled) north of Preston.

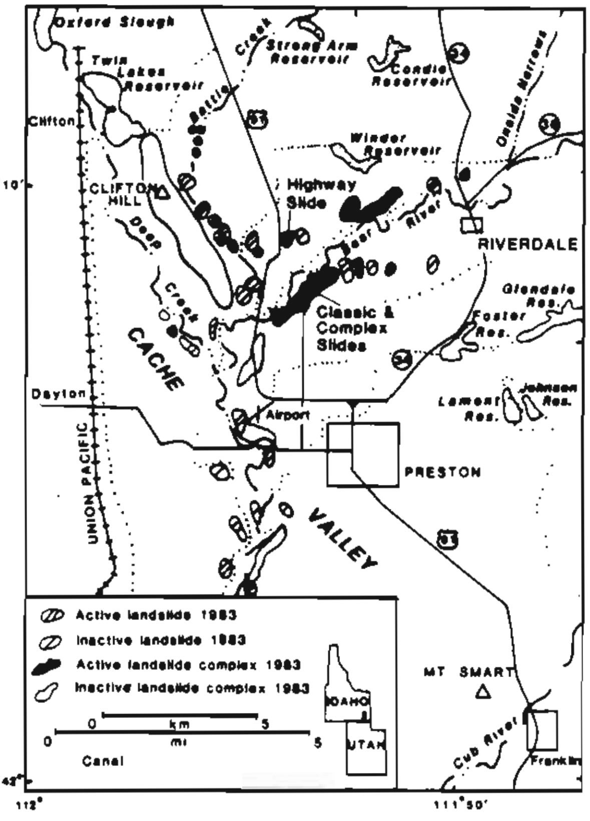


FIGURE 2: Map of northern Cache Valley, Idaho showing landslide activity as of 1983, after Othberg (1984b, Plate 1).

The current investigation was initiated following three years of abnormally high landslide activity from 1981-1984. These recent movements resulted in disruption of irrigation systems, loss of productive farmland, destruction of several secondary roads, and severe undermining of U.S. Highway 91, which may have to be relocated in the near future. This paper will describe geologic, hydrologic, engineering, and historical aspects of the landslide complex.

GEOLOGIC SETTING

The Bear River Landslide Complex is located in northern Cache Valley, along the Bear River and its tributaries, Battle and Deep Creeks (Figure 2). Situated in the northeast corner of the Basin and Range Province, Cache Valley is a complex structural graben produced by Neogene extension. The valley is bounded on the west by the Clarkson and Dayton fault zone, and on the east by the East Cache fault zone, both classified as potentially active (Williams, 1962; Othberg, 1984a and b).

The mountains bordering northern Cache Valley include the Bear River-Portneuf Ranges to the east, and the Bannock-Malad Ranges to the west (Figure 1). These mountains contain thick sections of folded and faulted Precambrian and Paleozoic quartzites and carbonates (Williams, 1958; Oriel and Platt, 1982; Link and others, 1985).

In the foothills surrounding the valley, Paleozoic and Precambrian rocks are unconformably overlain by tuffaceous and conglomeratic fluvial and lacustrine sediments of the Miocene-Pliocene Salt Lake Group (Adamson and others, 1955; Danzl, 1982). The Salt Lake Group is faulted and tilted, and dips locally up to 80 degrees. Faulting may have begun in Miocene time, and continues to the present (Sacks and Platt, 1985). Thick sequences of down-faulted Salt Lake Group strata occur in central Cache Valley beneath a thin veneer of Quaternary deposits (Stanley, 1972; Scheu, 1985). The Salt Lake Group is unconformably overlain by Quaternary lacustrine and fluvial sediments, primarily those deposited in Pleistocene Lakes Bonneville and Provo and their predecessors.

Recent stratigraphic investigations (Currey and others, 1983; 1984; Scott and others, 1983; Currey and Oviatt, 1985; McCoy, 1987) have significantly revised previous interpretations of the Quaternary chronology of the Bonneville Basin. The use of aminostratigraphy and radiocarbon dating have constrained timing of lake level fluctuations and led to more accurate interpretations of the lake's history (Figure 3). Isostatic rebound along the margins of the Bonneville Basin has resulted in irregular displacement of ancient shorelines, and causes variation in citations of shoreline elevations in the literature.

Evidence of lake level fluctuations prior to the Bonneville lake cycle is lacking in surface exposures in northern Cache Valley, though earlier lakes may well have existed. The deposits of the Bonneville lake cycle, particularly Bear River deltaic sediments, host the landslide complex.

The Bonneville lake cycle refers to a period of rising lake level between about 32,000-14,500 years before present (ybp). At the end of the cycle Lake Bonneville reached its highest level of approximately 5090 feet (1552 m) (Currey and others, 1984, McCoy, 1987). This rise was fairly steady, with relatively minor fluctuations (Currey and others, 1983). The addition of the Bear River drainage to the Bonneville Basin (discussed in the following section) was probably instrumental in the rise of the lake to the Bonneville shoreline. According to Currey and others (1984), the lake occupied the Bonneville shoreline from about 16,000 to 14,500 ybp, maintaining its level by intermittent overflow at the Zenda Threshold, approximately 2 miles (3.3 km) north of Red Rock Pass (Figure 1).

The stillstand of Lake Bonneville at the Bonneville shoreline ended abruptly with the catastrophic collapse of the Zenda Threshold and the ensuing Bonneville flood between 14,500 and 13,500 ybp (Malde, 1968; Scott and others, 1983; Currey and others, 1983, Bright and Ore, 1987). Lake level quickly dropped approximately 350 feet (106 m), from 5090 to 4740 feet. Overflow ceased when erosion reached resistant bedrock near Red Rock Pass. The elevation of the bedrock pass controlled the level of the newly established Provo shoreline at approximately 4740 feet (1445 m). Lake level was maintained at the Provo shoreline for about 1000 years by intermittent overflow at the bedrock lip. Figure 4 shows the approximate geography of southeast Idaho at various stages in the lake's history.

By 13,000 ybp, lake level had receded below the Provo shoreline, and dropped rapidly in conjunction with the waning of the late Pinedale glaciation. The lake reached its current level of about 4200 feet (1280 m) approximately 11,000 ybp, and has fluctuated less than 20 feet (6 m) since that time (Currey and others, 1984).

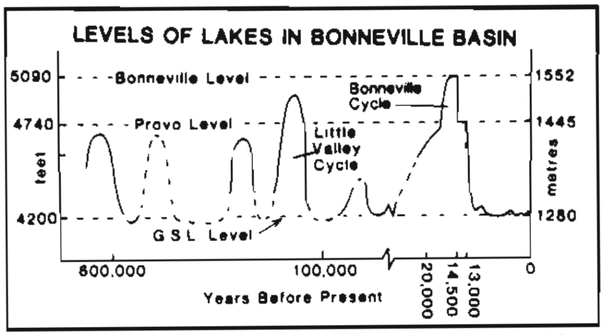


FIGURE 3: Late Quaternary lake levels in the Bonneville Basin, after Currey and others (1984) and McCoy (1987).

Diversion of Bear River

As mentioned previously, the addition of Bear River discharge to the Bonneville Basin may have had a significant effect on lake level rise (Bright, 1963, 1967; Scott and others, 1982). Prior to major volcanism in the Gem Valley lava field, the Bear River probably flowed northward via the ancestral Portneuf River into the Snake River (Figure 4a). Oneida Narrows, the river's current outlet to the south, was at that time a bedrock divide between the Snake River drainage and the Bonneville (Great) Basin (Bright, 1963).

Volcanism associated with the Pleistocene Gem Valley/Blackfoot Lava fields resulted in a damming of the northward draining Bear River, severely limiting northward drainage, and creating a lake in southern Gem Valley as early as 2 mybp (Figure 3b)(McCoy 1987). Lakes existed periodically in Thatcher basin until approximately 30,000 ybp, when ancestral Lake Thatcher reached its highest level of 5450 feet (1660 m) and spilled over the bedrock divide at Oneida Narrows. Relatively rapid downcutting of the divide occurred between 30,000 and 20,000 ybp based on 30,000 +/- 10,000 ybp dates from the Thatcher Basin lake deposits (Bright, 1963, McCoy, 1987). The development of a southern outlet for the Bear River drainage was contemporaneous with and probably instrumental in the final rise of the Bonneville lake cycle (Figure 3)(Scott and others, 1982).

FIGURE 4: Drainage history of southeast Idaho

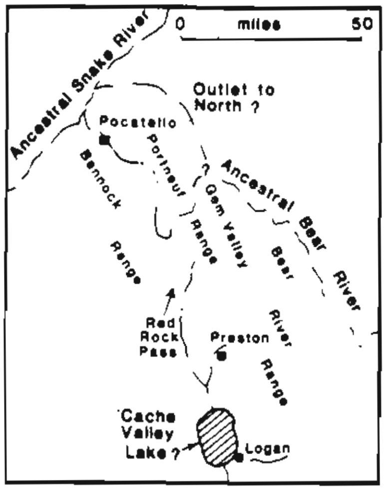
A) BEAR RIVER FLOWS NORTHWARD--In the early Pleistocene (?), Ancestral Bear River probably drained northward through Gem Valley and across the Portneuf Range through what is now the Portneuf River Canyon. Alternatively, it may have drained northward toward the Ancestral Snake River from northern Gem Valley. A lake may have existed in Cache Valley, fed by streams draining adjacent ranges.

B) LAKE THATCHER--Pleistocene basaltic volcanism in Gem Valley formed a lava field which blocked the northward surface drainage of Bear River. Lake Thatcher formed in southern Gem Valley as northward drainage was blocked (Bright, 1963). Bear River may have drained southward into Lake Thatcher or may have lost much of its water to the subsurface through porous basalt flows. About 600,000 years ago two basalt flows moved 50 miles down the Portneuf River Canyon to the site of Pocatello (Scott and others, 1982).

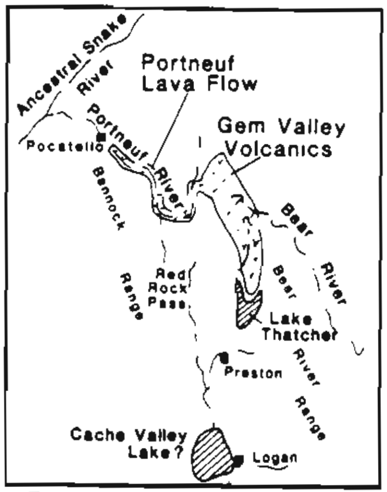
C) LAKE BONNEVILLE--the southward overflow of Lake Thatcher and cutting of Oneida Narrows was instrumental in causing the rise of Lake Bonneville. This diagram shows the maximum extent of the lake northward into Gem Valley and the extent of the Bear River Delta (stippled).

D) LAKE BONNEVILLE FLOOD AND LAKE PROVO--The Bonneville Flood emptied northward after failure of an alluvial dam at the Zenda Threshold, just north of Red Rock Pass. Lake Provo drained northward over the bedrock lip at Red Rock Pass until it began to recede rapidly about 13,000 years ago.

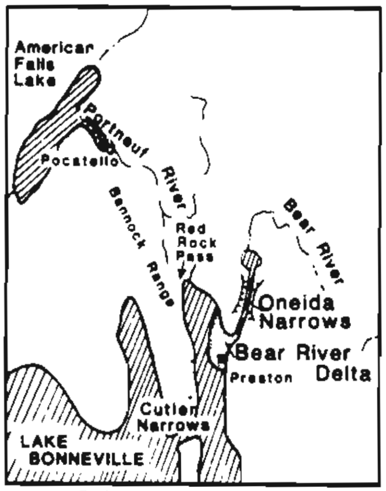
E) MODERN DRAINAGE PATTERNS--Stippled area north of Preston is the Bear River Delta.



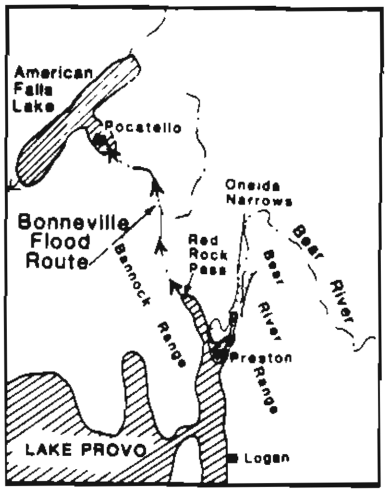
A-LATE PLIOCENE



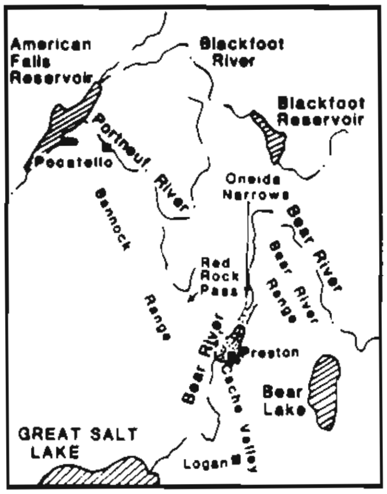
B- 600,000 YEARS AGO



C- ABOUT 15,000 YEARS AGO



D-14,500 to 13,500 YEARS AGO



E-RECENT

Sedimentation patterns in northern Cache Valley were profoundly influenced by the diversion of the Bear River. Immediately following the spillover of Lake Thatcher and the initiation of downcutting at Oneida Narrows, the Bear River deposited coarse alluvial gravels on the pre-Bonneville surface in northern Cache Valley. Upon completion of downcutting at Oneida Narrows, the supply of coarse clastic material decreased markedly, as evidenced by a distinct fining upward sequence (gravels to coarse sand) at the base of the Bear River delta complex. Deposition of increasingly finer grained sediments occured as the depositional environment evolved from alluvial fan to fan-delta to delta concomitant with the rise of the lake.

Bear River Delta

The delta complex aggraded rapidly, reaching a maximum thickness of 510 feet (~155 m) north of Preston, and extending 9 miles (15 km) southwest of Oneida Narrows. The distal terminus of the deltaic sediments is just south of Clifton Hill (Little Mountain).

When Lake Bonneville was at its highest level, both Oneida Narrows and Thatcher Basin were inundated, and only extremely fine grained material reached Cache Valley (Figure 3c). Deposition was limited to pro-delta clays and very fine silts, as evidenced by a 50 foot (15 m) thick clay section at the top of the deltaic sequence.

The fine grained nature of the Bear River delta contrasts markedly with the much coarser grained character of other deltas in the Bonneville Basin, most notably the Logan Canyon and Weber River deltas, and leads to restricted permeability and a concentration of groundwater in perched aquifers (Feth and others, 1966). Although the other deltas also contain thick lacustrine clay sequences at the top, they contain horizons of coarse sand and gravel which increase groundwater flow, reduce the number of confined aquifers in the sediments and increase slope stability. The Bear River Delta is much more prone to earth failures than the other deltas.

The grain size contrast between deltas is due to two factors:

1) location - the Bear River delta is not located immediately adjacent to steep mountain canyons, and therefore does not have the coarse clastic load characteristic of other deltas; in addition, southern Gem Valley acted as a "catchment" basin for the coarser clastic material carried by the Bear River;

2) source area - the sediment load of the Bear River is primarily fine sand and silt derived from Mesozoic siltstones and Neogene basalts of the Idaho-Wyoming thrust belt to the east so the initial coarse clastic load is generally lower than other drainages.

The dramatic drop in lake level (5090-4740 ft) following the Bonneville Flood exposed the upper portion of the delta complex to erosion and reworking by fluvial processes. The medial and lower portions of the delta remained below water level, and were less profoundly affected by base level readjustment. The resulting post-Bonneville Flood unconformity is widespread, represented below the Provo Shoreline (4740 ft/1445 m) by an abrupt contact between lacustrine and deltaic distal fine silts and clays and overlying coarse sands deposited in the delta of Lake Provo. The town of Preston is located on the flat surface of the Provo delta. Above 4740 feet (1445 m) the post-Bonneville Flood unconformity is overlain by sands and gravels deposited as streams became graded to the Provo Shoreline.

Sediments deposited during the stillstand at the Provo level are overlain by the post-Provo unconformity, which separates Provo lake sediments from fluvial sands and gravels deposited as the lake lowered to the Great Salt Lake level. Rapid decreases in lake level, both before and after the Provo stillstand, initiated downcutting of the Bear River through its own deltaic sediments, as the river attempted to reequilibrate to the lowering base level. The river occupied numerous terrace levels as base level dropped; remnants of these terraces are represented by flat aprons of fluvial sand and gravel along the sides of the river valley. These terraces are more stable than the deltaic sediments upon which they rest, apparently because they are more easily drained, and are therefore somewhat more resistant to earth failures. North of Preston, the modern Bear River is now an entrenched meandering stream which occupies a one mile wide floodplain 350 to 490 feet (106-150 m) below the delta surface.

Stratigraphy

Numerous partial stratigraphic sections of the delta are exposed in various drainages and within the head scarps of landslides. Sparse drill hole information is also available. Generally, the Bonneville delta complex contains coarse sands and gravels at the base, a thick middle portion of fine sands, silts, and thin clays, and an upper thick clay. It is overlain unconformably by sands and clays of the Provo delta and by post-Provo fluvial sands. Variations in observed thickness of the upper clay are partially due to post-Bonneville erosion.

The Bear River delta strata are dominated by meter to decimeter thick fining and thinning upward units of fine sand, silt, and clay. Although the entire deltaic sequence fines upward, it contains numerous smaller scale (centimeter to meter) variations and numerous disconformities (Figure 6).

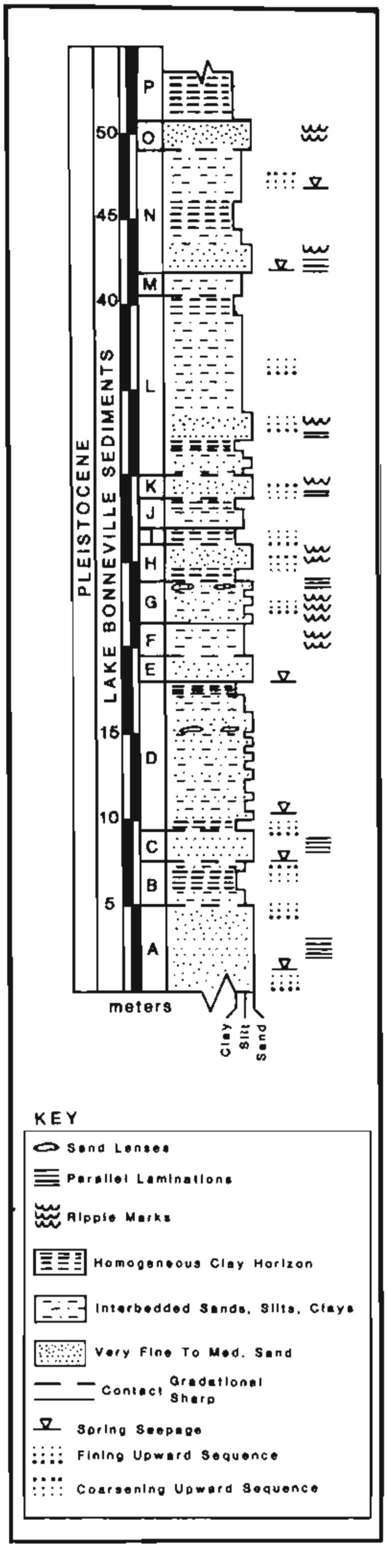


FIGURE 5: Partial stratigraphic section of Bonneville Alloformation northwest of Riverdale. Location of section is shown in Figure 8. Note numerous perched water tables and clay aquitards.

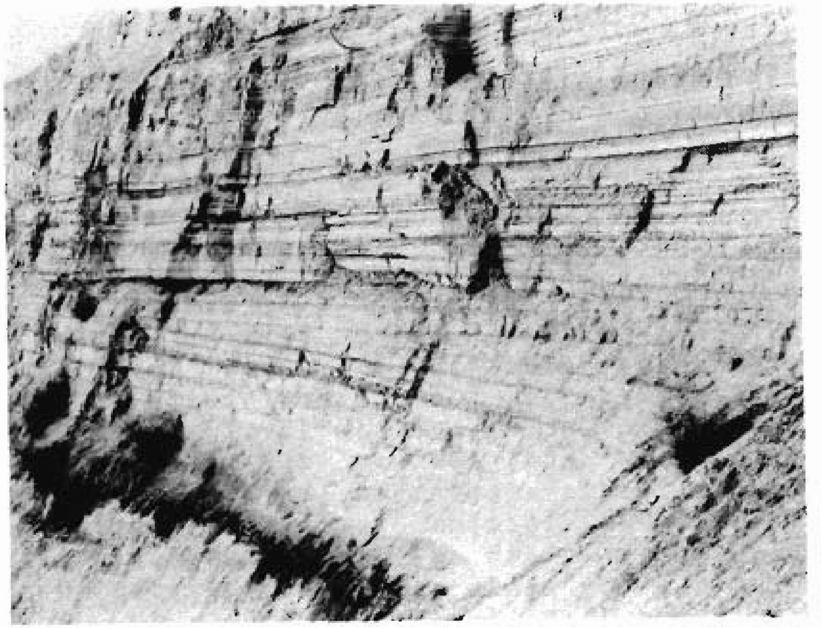


FIGURE 6: Units D to G of measured section in Bonneville Alloformation northwest of Riverdale (approximate thickness shown is 7 metres). Dark saturated zone at bottom of picture is at contact between clays of unit D and sands of unit E. Unit E grades into sands and silts of unit F, which is overlain by thin silt-clay couplets of unit G along the low angle unconformity evident near middle of photo.

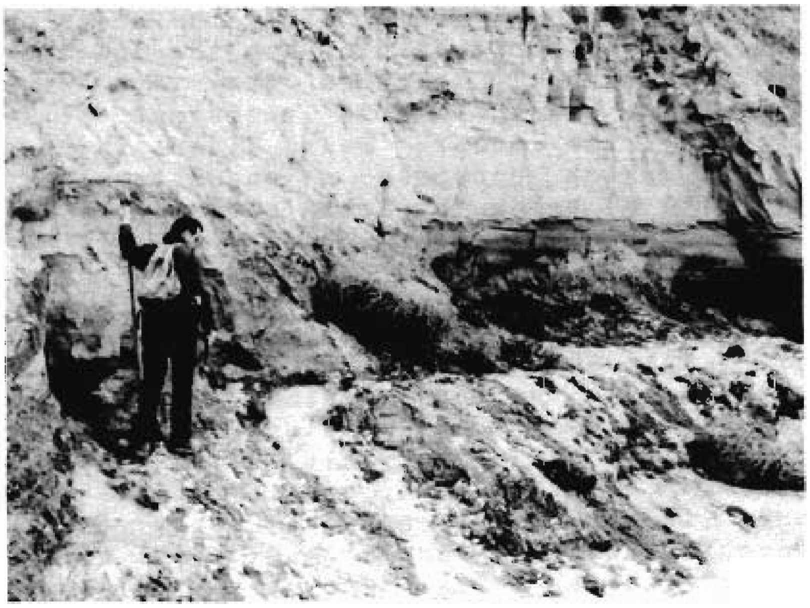


FIGURE 7: Saturated zone (note frozen springs) at base of sand bed near top of Bonneville Alloformation in southeast headwall of Classic Slide, south of Bear River. This delta-front sand lies immediately below thick (15 m) prodelta clay at the top of the Bonneville deposits.

In the area between Riverdale and Preston the two units exposed are the middle (delta front) silts and the upper (pro-delta) clay of the Bonneville delta. A generalized stratigraphic section measured north of Riverdale is shown in Figure 4. Unit P at the top represents the upper pro-delta clay, while the main part of the section demonstrates the variability of the delta front deposits.

Within the middle unit, rapid facies changes prohibit specific bed-by-bed correlation. Individual units thin and pinch out laterally, commonly in very short distances. Bed thickness varies within the section, with most horizons averaging 5-20 cm in thickness. The majority of contacts are gradational, with coarsening then fining upward beds of silt and fine sand separated by homogeneous laminated clay horizons of variable thickness (<1cm to >1m). All units are well sorted. The coarsest grain size observed was .25-.5mm (medium sand), with the majority of sediment in the coarse silt to clay range (<.062mm). The most striking characteristic of the section is the overall banded appearance derived from the interbedding of laminated clays with fine sand to silt horizons. The major vertical variation is in the percent of clay, which is quite low in the basal portions of the section (10-15%), increasing to near 80% in the upper portions.

Sedimentary structures in the sands and silts of the middle unit are common; they include (in order of decreasing abundance): graded bedding, climbing ripple marks, planar laminations, cross bedding, and convolute bedding. These structures suggest tractive and density current flows on the prograding delta front. Interbedded clays were deposited from suspension outside of the area of active sedimentation.

The upper thick clay unit contains only planar laminations and was deposited from suspension in a deep water pro-delta environment during time of highest lake level. Rippled silt and fine sand layers within this unit may have been deposited by distal density currents.

Longitudinally the deltaic sediments decrease in grain size and in total thickness toward the distal end of the delta. At the outer margins of the delta, deltaic clays and silts interfinger with coarser grained lacustrine and fluvial sediments. The coarse sediment at the delta fringe significantly affects groundwater migration by allowing better drainage, reducing the number of perched aquifers, and therefore decreasing susceptibility to earth movements.

The most obvious characteristic of the clay-rich sediments is their overall red color, which imparts a distinctive red hue to the soils developed on the delta surface. Color is one criterion that has been used to differentiate deposits of the delta from coeval lacustrine deposits with different provenance. These clays are probably derived from the Mezozoic red beds and Neogene basalts east and north of Oneida Narrows (Bright, 1963).

HYDROLOGIC CHARACTERISTICS

On a large scale, the hydrologic properties of the delta in the area of the landslide complex are controlled by the interbedded character of the sediments. The sands, silts, and clays of the middle unit have variable hydraulic conductivities, the upper thick clay acts as an aquiclude, and the overlying post-Bonneville sands have high conductivities. Within the middle unit, numerous homogeneous clay horizons act as aquitards, while the interbedded well sorted fine sands are highly permeable. Rapid facies changes produce lateral heterogeneities in the aquifer system. On a smaller scale, the laterally variable sediments make hydrologic generalizations difficult.

Bjorkland and McGreevy (1971, Plate 4) chart the potentiometric surface in the area of the delta, but discussion is limited to the upper unconfined aquifer, and little is known about water levels at depth. Field observations suggest variability in groundwater movement direction, levels of potentiomentric surfaces, water pressure characteristics, and areas of discharge. Quantification of these variables would be difficult without an extensive drilling program.

Laterally discontinous sand beds and abundant aquitards result in numerous perched aquifers throughout the section (Figure 7, 9b). The thickness of the aquifers varies from 1.5 m sand beds to 3-5 cm sand lenses. The amount of water and levels of saturation within the aquifers is variable, and is not dependent on vertical position. Saturation levels within the aquifers vary from damp zones at the base of medium-bedded sand horizons to thin pressurized sand laminae with artesian characteristics.

The aquifers always directly overlie an impermeable clay horizon. The clay/porous zone interface forms a plane of weakness prone to failure, and commonly acts as a slippage plane during earth movements. Multiple confined aquifers within vertical sequences produce several zones of weakness susceptible to slip plane formation.

MASS MOVEMENT TYPES WITHIN THE LANDSLIDE COMPLEX

Earth movements of the Bear River Landslide Complex have been classified according to kind of movement, rate of movement, type of material, geometry of the slide area, and moisture content. Nomenclature follows that of Varnes (1978).

The landslide complex contains several different types of earth failures, including, but not limited to, earth falls, lateral spreads, rotational slides, translational slides, earth flows (rapid and slow), and complex movements. The majority of movements are properly classified as complex, exhibiting several types, rates and periods of movement. In addition, modes of failure of a given mass movement evolve through time as a result of modifications of both geologic and hydrologic factors. Each movement is the result of a localized combination of factors including the kind of material involved, bed thickness, moisture content, slope angle, amount of water present, location of seepage zones, and previous activity.

The simplest forms of earth movement in the complex are earth falls and dry sand flows (Figure 9d), which result mainly from an oversteepening of stream banks by undercutting. These movements occur in fine and medium grained sands, and are located primarily beyond the outer edge of the Bear River delta, along Deep Creek, west of Clifton Hill (Figure 2). In this area, little clay is present in the upper portion of the section, and drainage is good. Movement is stabilized as the slope angle is reduced, and the landslide remains inactive until stream erosion removes the buttressing effect of the debris at the toe.

A large area of active failures occurs south of Bear River, between Highway 91 and the Dugway Road (Figure 8, 9a). The failures display classic landslide features, including an "hourglass" configuration, steep head scarps within symmetrical cirque-like head regions, abundant transverse and crown cracks, bulbous toe regions, numerous sag ponds, and well defined lateral margins. The toe regions of the slides tend to coalesce on the river bottom, but sharp cusps in the flank regions delineate individual slides. The dominant type of movement during the 1981-1984 period in this area is classified as slump-earth flow.

Two slides within this area have been named for discussion purposes: the Classic Slide (Figures 8, 9a; 11a of Link and others, this volume), which has a textbook hourglass configuration, and the Complex Slide (Figure 11b of Link and others, this volume), which exhibits several different types and rates of movement.

BEAR RIVER LANDSLIDE COMPLEX

LANDSLIDE LOCATION MAP

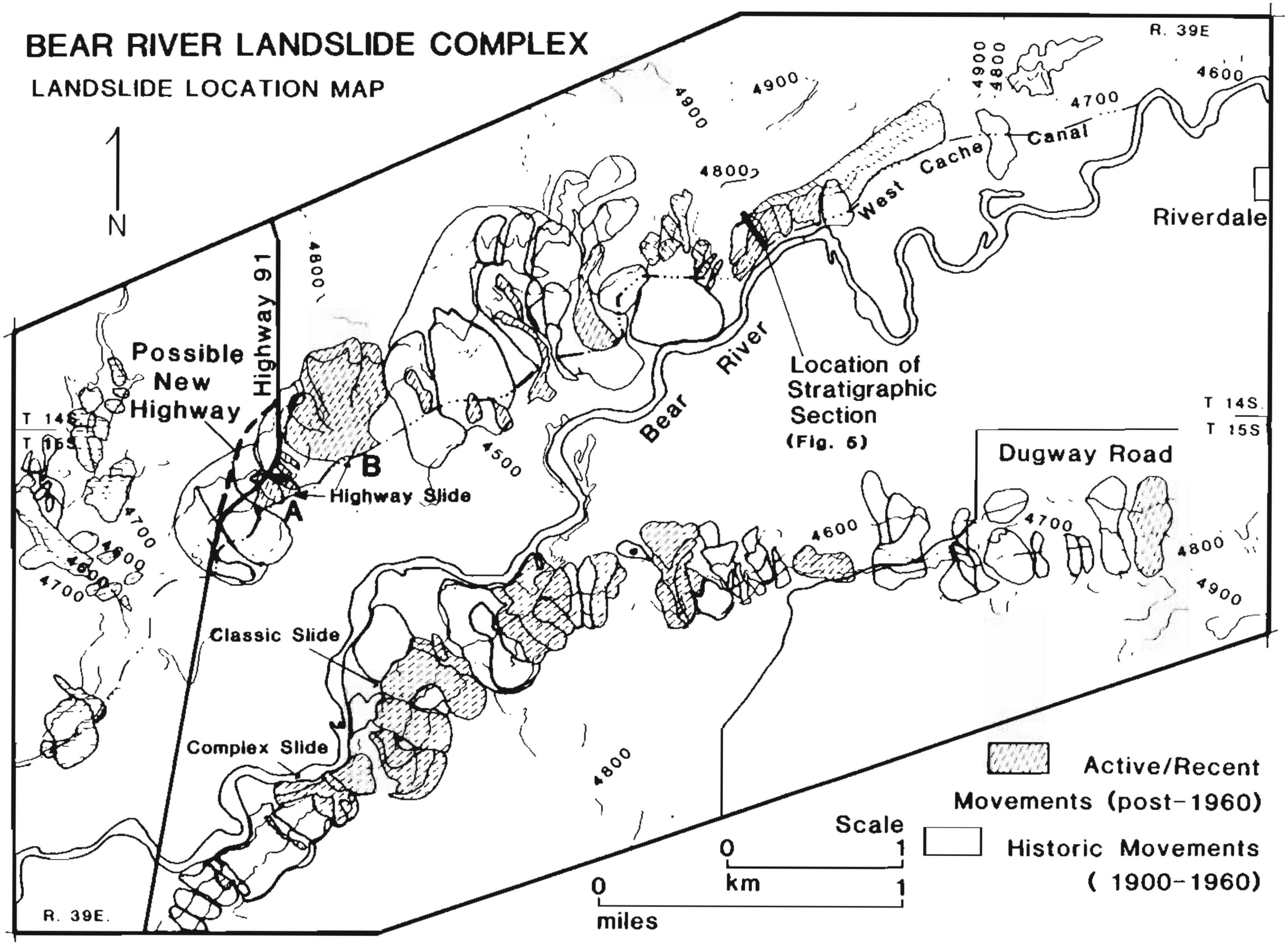


FIGURE 8

Contour Interval 100 feet
Base from Riverdale & Banida Quadrangles

Slide movement south of the river is characterized by failure of a lower saturated horizon, creating a rapid earth flow of semi-liquefied sediment that thins and spreads laterally up to 500 m upon reaching the valley bottom. Coherent upper units subside with back rotation of up to 45-50 degrees (Figure 8d, Link and others, this volume). It is uncertain whether subjacent earth flow initiates failure of the upper units, or if initial slump within the upper units produces abnormal pore pressure in the lower porous units, inducing failure.

The slide areas contain numerous springs at different levels, with a concentration in the central portions of the slide masses. Numerous ponded areas preserve a high level of saturation within the displaced material, significantly decreasing stability.

Activity of individual earth movements between Highway 91 and the Dugway road alternates laterally, with the more recent slides commonly flanking older movements. Rates of movement differ and can be classified as very rapid to slow (Varnes, 1978).

Farther east, in the area of the Dugway Road (Figure 8), movement is characterized by slow creep of surficial layers, with downslope movement occurring at a relatively constant rate. Interviews with local residents suggest that the area has been subject to minor moist rotational earth slumps over the past decade, with slope modifications by county road crews possibly causing recent movements. Although large-scale earth movements have not occurred in the last few years, aerial photograph analysis and field observations suggest that catastrophic movements have occurred during historic times. Modification of groundwater flow patterns by landslide activity may have resulted in stabilization of slopes in the area of the Dugway Road. This hypothesis is supported by the fairly uniform distribution of well-drained springs throughout the slope region; abundant well-drained springs serve to prevent destabilizing water pressure build-up (Sowers and Royster, 1978).

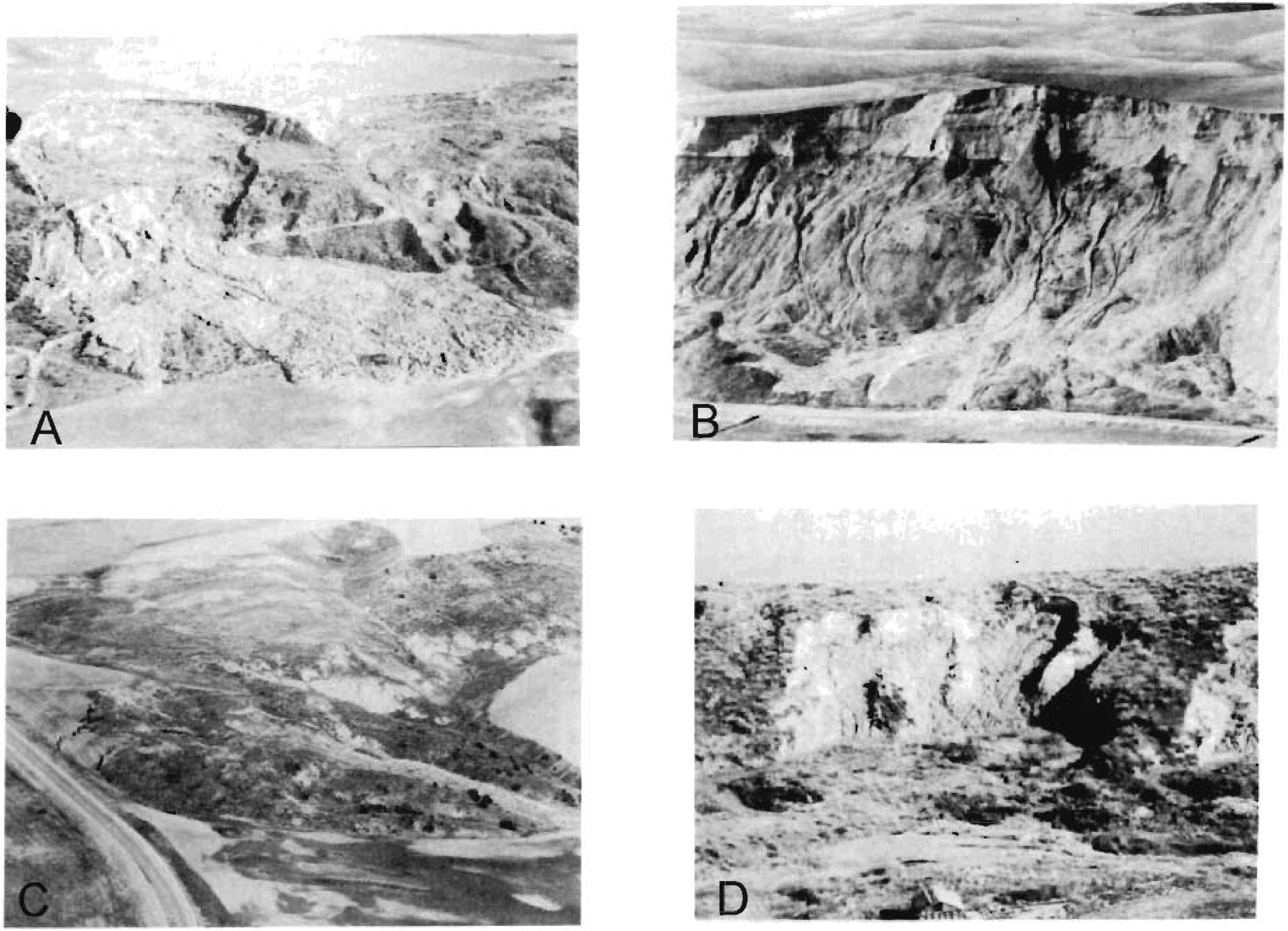
North of the Bear River, in the prominent bluffs north of Riverdale (**Figure 9b**), movement has apparently been facilitated by progressive slumping and earth fall of overlying coherent units and slow earth flows within lower saturated sand horizons. The progressive slumping of the clay-rich upper units creates a gradual recession of the cliffs, which allows the upper units to develop a vertical cliff face. Saturated zones are are most common in the lower third of the section, where medium-bedded fine sand horizons distribute moisture and prevent significant pressure build-up. The movements in this area are much slower than in areas south of the river, with a lower overall moisture content apparently precluding catastrophic collapse.

Following establishment of steep cliff faces, the dominant form of movement is earth fall. The cliff region is the only area within the slide complex in which translational movement is believed to occur, although the disaggregated nature of the toe region makes documentation difficult.

The area between the prominent bluffs north of Riverdale and Highway 91 on the north side of the river (Figure 8) contains large earth movements with fairly low slope angles (7-15 degrees). These earth movements apparently predate the most recent period of activity. Recent movement in this area involves minor slow earth flows within older slide masses.

The earth movements directly east of Highway 91 on the north side of the river (Highway Slides A and B, Figure 8) are the most problematic within the complex. The northernmost slide (Highway Slide B) east of the highway is the largest slide in the complex, with an extremely wide head region (~1200 ft/350 m). Aerial photograph analysis suggests this is a fairly stable area, with a central drainage gulley and a low (5-7 degree) slope angle. However, this area exhibited the most drastic headward movement within the complex during the recent period of activity (on the order of 1000 ft/305 m between 1982-1986). There is a major flow component to the movement, with a slow earth flow apparently following the previously established central drainage. Flow movement creates rotational block slumping of upper coherent units, which produces headward erosion. This slide is of major concern to the Idaho Department of Transportation, as any major additional movement will undermine Highway 91.

FIGURE 9: Variety of Mass Movement Types in Bear River Landslide Complex
A) Classic Slide--a slump-earthflow. Note abandoned road in center of photo.
B) Winder Bluffs northwest of Riverdale. Note earthflows at base of section. Upper cliff erodes by earthfall. Prominent dark band near top of cliff is saturated zone at base of sand bed (probably bed E of measured section, Figure 5). Vertical upper part of cliff is mostly red prodelta clay. West Cache Canal runs at base of cliff. A wagon path climbed this hill as recently as 1920. Installation of reservoirs on the delta surface a few miles away caused an increase in landslide activity and destroyed the road.
C) Highway Slide B north of Bear River. U.S. 91 is in lower left corner. Note headwall scarp in wheatfield a few metres from the road. This is the area of field trip stop 2 (Link and others, roadlog, this volume).
D) Slump due to undercutting of cliff east of Battle Creek, west of Bear River.


A
B
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Highway Slide A (Figure 8) is particularly troublesome to the Idaho Department of Transportation due to progressive failure which has destabilzed the roadbed. Highway slide A is actually a relatively small earth movement which is nested inside a much larger slump-earth flow failure (Figures 9 and 10, Link and others, this volume). The area of the slide has undergone multiple phases of movement, which have progressively moved down slope and become smaller.

The location of Highway Slide A within an older movement suggests that further headward erosion will be somewhat restricted, as movement is probably controlled by groundwater conditions within the previously displaced material, instead of being controlled by initial stratigraphic conditions. Headward erosion will be constrained until progressive movements lessen the buttressing effect of previous displacements, allowing shear stress to exceed shear resistance in the undisturbed sediments above the slide.

Both a highway department drilling program in the area of the Highway Slides and field investigations have failed to identify any common plane of slippage or horizon of failure within the landslide complex. Planes of weakness occur at clay/porous zone interfaces, but the location of the plane of failure varies, depending on the amount of overlying material, moisture content of the entire failure area, and the amount of previous movement (i.e. inherent stability of the entire area). Slope indicator measurements suggest the failure plane within Highway Slide A is at 20-25 feet (~7m) below present highway elevation, whereas field observations suggest the failure plane within the Classic Slide on the south side of the river to be much deeper (60 ft/18 m).

Reactivation within old movements occurs along fresh slippage planes rather than along reactivated former slip planes. This may be the result of the sealing off of seepage zones during initial slide movement, and relocation of paths of groundwater migration and pressure buildup.

ENGINEERING ASPECTS

Road reclamation is regularly required in the Preston-Riverdale area after periods of high landslide activity. U.S. Highway 91, State Highways 36 and 34, the Riverdale Dugway road, and canal access roads are particularly vulnerable. Damage caused by landslide movement has required patching of the road surface, ditchline and culvert maintenance, grading of slide debris, road relocation away from slide areas, or complete abandonment.

The Idaho Department of Transportation became involved with the landslide complex in the spring of 1983 when a small mudflow (Highway Slide A) undermined U.S. Highway 91 north of the Bear River (Figures 9, 10, Link and others, this volume). An investigation was intitiated when it became apparent that remedial maintenance was not going to insure a stable road surface. Increasingly severe slide encroachment coupled with the headward expansion of Highway Slide B 800 feet (244 m) to the north necessitated a temporary shift of the roadway into the hillside and the construction of a crude French drain in the west ditch. This temporary mitigation measure has stabilized the existing road surface from 1984-1987 while relocation plans were developed.

A number of economically feasible relocation alignments were considered within a banana-shaped corridor connected with the existing roadway at the top and bottom of the hill, and extending 1100 feet (335 m) west of the existing roadway (Figure 8). An extensive drilling program, including standard penetration tests and core sampling, was inititiated along the existing roadway and the proposed relocation alignments.

Test holes were spaced in order to establish the basic stratigraphic profile within the corridor, to confirm the presence of ancient landside elements identified through aerial photograph analysis, to provide information on engineering properties, and to identify any discernable slip planes or specific parameters critical for failure. Test holes were shallow, extending no more than 40 feet (12m) below the proposed ditchlines.

Abrupt lateral and vertical gradations within the deltaic sediments make stratigraphic correlations between drill holes difficult at feasible test hole spacings. The combination of shallow drill holes and restricted areal distribution prevented the drilling program from defining completely the lateral and vertical sediment variation. An expanded (and expensive) drilling program would more completely characterize these variations, but the findings might not significantly aid in design of the new roadway.

The drilling program established the existance of three sediment units with distinctly different engineering properties. The upper unit consists of Provo(?) and post-Provo sands and gravels up to 41 feet (12.5 m) thick. The underlying Bonneville pro-delta clay is divisible into units based on color and engineering characteristics caused by differences in moisture content and oxidation states.

The upper part of the unit consists of highly fractured blocky red clay. The unit contains free water in vertical and horizontal fractures, indicating the unit has a higher permeability than index properties would suggest. Below the red unit is gray clay with a high moisture content. Quantification of vertical variations in the gray clay is difficult due to sample recovery problems created by the high moisture content and viscid consistancy.

The two clay units have similar liquid limits, plastic limits, residual shear strengths and grain size. Field observations reveal red coloration along fractures in the gray clays and vertical and lateral color gradations from red to gray clays.

Differences in engineering properties between the clays primarily involve differences in in situ moisture content, permeability, angle of internal friction, degree of overconsolidation (due to desiccation), and undrained shear strengths. The red clay has a lower moisture content, and higher permeability, angle of internal friction, degree of overconsolidation, and undrained shear strength. The gray clay has just the opposite characteristics. These differences have important ramifications for engineering plans and construction techniques. The very low undrained shear strength and lower permeability of the gray clay make it desirable to have road alignments and designs which avoid its exposure and use.

The differences in peak shear strengths between the red and grey clays are quite significant (up to 20 degrees), while the values for residual shear strength are nearly identical. This suggests that, while the red clay is much stronger in an undisturbed state, once it has been disturbed by mass movement its higher permeability makes it more susceptible to ground water saturation and earth movement. Thus it may be as great an engineering hazard as the gray clay. This observation illustrates the desirability of road realignments minimizing contact with old landslide elements, particularly if groundwater flow is high.

Test holes were also utilized to analyze old landslide elements in the subsurface. Drill holes in the vicinity of Highway Slide A revealed rotated strata outside of the active failure zone, confirming that the slide is actually a smaller movement nested within a larger, older failure. Old landslides which lack surface expression were identified in the subsurface by marked differences in elevation of the upper surface of the main clay horizon, and by rotated strata and slickenslides within the clay units. Avoidance of old slides was a primary factor in the choice of relocation alignments.

Upon completion of the drilling program, field observations and test hole data were evaluated and compared to previously considered road realignments, and a preferred alignment was selected (Figure 8). The most westerly alignment was selected due to: 1) distance from active slides; 2) least involvement with ancient landslide elements (roadway itself would be completely outside ancient landslide mass); 3) most favorable groundwater conditions of all alignments evaluated; 4) least amount of cut required in the gray clay; 5) alignments outside the initial corridor are not economically feasible.

HISTORY AND CAUSES OF RECENT MOVEMENTS

Research on the history of the landslide complex was conducted to identify cyclicity and frequency of movement, determine economic impact, and identify cultural influences on landslide activity. Aerial photographs, newspaper articles, and interviews with local residents provided evidence of landslide activity over the past century. Information on specific events and periods of movement is derived largely from the recollections of local residents, which inevitably results in a bias towards more spectacular events. Figures 10 and 11 show peaks of landslide activity.

Movement within the complex is sporadic, with long periods (10-20 years) of relative quiescence punctuated by brief periods (2-3 years) of intense activity. Small scale movements, such as minor earth falls and small volume slumps occur at a relatively continuous rate, whereas large, catastrophic movements occur infrequently, commonly separated by 10-20 year periods. Notable periods of activity this century include: 1942 (large slide south of Riverdale); 1947-1949 (required relocation of Mink Creek Canal); 1974 (diversion of Bear River from north side, west of Riverdale); 1981-1984 (large scale movements on both sides of Bear River).

Effect of Precipitation

Major mass movements correlate strongly with abnormally high precipitation years (Figure 10). Northern Cache Valley has average annual precipitation of approximately 14-16 inches (37-40 cm) per year; highest monthly totals are in the spring, from April to June. Above average rainfall, combined with spring run-off from the mountain snowpack, results in high groundwater levels in the spring. Comparison of precipitation amounts and high earth movement activity suggests that an increase of ~30% in precipitation over a two year period is enough to cause significant activity. Bear River annual discharge records also suggest a correlation between abnormal hydrologic conditions and landslide activity (Figure 11).

Periods of abnormally high precipitation (including rainfall and mountain snow accumulation) are commonly followed within about a year by abnormally high movement activity. The most recent period of significant activity (1981-84) serves as a case in point. Following a seven year period of abnormally low precipitation, precipitation in 1980 was about three times higher than the 1979 total (26.8" vs. 9.5") (Figure 10). Above average precipitation continued through 1983 before returning to normal. This period of high precipitation was immediately followed by the most intense period of landslide activity on record (1981-84). Similar cause and effect relationships may be documented at other times thoughout the century (e.g. early 1940's, late 1940's, mid 1970's)(Figures 10,11).

Cultural Influences

While it is apparent that abnormal precipitation is a major factor in increased landslide activity, historical reports suggest that this has not always been the case. The establishment of an extensive irrigation system in northern Cache Valley has increased the volume of groundwater present in the deltaic sediments, and thereby decreased their stability.

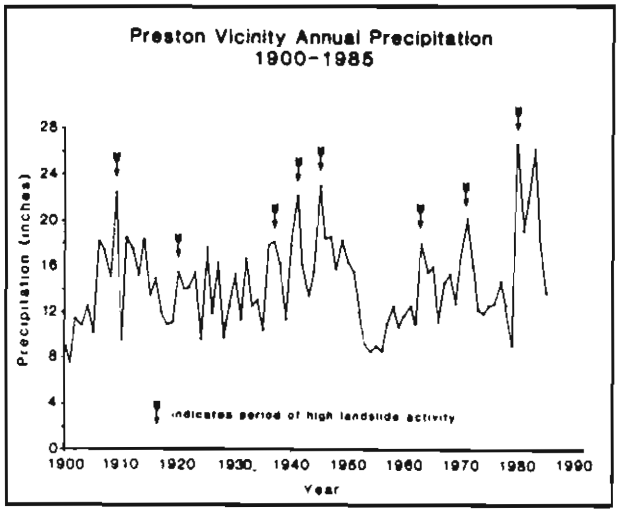

FIGURE 10: Yearly precipitation, Preston area, compiled from various sources. Note correlation between peak precipitation years and high landslide activity.

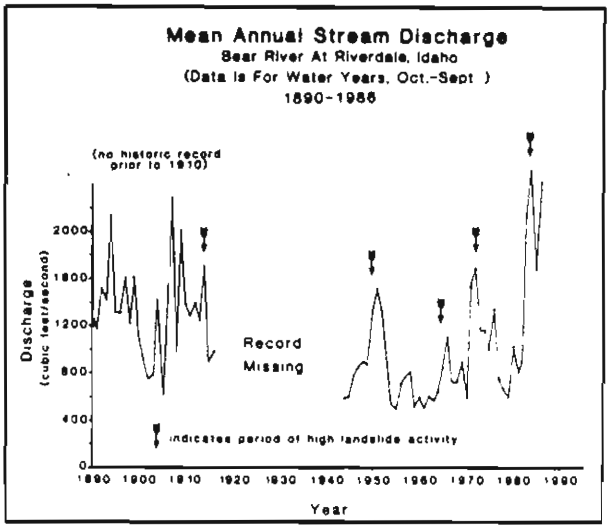

FIGURE 11: Average yearly stream discharge (cfs) of Bear River measured north of Riverdale. Note correlation between landslide activity and high discharge. Source: U.S.G.S.-Water Resources Division, Salt Lake City, Utah.

Between 1880 and 1910, an extensive canal system was installed along the margins of the Bear River flood plain. Canals divert water from the river and channel it along the margins of the river valley. Seepage from the canals commonly creates springs within the unconsolidated sediments, which destablize the bases of slopes and cause earth movements in the slopes above due to loss of lateral support.

Continual reclamation work is required on the canals, especially during the spring when high groundwater levels increase instability. Instability and repeated earth movements along the initial Mink Creek Canal, which ran along the south side of the river between Riverdale and Highway 91, eventually required its abandonment in the early 1950's, as the cost of maintenence exceeded relocation costs. The use of fiberglass culverts and special liners has reduced the seepage problem over the last two decades.

In the late 1920's and early 1930's, the irrigation system was expanded when a series of reservoirs and distributary canals was installed in the farmland on the delta surface above the river valley (Figure 2). While the effects of seepage from the canals along the river is relatively localized, seepage from the reservoirs and the upper canals apparently has wide ranging consequences. Soon after installation of the reservoirs, residents began noticing seepage zones along the valley walls, at much higher elevations than any previous seeps or in places where there had been no springs previously. Culinary springs along the Dugway Road, which had been stable for 15-20 years, nearly doubled in volume within three years of the installation of the Glendale Reservoir in the early 1930's. Prior to irrigation, residents between the river and the city center had to drill up to 40 feet (12 m) to find potable water; groundwater in these areas is now within 6 feet (2 m) of the surface (Kay Anderson, personal communication).

New drainage paths rapidly developed as springs became established and slope instability increased dramatically. Earth movements along both sides of the river increased in size, frequency and intensity. Areas which had been stable for decades began to destabilize. The configuration of the valley walls on the south side of the river changed markedly, from vegetation-covered slopes to a series of fresh, coalesing landslides.

Changes were most noticable along the bluffs north of Riverdale (Figure 8 and 9b). Although saturated zones had been noticed prior to reservoir installation, earth movements had been infrequent, and the area consisted of vegetated slopes which supported a farm service road. After installation of the Winder Reservoir, saturated zones within the bluffs increased in number and in discharge rates. Earth movements became common each spring in lower parts of the slope, and subsequent earth falls created the nearly vertical cliffs present today.

The location of the reservoirs and small irrigation holding ponds on top of the delta and along its margins apparently allows vertical and lateral water migration. This artificially-created recharge, coupled with high groundwater levels during wet years, increases landslide susceptibility.

Earth movements within the landslide complex have had an economic impact on the surrounding communities. The most significant impact has been on the canal company shareholders. High maintenence costs, particularly during the most recent spate of activity, has at least doubled the cost of irrigation over the last five years (e.g. $6/acre to $14/acre for shareholders of the Preston-Riverdale-Mink Creek canal). Landowners within the landslide complex have suffered a loss of acreage resulting from headward erosion in scarp areas, bottomland covered by landslide toe deposits, and the removal of acreage within the slides from cultivation. For example, north of Riverdale, about 20-30 acres were lost between 1965-1985. Economic loss is especially high when a major movement disrupts the Bear River, diverting it over productive farmland and stripping off the topsoil. This has happened at least three times since the mid-1970's (1972,1983,1984).

DISCUSSION

Earth movements within the Bear River Landslide Complex result from a complex interaction of geomorphic, stratigraphic, hydrologic and cultural influences. Although no single factor is solely responsible for earth movements, it is possible to determine a hierarchy of causes.

The first order cause of the landslide complex is the incision of the interbedded fine-grained delta sediments by the Bear River during the past 13,000 years. The lowering of lake level from the Bonneville level (5090 ft/1552 m) to its present level (1280 m/4200 ft) has caused entrenchment of the Bear River in the unconsolidated sediments. The river, now 350-480 feet (106-150 m) below the Bonneville and Provo delta surfaces, is bordered by steep, locally unstable slopes.

Rapid downcutting by the Bear River prevented concurrent development of sufficient secondary drainage systems to drain the delta surfaces, thereby increasing the importance of groundwater flow.

The diversity of types and rates of earth movements within the landslide complex is produced by the variability of sediment distribution in the delta, and its control on groundwater flow patterns. Vertical migration is restricted, and porous sands above clay layers are commonly saturated. The generally fine-grained and laterally discontinuous nature of the deltaic sediments results in an uneven concentration of saturated zones below the thick upper clay. The numerous confined aquifers produce destabilizing saturated zones where they intersect the ground surface.

The second order cause of the landslide complex involves the relative amount of water available at any one time for infiltration into the unconsolidated sediments. Prior to the advent of irrigation systems, the water volume available for recharge was controlled by climatic factors. Earth movements probably occurred only after extended periods of abnormally high precipitation.

With the addition of extensive irrigation systems during the early 1900's, the amount of water available for infiltration increased dramatically. Irrigation of farmland and the presence of reservoirs and distributary canals on the delta surface above the river increased infiltration amounts. This in turn significantly increased the level of saturation in the sediments. Thus, landslide susceptibility under even slightly above normal precipitation rates is increased.

Third order causes of the landslide complex involve a multitude of factors which may trigger specific earth movements. Seismic activity, in particular the 1962 Richmond earthquake, is known to have caused earth movement within the complex (R.C. Bright, personal communication).

The fundamental cause of the landslide complex is incision of the Bear River into unconsolidated deltaic sediments in response to base level lowering caused by the recession of the lake within the Bonneville Basin. Therefore, earth movements will continue in geologic time despite short term climatic changes or modifications by human activity. It is possible that modification of irrigation techniques (lining of reservoirs and canals, sprinkler rather than flood irrigation, etc.) would eventually lower groundwater levels slightly, but most mitigation measures require additional expenses which local residents are unwilling or unable to invest.

Acknowledgements

The compilation of this manuscript was facilitated by assistance from numerous people. The authors wish to express their thanks to Marie Hollist and Jim Olsen for help with figures; Matt Grizzel, Steve Koch, and Russell Sorenson of Preston for historical research; the Preston Citizen for access to their records; Lee

Robinson for use of survey equipment; R.C Bright, H.T. Ore and Linda Davis for critical review; and to the people of Preston for their openness and hospitality. All aspects of this study were funded by Idaho State University Faculty Research Grant #588 to P.K. Link.

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