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STABILITY OF TOUTLE RIVER BLOCKAGE: MT. ST. HELENS HAZARDS INVESTIGATIONS

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Introduction

During events associated with the May 18, 1980, eruption of Mt. St. Helens, a major blockage of the north fork of the Toutle River occurred due to accumulation of debris from the massive landslide (possibly the largest in recorded history) on the north side of Mt. St. Helens and ash from the volcanic eruption. We estimate the volume of accumulated debris in the Toutle River valley below Spirit Lake to be greater than 3 billion cubic yards. The events on May 18 raised the water level in Spirit Lake about 200 ft due to the blockage of the river, floods from Mt. St. Helens, and partial filling of the lake with debris.

During the eruptive sequence, a flood of water and sediment swept down the Toutle River causing considerable damage and siltation along downstream rivers as far as Longview, Washington, where the Columbia River was partly blocked with silt. The latter blockage prevented passage of large ships in an important shipping lane. The debris blockage in the Toutle River posed the hazard of an even greater flood of water and debris should the blockage give way or breach. The purpose of this investigation was to evaluate the stability of the Toutle River blockage and the potential for catastrophic breach of that embankment.

Failure of the Toutle River blockage could occur by any one or a combination of three possible processes. (1) The debris embankment could become unstable due to gravitational forces or possible earthquake shaking and slip or flow downstream releasing a torrent of water from Spirit Lake. (2) Water seeping through the embankment from the impounded lake could erode a tube or channel breaching the embankment, a process called "piping." (3) Water level in the lake could rise, overtop the embankment, rapidly cut a channel through the easily erodible debris, and release a flood of water from Spirit Lake. The possibility of failure from each of these modes is considered herein.

Field Investigations

Between May 19 and 22, Ray Wilson flew two reconnaissance flights over the debris blockage in the Toutle River. From visual observations, comparisons with pre-eruption topography, and a few helicopter altimeter measurements, Ray drafted the preliminary section through the blockage shown in figure 1. Other investigators drafted the lateral extent of the blockage as shown in figure 2.

On the morning of May 23, Ray Wilson and Les Youd, in company with Barry Voight, Pennsylvania State University, flew up the Toutle River by helicopter to inspect the blockage and surrounding area. Pertinent observations from this flight are as follows:

Flow in the river immediately below the blockage was relatively low (estimated to be about 50 cubic feet per second (cfs)). Considerable erosion of the downstream edge of the blockage had occurred during the flooding immediately after the eruption. Active erosion, however, had virtually ceased by the time of our visit.

The surface of the blockage was highly irregular with many hummocks, depressions, and pits. Maximum relief on the hummocks and depressions was about 200 ft. Some pits and depressions contained ponded water. Perceptible flow or seepage could not be seen entering or leaving any of these ponds, however. Many scarps and fissures cut the ground surface. Most of these scarps and fissures evidently were caused by localized slumping near steep slopes. We saw no systematic set of ground cracks indicative of mass, post-depositional, downstream movement of any part of the blockage.

We landed on the debris embankment (near Point 1 on figure 2) to inspect materials exposed by incisions into hummocks and pit walls. Within a foot or two of the surface the materials were fine-sand-sized ash which in topographically lower areas was wet and may have been reworked by water. Below the ash, the sediments were a heterogeneous mixture of sands, gravels, cobbles and boulders, with sporadically distributed large blocks of ice. The color, texture, and mineral composition of the coarse-grained matrix varied greatly from place to place. However, the material was consistently well graded (poorly sorted), ranged in size from fine sand to large boulders, and was loosely packed. The coarser grained material is landslide debris from the massive slope failure that occurred on the north side of Mt. St. Helens at the time of the May 18 eruption. The hummocky nature of the ground surface and the nature of the materials exposed in outcrops indicate that the bulk of the Toutle River blockage is coarse-grained landslide debris covered by a thin veneer of volcanic ash.

After flying over the crest of the blockage, we flew over and around the remains of Spirit Lake. The lake was covered with floating, dust-covered logs. Jagged mounds of broken rock formed islands at several locations indicating that a considerable amount of debris had entered the lake and probably was responsible in large part for the approximate 200-ft rise in lake level. Boiling spouts of water marked locations of hot rocks on the lake bottom and indicated that water temperature and evaporation rates were high. Many small streams and rivulets were flowing into the lake, the largest of which was carrying less than 20 cfs. We estimated total flow into the lake was between 40 and 100 cfs. Shoreline beaches and a set of markers left by a previous field party showed that lake level was slowly declining, about 6 in in the previous 2 days.

We measured the altitude at lake level with the helicopter altimeter and measured the altitude of the lowest point on the crest of the blockage (point 2 on Fig. 2) in a similar manner. The difference between the two measurements was 200 ft plus or minus about 10 ft. At the crest, the surface of the blockage is covered with several feet of ash; however, the surface is hummocky and a few exposures revealed coarse-grained landslide debris beneath the ash.

The length of the blockage as shown on figures 1 and 2 is about 11 miles. The depth of the debris ranges up to approximately 600 ft with an average depth of about 300 ft. General slopes on the blockage range from about 3.8 percent on the long downstream tail of the embankment to about 6.7 percent on both sides of the crest. Locally, near hummocks and depressions, the slopes are relatively steep.

Evaluation of Failure Potential

Slippage or liquefied flow due to gravitational or seismic forces.--During the field investigation, we found no evidence of post-depositional massive slope movements in the debris embankment. Scarps and fissures marked locations of localized slumping on steep hummock or pit slopes. These local faliures, reflect random local motions and thus do not affect the overall stability of the blockage. The field observations indicate that the embankment is safe against slope instability due to gravitational forces.

To check this conclusion, a slope stability analysis was made for the embankment using standard engineering calculations. For the analysis the embankment was assumed to be an infinite slope with seepage flowing parallel to the embankment surface. The factor of safety, F, against slope failure for this case is (Skempton and Hutchinson, 1969):

$$F = (c' + z \cos^2\beta\,(\gamma - m\gamma_w)\tan\phi')/(\gamma z \cos\beta \sin\beta) \qquad (1)$$

where c' is the effective cohesion, z is depth to the failure plane, β is the slope of the failure surface, γ is the unit weight of the debris, γ_w is the unit weight of water, m is the ratio of the depth of water-saturated sediments above the failure plane to the depth of the failure plane, and ϕ' is the effective angle of internal friction. For loose granular debris, such as those in the debris blockage, c' = 0, and equation 1 simplifies to:

$$F = (1 - m(\gamma_w/\gamma)\tan\phi')/\tan\beta \qquad (2)$$

For these calculations, we assumed conservative values for γ and ϕ' of 125 lb/ft^3, and 26 degrees ($\tan\phi'$ = 0.5), respectively. For these values, equation 2 reduces to:

$$F = (0.5 - 0.25m)/\tan\beta \qquad (3)$$

First, we analyzed the stability of the embankment under probable (May 23) conditions. We set lake level at elevation 3400 ft, assumed steady state seepage through the embankment, and set the depth to the saturated zone equal to half the depth to the potential failure plane (m = 0.5). For the 3.8 percent average general slope on the long downstream face of the blockage, the factor of safety against slope failure is:

$$F = (0.5 - 0.125)/(0.038) = 9.9$$

For the maximum general slope of 6.7 percent, the factor of safety is:

$$F = (0.5 - 0.125)/(0.067) = 5.6$$

Both of these calculations indicate that the blockage is very stable against massive slope failure.

For a worst case condition, we assumed the debris blockage to be totally saturated (m = 1.0). This condition would require lake level at the crest of the blockage and precipitation infiltrating into the slope. For a slope of 3.8 percent, the factor of safety is:

$F = (0.5 - 0.25)/(0.038) = 6.6$

For a slope of 6.7 percent, the factor of safety is:

$F = (0.5 - 0.25)/(0.067) = 3.7$

Apparently, the blockage is stable even under these severe conditions.

In the event of an earthquake of magnitude 5 or greater, some settlement of the debris emebankment could occur due to compaction, perhaps as much as a few feet in a large event. Lateral spreading of the embankment would also probably occur, but lateral displacement of the mass would not likely exceed several feet even in a large event. Local displacements could be much greater, but would not affect the overall stability of the embankment. Consideration was given to the possibility of liquefaction and massive downstream flow failure of the blockage. Past experience indicates that such flows do not develop on slopes of less than 5 percent (Youd, 1978, p. 48). The slope of the Toutle River valley is about 2.5 percent, and hence, effectively eliminates potential for flow failure.

Failure by piping.--We saw no evidence of rapid erosion or substantial flow from the toe or downstream face of the debris embankment during our field investigation. These actions are integral parts of the piping process. Hence, there was no threat of piping failure on May 23.

To confirm this conclusion, calculations were made to check the safety of the blockage against piping. A standard engineering analysis for safety of embankments against piping is to compare the "weighted creep ratio", C_{we}, calculated from the embankment geometry to the maximum weighted creep value, C_{wm}, for which piping has occurred in a given type of material. The factor of safety against piping can be stated as:

$$F = C_{we}/C_{wm} \quad (4)$$

C_{wm} for the coarse-grained slide debris in the blockage (approximately equivalent to gravel) is about 3. C_{wm} for the veneer of ash (equivalent to fine sand) is about 8. For planar flow, the equation for C_{we} is (Terzaghi and Peck, 1967, p. 617):

$$C_{we} = B/3h_{cr} \quad (5)$$

where B is the width of the embankment, and h_{cr} is the difference in elevation between water level in front of the blockage and water level at the point of seepage outflow.

For lake level at 3400 ft (May 23 level) and seepage emerging at the head of channels eroded into the toe 11.4 mi (60,000 ft) downstream at elevation 1600 ft,

$$C_{we} = (60,000)/3(1,800) = 11.1.$$

For the coarse grained body of the blockage, the factor of safety against piping is:

$$F = 11.1/3 = 3.7,$$

indicating that the embankment is safe against piping. (Calculations were also made for seepage emanating from the embankment upslope from the toe, but in all instances the calculated factor of safety was higher than at the toe.)

Should a continuous layer of ash lie within the blockage (such as beneath the landslide debris) the factor of safety against piping for that layer is:

$$F = 11.1/8 = 1.4.$$

Safety against piping in such a layer would be marginal. It is unlikely that such a continuous layer of ash exists in the embankment. Furthermore, should piping develop in an ash layer, coarse grained material would likely collapse into the pipe, effectively increase C_{wm}, and stop the erosion.

Safety against piping was also analysed for a worst case condition, lake level at the crest of the embankment (3600 ft), an seepage out the toe. C_{we} for this case is,

C_{we} = 60,000)/3(2000) = 10.0,

and the safety factor against piping for the landslide debris is,

F = 10.0/3 = 3.3,

and for the unlikely case of a continuous ash layer,

F = 10.0/8 = 1.2.

These calculations indicate that the embankment apparently is safe against piping even if lake level were to rise to its maximum level.

In the unlikely event that piping should develop, the volume of the blockage (more than 3 billion cubic yards) would prevent rapid catastrophic breach of the embankment. Erosion of a channel through the embankment probably would require a volume of water greater than the present volume of Spirit Lake, and a substantial period of time, possibly months. Thus, there would be ample lead time for a hazard warning, if needed, to the residents downstream.

Failure by overtopping.--With lake level 200 ft below the crest of the blockage and falling, there was no immediate threat of water overtopping and eroding a breach through the embankment on May 23. During future periods of high runoff, it may be possible for the lake to fill and flow over the blockage. (It is also possible that sufficient water will seep through the embankment to prevent overtopping.) As with piping, a considerable volume of water would be required to erode a deep channel through the embankment and release a flood from the lake. We estimate the volume of debris to be washed out of such a channel would be tens of millions of cubic yards, and the amount of water required to wash the channel would be several tens of millions of cubic yards. Such actions would take considerable time to occur allowing time for a warning to downstream residents of the pending hazard.

Perhaps the greatest long term problem associate with the blockage is the amount of sediment that may eventully be flushed downstream by erosion of the debris embankment. Erosion could result from overtopping of the embankment as well as from streams feeding onto the embankment from adjacent drainages. Erosion and flushing of sediment could be a continual action during periods of high runoff for many decades to come.

Cold Water Creek

The debris embankment also covered the mouth of Cold Water Creek, a small tributary to the north fork of the Toutle River, impounding a lake behind the embankment in that drainage. The lake was small, well below the top of the embankment, and there were no indications of instability or erosion of the blockage. No calculations were made, but that embankment appears equally or more safe than the blockage of the Toutle River.

Conclusions

Based on our field investigations and engineering calculations, we conclude:

1. The blockage in the Toutle River drainage is presently (May 23, 1980) stable against failure due to (a) slope instability either from gravitational or earthquake forces; (b) piping or erosion by seepage through the embankment; and (c) overtopping of the embankment by water from Spirit Lake.

2. A rise of water level to the crest of the embankment would increase potential for failure. Our calculations indicate, however, that the embankment would be stable against slope failure and piping even under this extreme condition. We also reckon that a large volume of water and considerable time would be required to erode a channel through the blockage either by piping or overtopping, thus giving time for a warning to residents downstream. Because our calculations are based on preliminary information and estimated values, we suggest that additional analysis be made when better data becomes available, and that the behavior of the embankment be monitored when or if the lake ever fills.

3. We believe that the greatest engineering problem associated with the blockage is the potential for erosion and flushing of sediment downstream during period of high runoff for decades to come.

4. The blockage of Cold Water Creek is stable against slope failure and piping, and there is no present threat that the small lake impounded in that drainage will overtop the embankment and

release a flood. Although overtopping is likely at some future time, it is unlikely that a catastrophic flood will be released from this small drainage.

References

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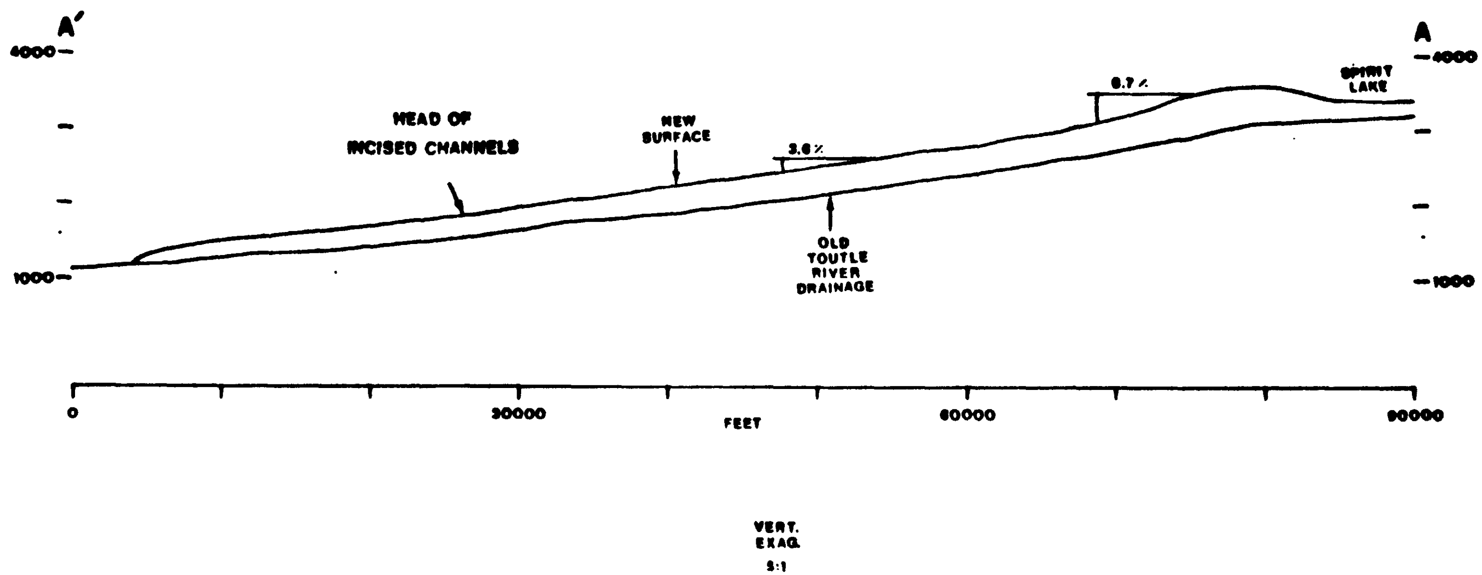

Figure 1.-- Preliminary Section through debris blockage in Toutle River drainage

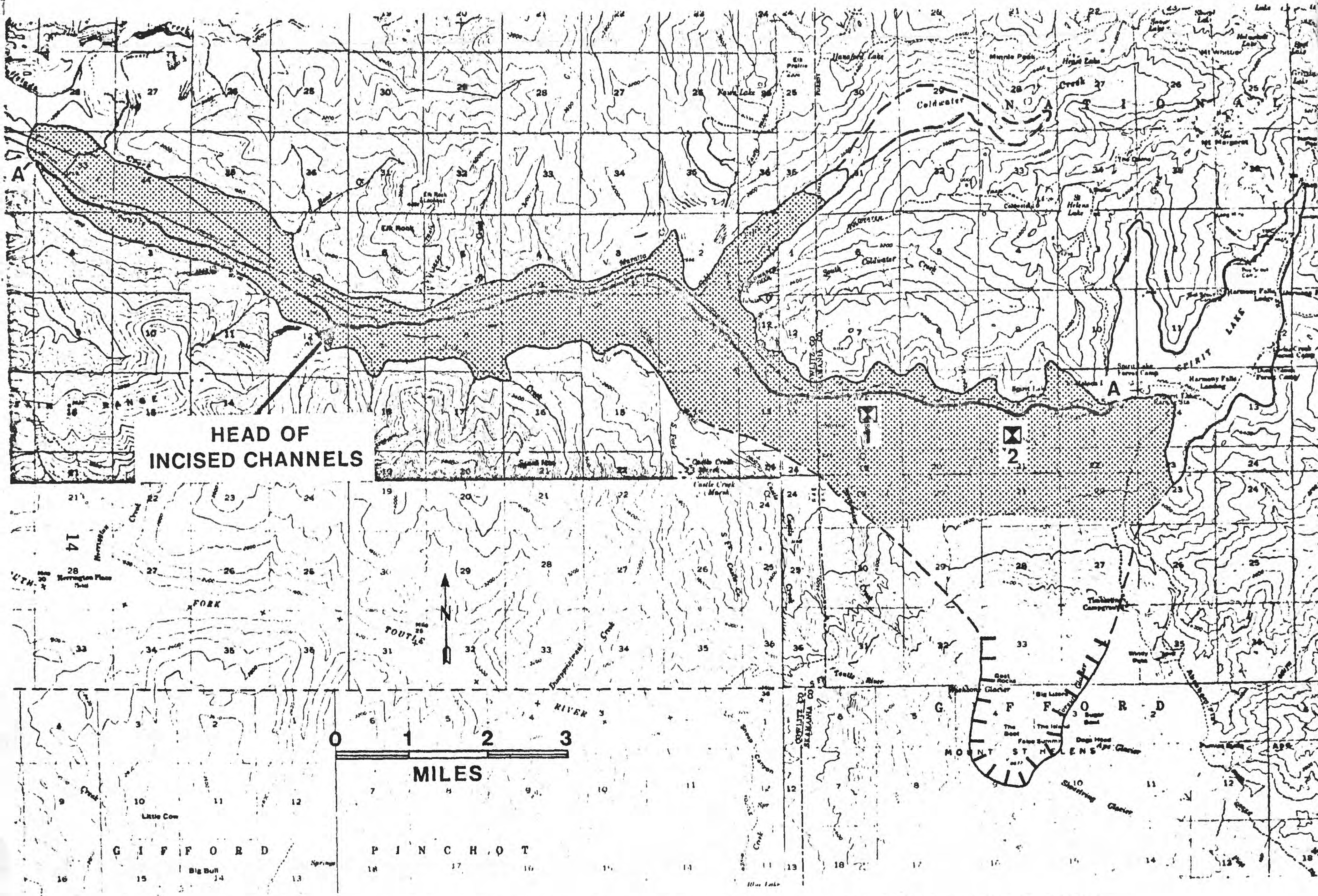

Figure 2.--Preliminary map of Toutle River debris flow adapted from an unpublished map by J. Moore, P. Lipman, and D. Swanson, U.S. Geological Survey. Points 1 and 2 are landing sites mentioned in text