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THE BORAH PEAK, IDAHO EARTHQUAKE OF OCTOBER 28, 1983

The Borah Peak, Idaho Earthquake of October 28, 1983—Hydrologic Effects

Spencer H. Wood, Caroline Wurts, Ted Lane, Nick Ballenger, Mary Shaleen, and Dolores Totorica

Spectacular groundwater effects accompanied the October 28, 1983 Idaho earthquake ($M_s = 7.3$). Groundwater discharge increased from many springs and base flow of major rivers significantly increased over an 18,000 km² region. In the epicentral area a 35-m surge in artesian pressure produced spectacular bursts of muddy water from carbonate bedrock hills at Chilly Buttes. This pressure surge was also manifested as a 1.4-km long zone of large sand boils erupted through the valley alluvium. At Smith's Fish Hatchery, sediment eroded by the surge of water clogged the fresh spring-water supply inlet pipes and led to suffocation of the entire crop of trout. North of the epicentral area a major warm springs dried up for 8 days and then recommenced flowing at an ever increasing rate until it stabilized at about 9 times the pre-earthquake flow. This flow of about 1400 l/s caused severe bank erosion of pastureland until diverted into an artificially excavated channel. At Clayton Silver Mine, 50 km north of the epicenter, increased seepage into the underground mine workings overwhelmed the mine-pump capacity and flooded the 330-meter level within 14 hrs. Thirty kms south of the epicenter a 200,000 m³ mudflow was apparently caused by increased spring flows. The valley fill failed two days after the earthquake and devastated a 3.5-km reach of Lupine Creek valley. Similar coseismic and post-seismic hydrologic effects were reported in studies of the 1952 Kern County, California earthquake, and the 1959 Hebgen Lake, Montana earthquake. Several mechanisms for these hydrologic phenomena are considered, but the most plausible cause is the sudden release of elastic strain in aquifer rocks. Sudden strain release of elastic rebound increases pore pressure in some confined aquifers thus leading to increase in discharge from springs that contribute to the base flow of major rivers.

INTRODUCTION

The October 28 earthquake increased the natural groundwater discharge and base flow of major rivers over an 18,000 km² area of south-central Idaho (Figs. 1 and 2). Flows from springs generally increased shortly after the main shock. Some of the hydrologic effects

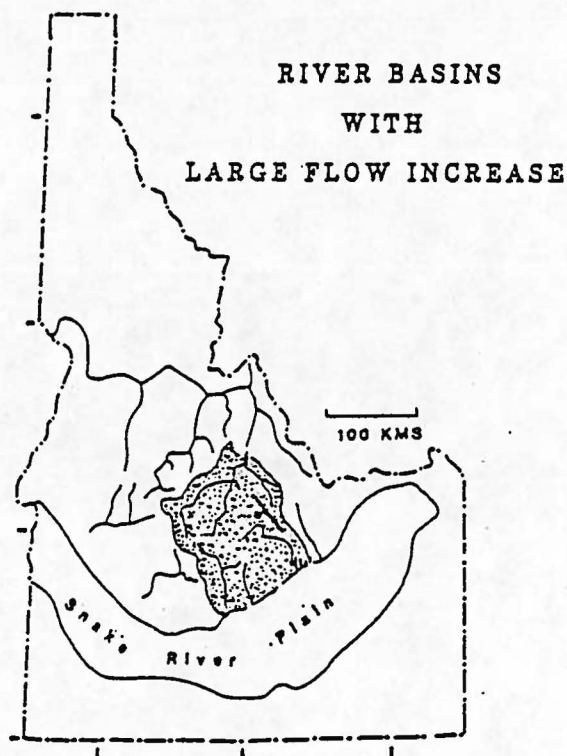


Fig. 1. Shaded region is the area of stream drainages showing significant increases in base-flow discharge following the October 28 earthquake. Hydrographs are published in Whitehead and others (1985), Wood (1985), and selected hydrographs are shown in Figures 3 and 4. Outlined area is location of Figure 2.

Major rivers draining the area of the earthquake underwent large increases in discharge within a day after the main shock (Figs. 1, 3, and 4). The stage recorder on the Big Lost River at Howell Ranch showed an increase in flow of 250 cfs (7075 l/s) that occurred over a 5-day period following the main shock. Additional flow at this point in the river remained above 250 cfs for 1.5 months and then declined back to normal over a period of 6 months to one year. At the underground Clayton Silver Mine, water levels had been sustained by pumping 980 gpm (62 l/s) at 1150

could have been hazardous in an urban area, and part of the initially assessed damage in Custer and Butte County was caused by flows of water, or loss of water supplies. It is the purpose of this report to document hydrologic observations and offer preliminary explanations for events following the earthquake.

In the epicentral area, a surge in artesian pressure of at least 115 ft (35 m) caused spectacular bursts of muddy water from carbonate-rock hills and caused fissure eruptions and boils of sand from the surrounding alluvium along a 1.4-km-long zone in the Chilly Buttes area. Similar destructive large flows of water occurred at spring areas on the west side of the Lost River Valley at Dick Smith's Fish Hatchery. Along the zone of surface breakage at Elkhorn Cr. several new springs issue from the surface fractures. At points 8 to 65 km from the zone of surface faulting, warm springs systems increased in flow. Perhaps the most interesting changes in warm-spring flows have occurred at Ingram's Warm Springs Creek south of Challis. The original flow of about 6 cfs (170 l/s) virtually ceased and the springs dried up following the earthquake.

Eight days later the springs recommenced flowing at an ever increasing rate. The flow peaked at 60 cfs (1700 l/s) two months later, and at the most recent measurement (July, 1985), the springs are flowing 40 cfs (1130 l/s), about 7 times their original flow.

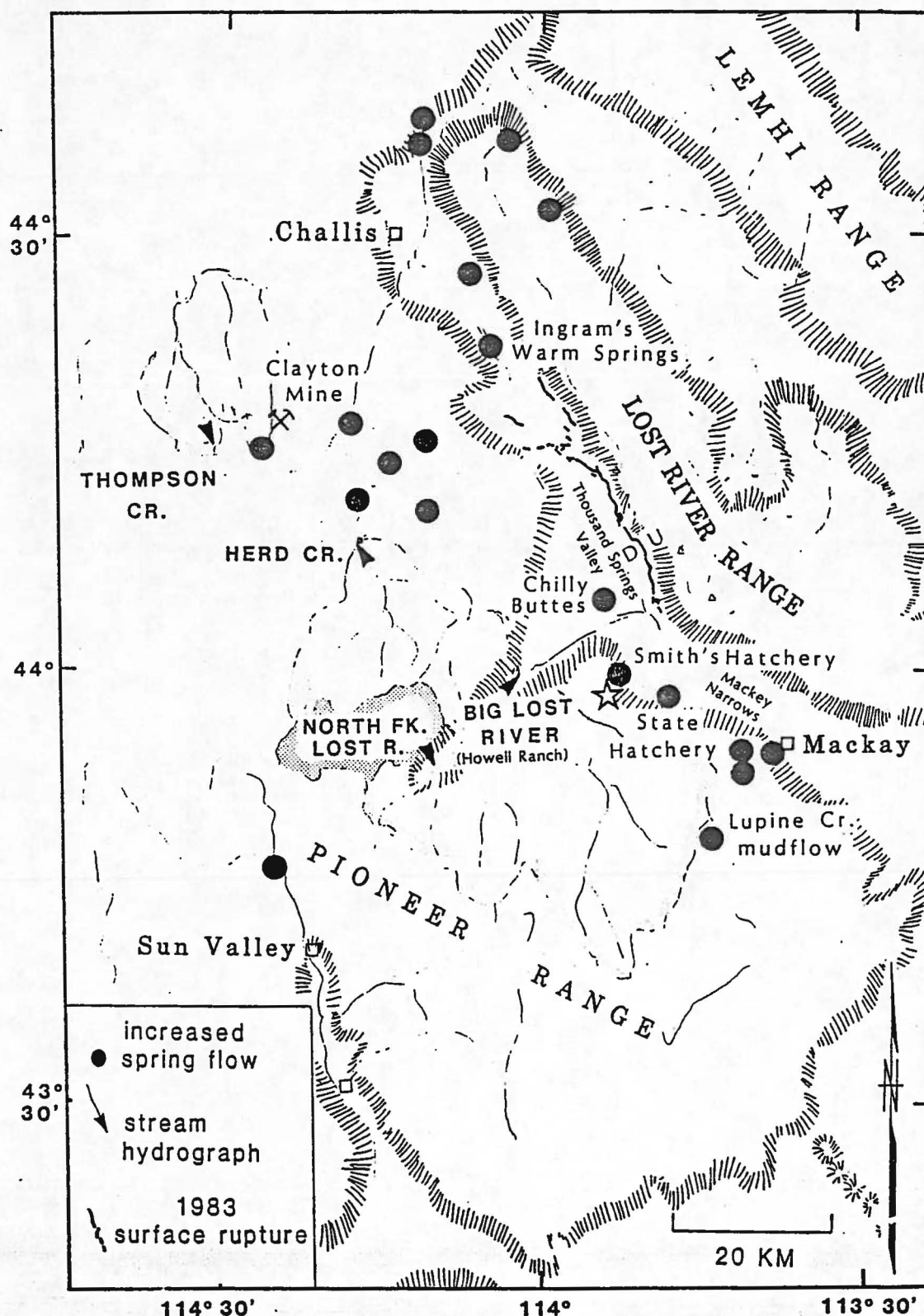


Figure 2. Map showing locations of springs that increased in flow following the October 28 earthquake. Springs are briefly described in Table 1. Location of the selected stream hydrographs of Figures 3 and 4 are shown with dark arrow and the drainage areas are outlined. Location of surface faulting is from Crone and Machette (1984).

North Fork of Big Lost River

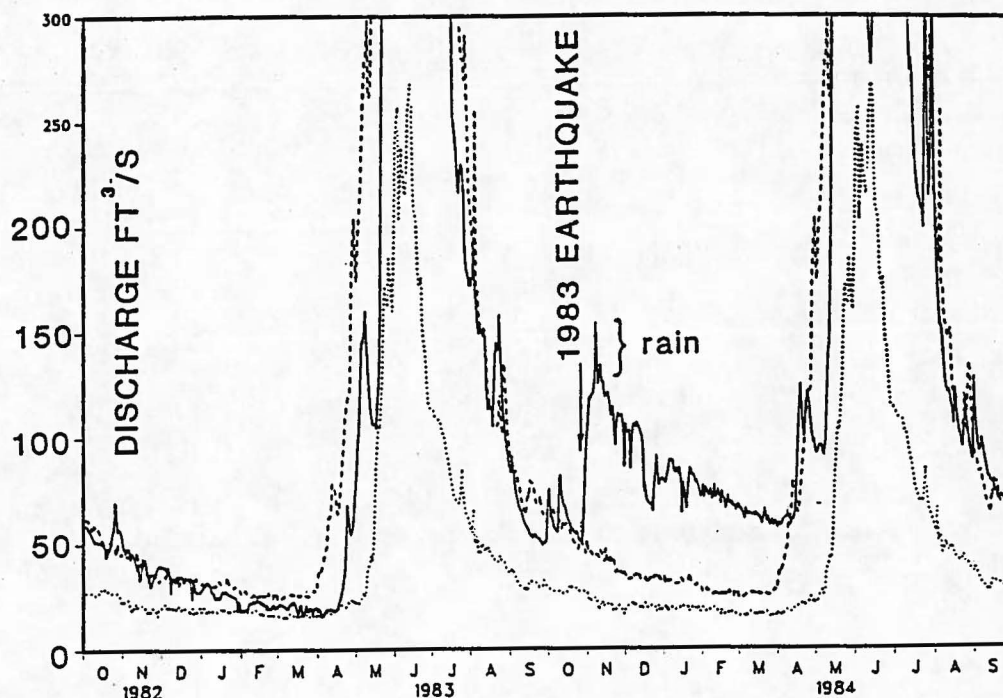


Figure 3. 1983/84 hydrograph (solid line) of the North Fork of the Big Lost River showing increased discharge after the earthquake of October 28.

ft (350 m) below the valley bottom elevation of 5890 ft in order to mine the 1100-ft level. Three hours after the main shock, water began to rise at a rate of 5 feet per hour in the shaft from which the water was being pumped. By November 7 it has risen 185 feet to the 965-ft level and continued rise was arrested by installing 2000-gpm (126-l/s) pumps that pumped the water level back to the 1100-ft level about January 1, 1984.

Hydrologic effects were particularly noted by residents of south-central Idaho because water supplies from spring flows are vital to many cattle ranching, farming, and fish hatchery operations in the area. The high mountainous terrain surrounding the Big Lost River and the Salmon River Valleys have large winter-snow accumulations which supply water to the complicated subsurface aquifer systems of folded and faulted Paleozoic sedimentary rocks and the Eocene Challis volcanic rocks and valley alluvium. Snowmelt runoff begins in mid-April and ends in mid-September (Figs. 3 and 4). Snowmelt flood flow in the Big Lost River typically peaks in mid-June between 1000 and 2000 cfs (28,320 to 56,640 l/s). Flow of the Big Lost River at Howell Ranch is typically less than 100 cfs (2,832 l/s) in the period from September to April. During this period of low flow most of the reach between the "Chilly Sinks" (just below Howell Ranch) and Mackay Narrows is dry, because the water percolates into the alluvium and the carbonate aquifer system in the vicinity of the "Chilly Sinks" (Crosthwaite and others, 1970). This "lost" flow reappears in the reach just above the Mackay Narrows. Flow from Thousand Springs Creek is derived mostly from the springs in the

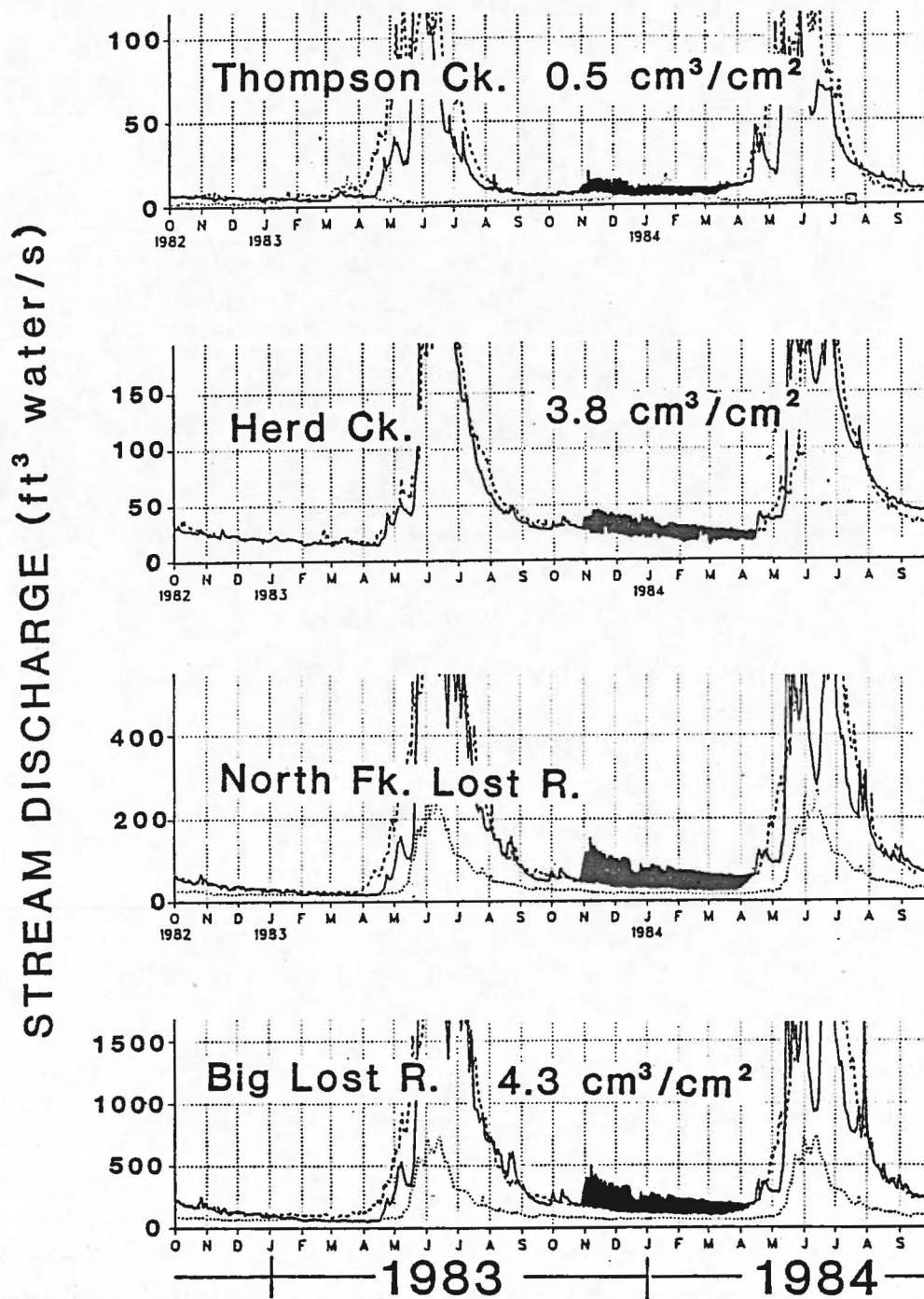


Figure 4. Hydrographs of selected streams in the Big Lost River and the Salmon River Basins. Drainage basin of each hydrograph is outlined in figure 2. Darkened area is flow induced by the earthquake. Earthquake-induced flow is recalculated as an equivalent rainfall event in units of cm^3/cm^2 . Data are from the USGS network of gaging stations in central Idaho.

TABLE 1. REPORTED CHANGES IN GROUND AND SURFACE WATER AFTER THE OCTOBER 28 EARTHQUAKE

Geographic name	Location Sec. T. R.	Comment	Source of Information
.....MACKAY 15-minute quadrangle.....			
Mackay City Spring	32 7N 24E	Discharge increased from 1.8 cfs to 4.5 and up to 7 cfs (see hydrograph)	Gail Lords, City of Mackay
.....COPPER BASIN 15-minute quadrangle.....			
Mackay State Fish Hatchery	34 8N 22E	Surge of water, 70 cfs followed earthquake, flow increased from 22 to 30 cfs	Bill Dorr, Lynn Walsh, Idaho State Fish & Game Dept.
Hamilton Spring (Dick Smith's Fish Hatchery)	29 8N 22E	Surge of water of about 100 cfs followed earthquake extensively damaged fish-rearing facilities and most of the fish crop was lost. Damage estimated at \$450,000. Prior to earthquake, flow was about 30 cfs. Flow after the earthquake was 57 to 65 cfs and has stabilized at 45 cfs. (see hydrograph)	Dick Smith, owner
.....CHILLY BUTTES 7½-minute quadrangle.....			
Chilly Buttes, San Felipe Ranch, (Anderson Springs)	30 9N 21E	Spectacular surge of water with a head of at least 115 ft., Flow in excess of 400 cfs, Sediment boils, (See report by Waag and others, this volume, and hydrograph)	Del Clark, San Felipe Ranch
Bartlett Creek	22 8N 21E	Unconfirmed reports of surge and increased flow	
..... MAY 15-minute quadrangle			
Sulphur Creek (warm springs)	14H 21E	Muddy water discharge after earthquake, flow increased from 17 cfs before quake (estimate) to 27 cfs	Richard Whitehead, USGS, Boise Mr. Urresti, rancher
.....DOUBLESRING 15-minute quadrangle.....			
Grouse Creek drainage		New 2-acre lake formed, 10 ft. deep	Ron Liebe, USFS, Challis
.....GROUSE 15-minute quadrangle			
Antelope Creek, past Grouse School, up Lupin Creek Draw		Landslide and new springs reported but not confirmed	
..... ELKHORN CREEK 7½-minute quadrangle.....			
Elkhorn Ck. Canyon (new springs)	26 9N 22E	About 2 cfs issues from new surface fractures and fissures along the zone of surface faulting about 30 ft above the creek, on a sage covered flat, near and old seepage area. (see hydrograph)	S.H. Wood and Ted Lane, B.S.U.

..... BORAH PEAK 7½-minute quadrangle.....			
Birch Springs	10 9N 22E	Landslide triggered by the earthquake, includes spring area and the newly formed fault scarp. Flow after earthquake is about 0.25 cfs, which is reported to be the pre-earthquake flow.	Ted Lane, B.S.U.
..... ZIEGLER BASIN 7½-minute quadrangle			
Un-named spring Canyon of the East Fk. Salmon R.	23 10N 18E	New spring reported	U.S.F.S. Challis office
Pine Creek	5 9N 18E	Flow appeared to be ¼ to ½ greater than normal, time of observation not known.	U.S.F.S. Challis office
.....TIE PAINT POT 7½-minute quadrangle			
Road Creek	20,21 10N 19E	Reported to be at least 2-times greater flow than normal for this time of year	Norm Solberg, Clayton, Id.
Bear Creek	36 10N 19E	New water on road	Norm Solberg, Clayton, Id.
..... AMBER LAKES 7½-minute quadrangle			
Easley Warm Spring	10 5N 16E	Reported to be at least 2 times the flow before the earthquake. Previous flow reported to be about 0.3 cfs.	John Hephworth, USFS, Ketchum Mrs. Moulin, Easley Store.
.....CLAYTON 15-minute quadrangle.....			
Clayton Silver Mine	13 11N 13E	Water rose in the mine 195 feet and flooded the 1100-ft level where ore was being mined. Mine forced to close, and install larger capacity pumps. (see record of water level in mine)	Roland Rovetto, Clayton Mine
Spring near Clayton Mine	13 11N 13E	spring reported to have diminished in flow and then increased after an aftershock	Norman Solberg, Clayton, Id.
un-named spring	1 11N 18E	spring flowing 1 to 2 cfs, never flowed in January.	
..... LONE PINE PEAK 15-minute quadrangle.....			
Tub Spring area	23 11N 19E	flow of about 1 cfs is twice that of last winter	Gary Ingram
Devils Canyon	12 12N 20E	increased flow	"
Lime Creek	2 12N 20E	two times increase in flow	"
Hole in the Rock Creek	27 13N 20E	two times increase in flow	"
Warm Springs Creek	10 12N 20E	A 6 cfs spring system dried up for 8 days and recommenced flowing at an increasing rate. Flow on Jan. 5, 1904 was 51.4 cfs. (see hydrograph and discussion in this report)	

valley and from runoff from the Lost River Range in Willow Creek, Rock Creek, Cedar Creek, and Elkhorn Creek. Flow of the Big Lost River at Howell Ranch was 150 cfs (4250 l/s) just prior to the earthquake. Flow from Thousand Springs Creek which enters the Big Lost River just below Howell Ranch is estimated to have been also about 150 cfs prior to the earthquake. Both flows were somewhat larger than normal because of higher than normal snowpack in the 1982/83 winter.

Major changes in spring and stream flows are documented with hydrographs in order to quantify the nature of the transient flows and the amounts of water released from the groundwater system because of the earthquake. Measurements on springs and small streams were made by standard methods with a current meter and by constructing wiers and stage recorders. Changes have doubtlessly occurred on many of the smaller springs which we did not have a chance to examine before the area was snow covered. The reports of springs shown on Figure 2 and in Table 1 were gathered from residents of the region, public officials, and our own observations. Large increases in base flow of the North Fork of the Big Lost River indicates many other springs in remote areas increased, but were not noticed. Thus the points shown in Figure 2 are not a complete sampling, and we have to rely on the outline of the drainage basins above hydrographs to determine the affected region shown in Figure 1.

A number of water wells underwent changes in water level throughout the southern Idaho area (Whitehead and others, 1985). Near the epicenter water-level hydrographs of two shallow observation wells in Thousand Springs Valley, showed a 1 to 2 m abrupt rise, and a gradual decay over a period of one month. Both stabilized at levels about 1 m above the pre-earthquake level (Whitehead and others, 1985). These wells are in alluvium of the valley and apparently not directly connected to the limestone bedrock aquifer that underwent such large pressure changes near Chilly Buttes. Unfortunately no deep-aquifer observation wells had been monitored in the region prior to the earthquake.

Fluctuations and permanent shifts in water levels in wells at distant points have been well documented in other earthquakes (Cooper and others, 1965), however the permanent shifts have never been well explained. These effects in data from the network of observation wells and stream gaging stations throughout Idaho and monitored by the U.S. Geological Survey, Water Resources Division during and after the earthquake have been reported by Whitehead and others (1985).

POSSIBLE MECHANISMS PRODUCING INCREASES IN SPRING FLOWS

Mechanisms by which spring flows increase in the region of a large earthquake have not before been considered in previous reports on earthquakes. In a summary of hydrologic hazards from the 1964 Alaskan and other large earthquakes the only similar effects noted are the short-lived groundwater spouting from alluvium (Goldthwait, 1968). Similar hydrologic phenomena were observed and well documented in the 1952 Kern County, California earthquake (Briggs and Troxell, 1955) and in the 1959 Hebgen Lake, Montana earthquake (Stermitz, 1964; Swensen, 1964; and Hadley, 1964). Changes in spring flow are also a characteristic of earthquake shaking above intensity VII, although we do not believe the transient effects of shaking to be the principal cause. In the earlier version of this paper written in January, 1984, we suggested 5 of the possible mechanisms listed below. The most plausible mechanism, that of

pore pressure increase caused by strain of aquifer rocks that underwent elastic rebound, was not originally listed. That mechanism became apparent after a review of the pattern of geodetically-measured strain release in large normal-fault earthquakes (Wood, 1984). This explanation for many of the hydrologic effects is more thoroughly discussed in Wood and others (1985) and Wood (1985a, 1985b). The idea that a major earthquake should increase pore pressure of rocks in the region of elastic rebound was originally proposed by Nur and Booker (1972).

The velocity of flow or the discharge of water from a permeable zone is related by Darcy's law to permeability of the zone and to pressure gradient along the flow path (Freeze and Cherry, 1979). Thus an increase in spring flow must be attributed either to an increase in aquifer pressure or to an increase in permeability along the flow path. Mechanisms that could cause an increase in spring discharge can be classified as follows according to these two parameters of Darcy's law.

An increase in aquifer pressure could be accomplished by the following mechanisms:

1) Coseismic strain release may cause a sudden increase in pore pressure in aquifer rocks within the zone of elastic rebound. This increase in pore pressure should cause increased discharge of springs that are hydraulically connected to strained aquifer rocks. This mechanism should work in the region of contractual strain which is mostly in the hanging wall in a normal-fault earthquake (see Fig. 5). Dilational strain of the footwall should, in principal, increase pore space and cause a pore pressure decrease in at least part of the footwall block. However, dilatational strain of the footwall block is small relative to contractual strain of the hanging wall, so that reduction of pore pressure in the footwall may be slight and may not cause cessation of spring flow. Figure 1 shows that flow increases are largely in the hanging wall block, but some flow increases also occurred in the footwall block north of the zone of surface faulting. Clearly needed to support the above hypothesis is a better understanding of the pattern of strain release in a normal-fault earthquake. To the best of our knowledge a realistic model and calculation of the pattern of permanent strain from elastic rebound of a normal-fault earthquake has not been published. Another implication of this hypothesis is that the pore pressure changes should gradually diminish by diffusion away from the strained region through hydraulically-connected aquifer rocks.

2) consolidation or compaction of aquifer rocks or alluvial material by shaking during the earthquake could diminish pore space and lead to a temporary pore pressure increase. This process could also include micro-displacements and crushing along fracture systems as well as packing and consolidation of alluvial material. This mechanism is similar to that of liquefaction of cohesionless materials. One would expect flows from this process to last only a short time after strong ground motion. The continuation of anomalous flows for several months tends to discount this as a principal mechanism.

3) Coseismic vertical tectonic deformation: Release of stored elastic strain caused a broad downward rebound of the hanging-wall block with maximum downward displacement of 6 to 10 ft (2 to 3 m) at the fault. A smaller magnitude tilting also occurs in the footwall block. Results from releveling (Stein and Barrientos, 1985) shows the vertical rebound in the hanging-wall block is about 5 ft (2 m), and in the foot-wall block it is only about 1 ft (0.3 m). In both blocks, tilt is down to the east. This tilt would increase the pressure gradient in aquifers that flow east in the hanging wall block to the Big Lost River Valley. The effect in the footwall (Lost River Mountains) would be less, because the tilt is apparently less. These tilts are distributed over several tens of kilometers so that the actual increase in hydraulic gradient is slight, and should not significantly affect the flow.

Increase in permeability along the flow path could be produced by the following mechanisms:

4) Fracturing and cracking along fault zones during the earthquake or its aftershocks. It is generally accepted that an earthquake creates a myriad of new fractures in rocks along zones of failure, but it is difficult to account for those springs with increased flow that are some distance from the zone of surface breakage.

5) Seismic shaking may induce several cycles of surging flows in aquifers throughout the area. It is possible that these flows clean out precipitated material in cracks and pore space and improve the permeability.

6) The pressure pulses produced by seismic shaking may cause hydraulic fracturing in some aquifers. Hydraulic fracturing is most likely in pressurized aquifers in an area under extensional tectonic stress (Hubbert, 1957). This is an attractive explanation for increased flows from flowing springs over a broad region. Dynamic pore pressure of about 33 psi may be associated with dynamic strain of 10^{-4} near the epicentral area (calculation of 333 psi by Wood (1985a) used an incorrect value for the compressibility of water and is too high by a factor of 10). This relatively low pressure suggests that if hydraulic fracturing occurs during the passage of seismic waves, it could occur only at a relatively shallow depth, probably less than 1000 ft. In order for hydraulic fracturing to occur the pore pressure must overcome the horizontal minimum-principal stress. The horizontal minimum-principal-stress gradient is about 520 psi/1000 ft depth in some extensional tectonic regions (McGarr, 1982, Fig.3; Zoback, 1985, fig. 5). This mechanism might explain why some spring systems are affected and increase in flow, and others change very little if at all. The existing joint orientation, the aquifer pressure, the rock type, and the orientation and magnitude of stress may differ considerably from one spring system to the next, and so might the susceptibility of the rocks to hydraulic fracturing from stress waves. Natural hydraulic fracturing as well as tectonic fracturing probably occurs near the zone of faulting, but it is unlikely that it occurs over the broad region of observed hydrologic effects.

SPRING FLOWS NEAR THE EPICENTER OF THE EARTHQUAKE AREA

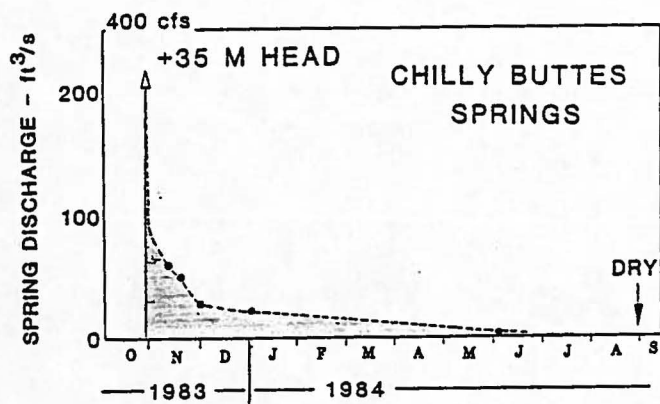


Figure 5. Hydrograph of spring flow from Chilly Buttes (Anderson Springs).

CHILLY BUTTES AREA

The most spectacular surge of water occurred in the epicentral area at Chilly Buttes during the earthquake (see Waag and others, this volume). Muddy waters burst from the hillside of the northernmost butte, 115 ft (35 m) above the surrounding alluvial plain. This surge of pressure also appears to be responsible for the large sand boils and sand-fissure eruptions from the alluvium. These features lie along a N 10°W alignment of a cavernous, permeable zone in the limestone bedrock. This permeable zone efficiently conducted the pressurized water to the surface. Mr. Merlin McAfee of the San Felipe Ranch estimated that 400 cfs was flowing from

various points at the base of the butte 1 hr after the earthquake. The initial surge flooded across the alluvial plain and through the livestock pens of the San Felipe Ranch and broke a small earth dam used to impound water in the spring for late summer use. By the following day, the lower part of Thousand Springs Valley was flooded by a small lake, mostly by water flowing from springs in the Chilly Buttes area (Fig. 5). The temporary lake receded rapidly in the following week as the spring flows declined. The hydrograph shows the initial surge and the decline in flow through November (Fig. 6). The flow gradually declined through the winter and was totally dry in August, 1985.

Springs on the north side of Chilly Buttes are called Anderson Springs in the report by Crosthwaite and others (1970). The spring discharge was measured at 8.1 cfs (230 l/s) on Sept. 23, 1968. It is puzzling that the spring was dry in the autumn of 1983 and in 1984, but was flowing in the autumn of 1968. We do not know the normal annual history of the springs. According to Del Clark of the San Felipe Ranch at the foot of Chilly Buttes, the spring flowed in the spring and early summer, but ran dry in late summer. The spring temperature of 54°F measured in 1968 was the same after the earthquake.

Thousand Springs is a large discharge area in the valley much lower in elevation and to the east. The total discharge from Thousand Springs Valley was measured at the box culvert on Trail Creek Pass road, and almost all of the additional flow measured there was the same as measured in the spring-system channel from Chilly Buttes (Fig. 5). Therefore none of the other tributary streams and springs of Thousand Springs Creek showed large discharges attributable to the earthquake. The only major

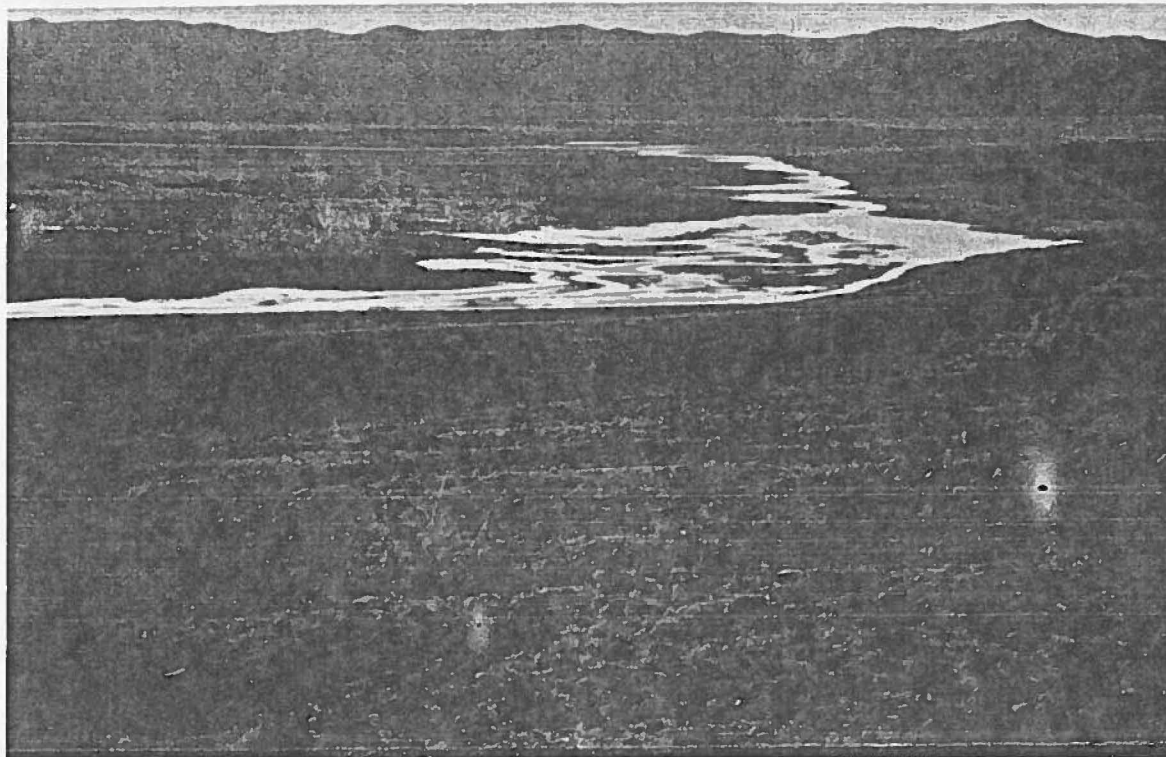


Figure 6. Photograph of flooding in the Thousand Springs Valley taken from Elkhorn Creek Canyon at 6:30 PM on October 29. View is to the northwest. Widest flooded area is about 1/2 mile wide at Whiskey Springs. Distance tributary from the left side of photo is the flow from the Chilly Buttes area. Outlet of Thousand Springs Creek is to the lower left (south). Photograph by S.H. Wood.

outpouring and new flow continuing through the winter was from the base of Chilly Buttes.

DICK SMITH'S FISH HATCHERY (HAMILTON SPRINGS)

Hamilton Springs also underwent a violent surge of water during and shortly after the earthquake. Peak flow estimate of 100 cfs in Fig. 2 is from Dick Smith's eyewitness accounts, and from high-water marks on the stream channels. The highest point of spring discharge during the surge was 25 ft (8 m) above the normal elevation of the springs. The surge of water eroded about a 2 meter thickness of soil and colluvium from a 60 x 200 ft² (18 x 60 m²) area, and produced gullying at another discharge point north of the spring. Sediment from these wash-out areas clogged and buried the intakes for two 18-inch pipes that are the source of fresh water for the fish hatchery. The entire crop of trout subsequently suffocated from lack of aerated fresh water. The reported damage from loss of fish and costs of repair were \$450,000. Flow before the earthquake is reported to have fluctuated between 20 and 33 cfs. For several months after the earthquake it appeared to have stabilized at 46 cfs. On July 17, 1985 the flow was 36.4 cfs.

The springs issue from quartzite bedrock at the west edge of the Big Lost River Valley. Water is probably from a carbonate rock aquifer that

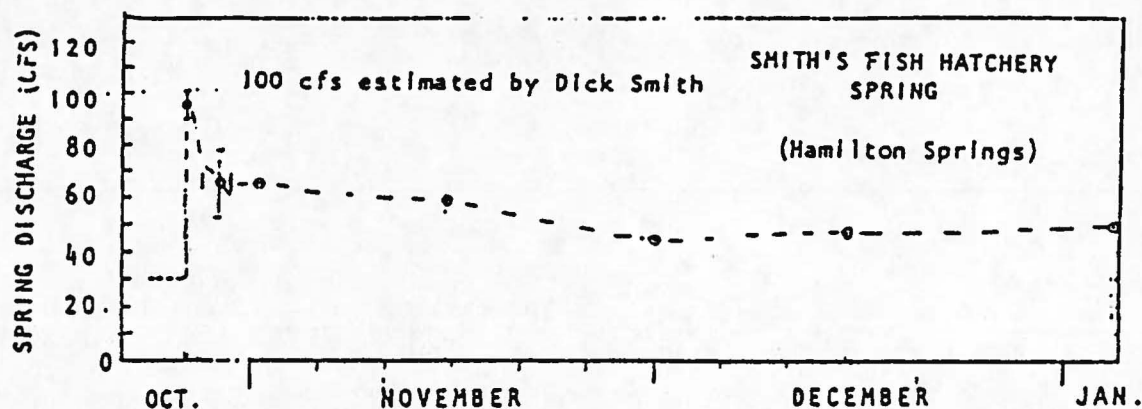


Figure 7. Hydrograph of spring flow from springs at Dick Smith's fish hatchery (Hamilton Springs)

discharges to a range-front fault at the base of the Pioneer Range, however the hydrogeology has not been studied..

MACKEY STATE FISH HATCHERY

The State Fish Hatchery springs underwent a surge of water commencing about 20 minutes after the earthquake. Timing of the onset of increased flow is important because it would appear that there is a finite time for the pressure front to reach the point of discharge. A flow of about 74 cfs was estimated after the earthquake. Flow before the earthquake was about 23 cfs. Since the earthquake the collected flow from the springs has declined and stabilized at 35 cfs (Fig. 8). Geologic setting of the spring is similar to that of Hamilton Springs, and it is presumed to be from a carbonate aquifer.

WARM SPRINGS CREEK

Prior to the earthquake, a large warm springs flowed about 6 cfs (Young and Lewis, 1982) and was the principal source of water for irrigating 1200 acres of pasture and hay fields in the Warm Springs Creek Valley and southern Round Valley near Challis. The springs issue from dolomitic quartzite bedrock in an area about 5 km from the northern extent of minor surface faulting associated with the earthquake (Fig. 2). The springs virtually dried up after the earthquake. At 10:20 AM, Will Ingram went to inspect the spring area. He observed the main springs had completely stopped flowing. Another smaller spring about 1/4 mile northwest of the main spring and 8 to 10 feet lower in elevation formerly flowed about 1.6 cfs and was flowing only about 0.2 cfs after the earthquake. By the morning of October 29, it too had completely stopped. Sue Villard of the Challis Messenger newspaper photographed the dry stream (Fig. 9). On November 4, at noon, (7 days after the earthquake) the lower spring was observed to flow about 0.3 cfs. The following day, the main spring re-commenced flowing (Shaleen and Totorica, 1984). On November 8, Will Ingram estimated the flow to be about 1 cfs. On the morning of November 10 we attempted to install a wier and stage recorder,

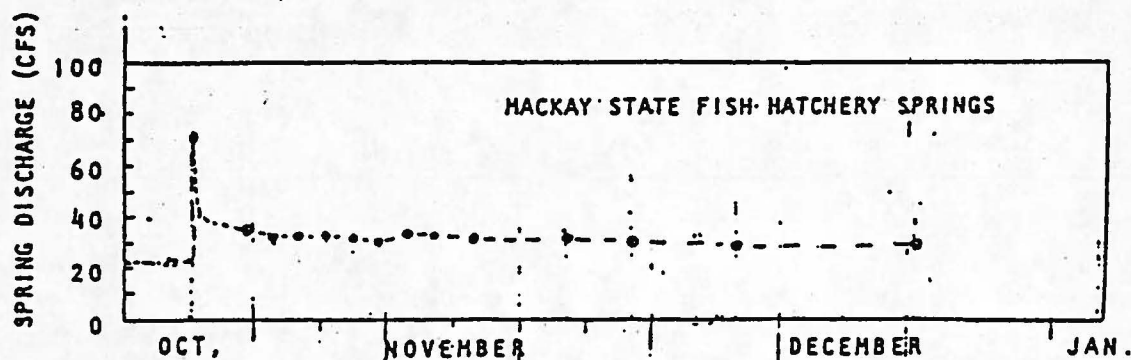


Figure 8. Hydrograph of spring flow at the Mackay State Hatchery.

but flow was increasing so rapidly that our initial structure was overtopped by mid-afternoon.. The weir was reconstructed that evening. The stage recorder showed an almost continuous increase of 1 cfs/day. The weir was again overtopped on about November 15. Flow was photographed (Fig. 10) and measured with a current meter by Richard Whitehead (USGS) at 16.5 cfs on November 14. The hydrograph of the flow recovery is shown in Fig. 11. A peak flow of 58 cfs was measured on December 23. Since then the flow has declined to about 40 cfs (Fig. 11), but appears to fluctuate seasonally.

Discharge points for the spring water rose in elevation through November and December following the earthquake. Highest points are 2 to 3 m above the pre-earthquake springs. Water flows from cracks in the bedrock and seeps from alluvium for a considerable reach of about 150 m along the stream.

Temperature of the several spring discharges varies from 86 to 95°F but the main flow is 92°F. Neither temperature nor specific electrical conductivity of the water have changed significantly since measured by Young and Lewis (1982) in 1979.

When the springs dried up following the earthquake there was great concern over the loss of an important water supply. The spectacular flow recovery and tenfold increase in flow caused severe bank erosion. It was anticipated that the increased base flow would be augmented by a spring snow-melt flow to produce flooding in Round Valley area south of Challis. About \$200,000 was spent in the late autumn to try to enlarge and stabilize part of the channel. The flood never occurred, but bank erosion of hay fields and pasture continued. The landowner, faced with costs of controlling erosion, subsequently constructed a low-gradient diversion canal along the west side of the valley, and drops the warm water flow through a penstock into an 850 kw hydroelectric plant. The project was almost complete in September, 1985. Although the hydrograph (fig. 12 suggests that the flow is gradually declining, it should sustain the power plant for several years to several tens of years, after which time it may be economic drill wells and pump water from the spring area into the canal.

Figure 9. Photograph looking south up the channel of Ingram's Warm Springs after the earthquake. Spring system is completely dried up. Dead fish are an introduced species for a hatchery operation. Photograph by Sue Villard and published with permission from the Challis Publishing Company.

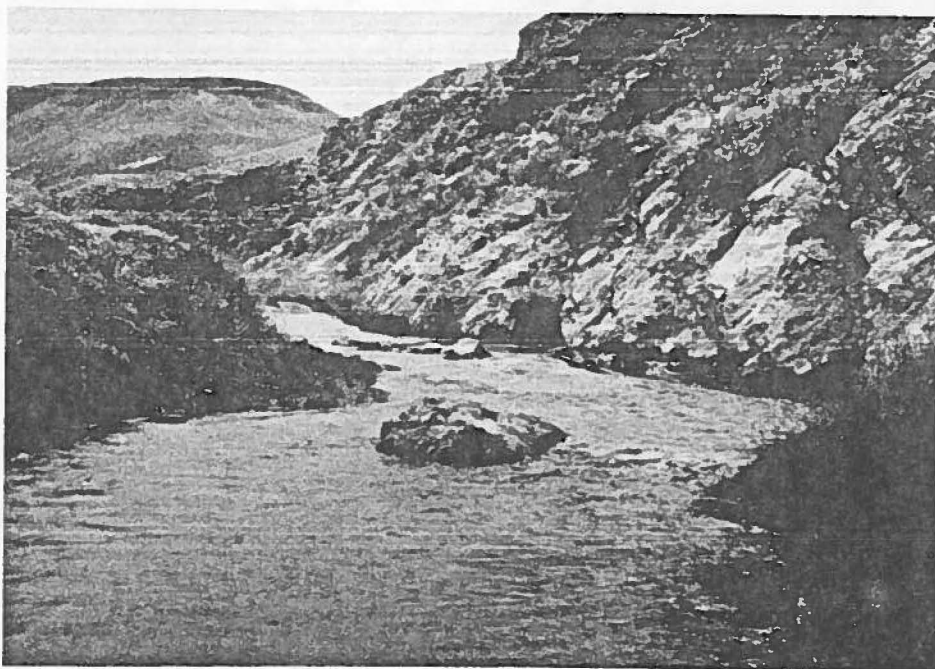


Figure 10. Photograph looking south up the channel of Ingram's Warm on November 15 when the spring had recommenced flowing at a rate of 16.5 cfs. Photograph by Richard Whitehead, U. S. Geological Survey, Boise office.

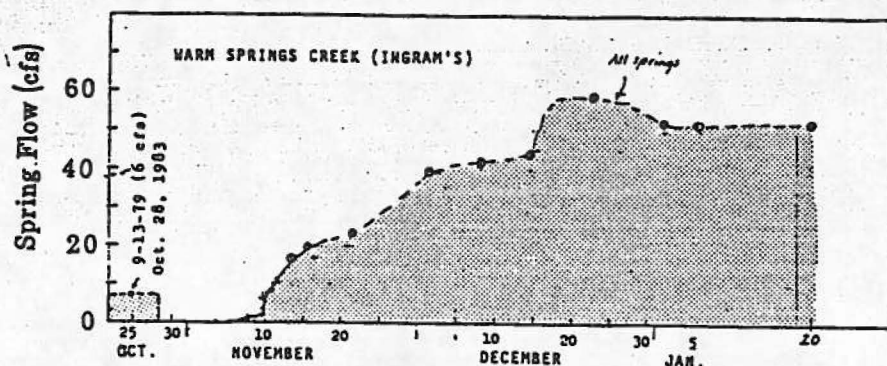


Fig. 11. Hydrograph of Ingram's Warm Springs compiled from measurements by Boise State University, the U. S. Geological Survey, and observations by W. Ingram, D. Totorica, and M. Shaleen.

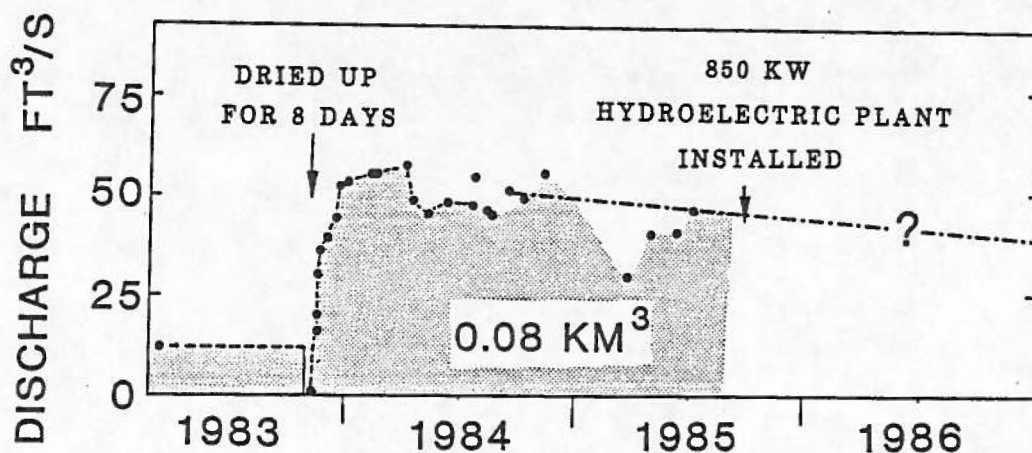


Figure 12. Hydrograph of Ingram's Warm Springs creek through August, 1985 compiled from all available measurements. Total volume of flow through mid-1985, 0.08 km^3 .

RIVER FLOWS

The best documented increase in stream flows are from the stage recorders in the Big Lost River at Howell Ranch and upstream at the confluence of the North and East forks (Fig. 3, 4, and 13). The early part of the stage record at Howell Ranch following the earthquake was lost because the strong shaking caused a slip in the cable. The recorder was reset a few days after the earthquake, and it showed an increase of about 250 cfs over a period of about 6 days, and then it leveled off. The recorder on the North Fork, about 7 miles upstream faithfully recorded the rate of flow increase following the earthquake, and shows that the stage began increasing about one day after the earthquake (Fig. 13). The increased stream discharge from 150 cfs to 400 cfs on the

This figure is not unlike those obtained during a study of the 1952 Kern County Earthquake by Briggs and Troxel (1952). They report an average yield attributed to earthquake effects of 0.28 inches (0.7 cm) over a 100-square-mile drainage within 20 miles of the epicenter, but they do not offer an explanation of the phenomena.

The increased runoff is clearly associated with the earthquake, since no significant precipitation or snowmelt events occurred during the interval from October 29 to November 4. The spike on both hydrographs, between November 5 and 10 was produced by a rainfall event (Richard Whitehead, USGS, Boise, personal communication).

Also shown on Figure 13 are the 20-year period maximum, mean, and minimum hydrographs for the North Fork gage. Runoff was clearly at a maximum this 1983 autumn, before the earthquake, and the November - December, 1983 base flows caused by the earthquake are the historical maximum flow for these months.

The earthquake-induced increased flow in the Big Lost River must be the result of increased ground-water discharge. Shown in Figure 4 are the hydrographs from Herd Creek and Thompson Creek. These hydrographs show similar effects, but when the volume of water produced through mid-April, 1984 is normalized to drainage area, the total amount of water (expressed as rainfall) attributed to the earthquake diminishes to the north. The total volume of water produced by this earthquake from the 450 m² area of the upper Big Lost River is 0.05 km³. The amount of water produced from Warm Springs Creek is about 0.08 km³. Collectively we estimate that the total amount of earthquake-induced groundwater discharge will ultimately be between 0.5 and 1 km³.

FLOODED MINE WORKINGS

A greatly increased flow of water issued from the 1100-ft level of the Clayton Silver Mine about 3 hours after the earthquake. The mine is located in a steep tributary valley of the Salmon River Canyon, about 15 miles (24 km) west of the nearest surface faulting from the earthquake (Fig. 2). By 1040 PM the 1100 ft level was flooded and pumps at that level incapacitated. Water was rising in the no. 2 shaft at a rate of 6 ft/hr. The water apparently issues from fractures between the 800 and 1100 ft levels. The no. 2 shaft was being continuously pumped at a rate of 980 gpm (62 l/s) before the earthquake in order to keep the 1100-ft-level stopes dry. The mining operation shut down after the earthquake. The water rose 195 feet in 10 days (Fig. 14) while pumping continuously at about 980 gallons per minute (62 l/s). On November 7, a 2000 gallon-per-minute pump system was installed, and the water level has been pumped back to the 1100-ft level by January 2, 1984. The mine resumed operation in the spring of 1984. The water is warm (67°F) and has a conductivity of 403 micro-mhos/cm and a pH of 6.5 ± 0.3). The temperature and conductivity indicate the water is from a deeply-percolating groundwater system, and not the near-surface groundwater system. The actual fracture system from which the water issues has not been examined but it is thought to be coming from the footwall of the fault system that controls the ore deposit. The fault trends N 11°E and dips 60° to the west.

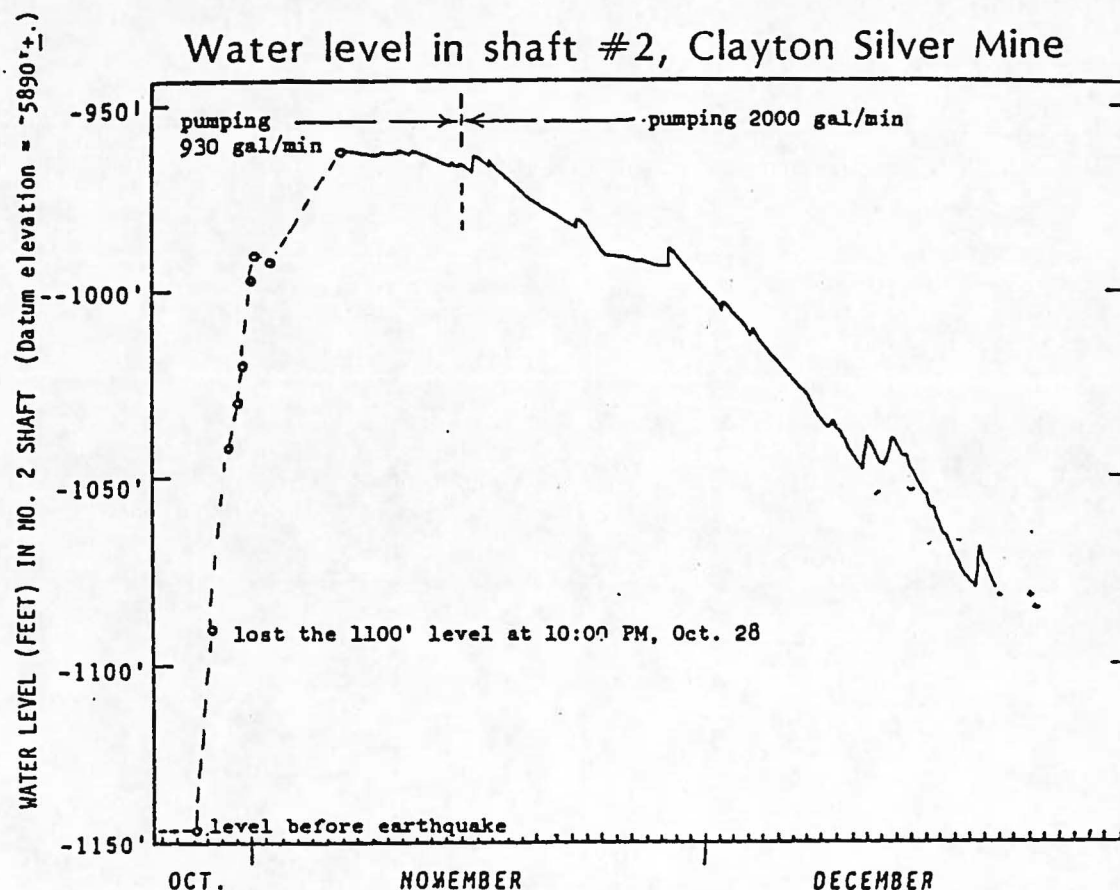


Fig. 14. Plot showing the rapid rise of water level in the Clayton Silver Mine following the October 28 earthquake, and the decline of water levels as the no. 2 shaft was pumped at 2000 gallons per minute. Water had been maintained at the 1145-ft level prior to the earthquake by continuous pumping of 980 gallons per minute. Water began to rise 3 hours after the earthquake at a rate of 6 ft/hr. The workings at the 1100-ft level were flooded by 1040 P.M. on the 28th. By November 7 the water had risen 245 feet to the 963-ft level. At that point the rise ceased and the levels started to decline slightly by pumping 930 gallons per minute. By November 15 a 2000 gallon per minute pump was installed, and the water levels began to decline at a greater rate. By December 17 the water was down to the 1080-ft level. Irregularities in the drawdown curve are caused when the pumps are at reduced capacity or are off for repairs. During the early part of the decline curve, water would rise at a rate of 0.7 ft per hour when pumps were off. During the later part of the decline curve, water would rise at 2.7 ft per hour when the pumps were off. Mine level is referred to a datum elevation of about 5890 ft at the office at the creek level below no. 1 shaft. Information courtesy of Mr. Roland Rovetto, Clayton Silver Mine.

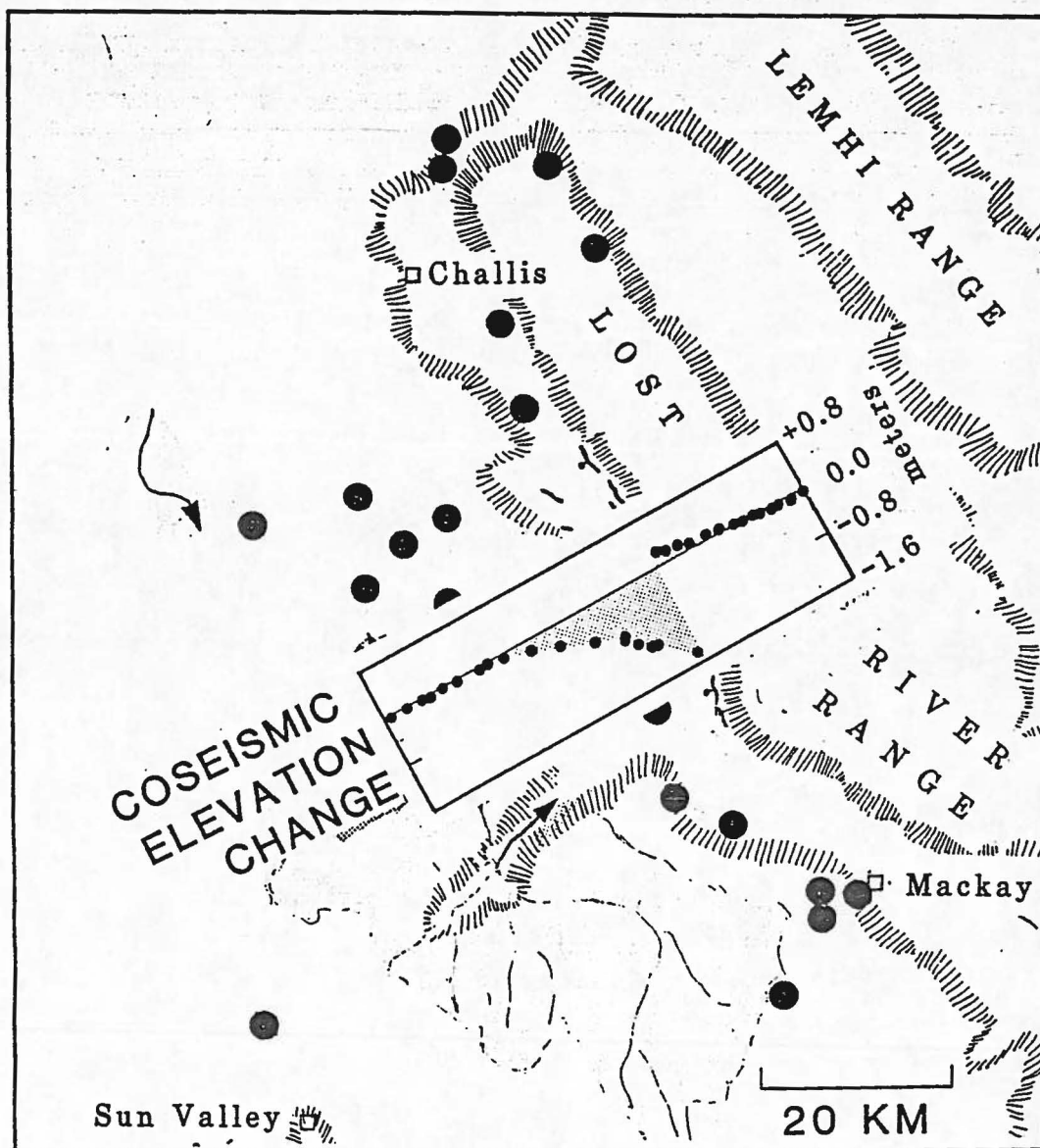


Figure 15. Profile of coseismic vertical deformation from Stein and Barrientos (1985). Black dots are increased spring flow also shown on Figure 2.

LUPINE CREEK MUDFLOW

About 2 days after the earthquake, the valley fill in upper Lupine Creek valley (Fig. 2) failed, and flowed down the valley as a rapidly moving mudflow for a distance of 3.5 km. Volume is estimated to be 200,000 cubic meters (see Keefer and others, this volume). The mudflow is significant because it was a delayed effect of the earthquake which Keefer and others attribute to increased spring flow. Their explanation is that spring discharge beneath the colluvium increased and ultimately saturated the valley fill. Increased pore pressure caused failure. A

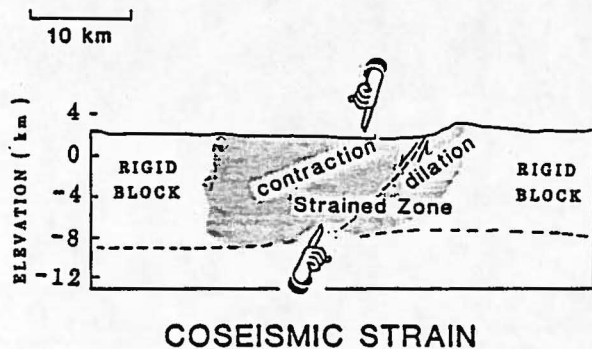


Figure 16. Cartoon showing the mechanism by which pore pressures increase as a result of release of elastic strain in an earthquake.

similar delayed earthflow also occurred 5 days after the 1959 Hebgen Lake earthquake. These are the only two such events reported in the literature, but since they both occurred in the two largest historic earthquakes in the Rocky Mountain area, this type of slope failure should be considered, for instance, in evaluation of potential earthquake hazards along the urbanized Wasatch Front of Utah. Conditions with this potential for slope failure should be recognizable.

CONCLUSIONS

Problems and hazards directly attributable to increased spring flows may be characteristic of the effects of large earthquakes in mountainous areas. The burst of water from the Chilly Buttes and large flows from the springs at the fish hatcheries may be a typical response of large spring systems in carbonate rocks near the epicenter. Similar conditions exist in urban areas along the Wasatch Front of Utah, and these flows and possible flooding should be anticipated in a large earthquake. The flooding of the Clayton Mine indicates that groundwater pressures and the flow of water into underground facilities can increase suddenly after an earthquake. This could create a hazardous situation in a critical underground facility in which the pump system was designed for a steady-state seepage into the facility. Delayed slope failures such as that which occurred at Lupine Creek are another type of hazard, because of their peculiar timing.

The widespread nature of increased discharge of groundwater indicates that a large earthquake produces significant changes in aquifer pressure. We believe that the principal cause of the phenomena described in this paper is the sudden strain of aquifer rocks that occurs during the elastic rebound process. The rocks of a part of the hanging wall of a normal fault undergo contractional strain (see Figs. 15 and 16). If this is the mechanism, the temporal and spatial pattern of the diffusion of a sudden pore pressure increase can be modeled using Theis' (1935) equations for unsteady flow in aquifers (Wood, 1985). Using equations for diffusion of instantaneous pressure increase in a permeability test published by Ferris and Knowles (1963), the spring hydrographs can be approximately modeled. The area over which spring flow and the base flow of streams increase may be a good indication of the region of strain release. In order to compare the area of these hydrologic effects with the area of strain release, we need a realistic calculation of the vertical and horizontal pattern of strain resulting from elastic rebound of a normal-fault earthquake. To the best of our knowledge that calculation is not available in the literature.