U.S. DEPARTMENT OF THE INTERIOR
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GEOLOGIC HAZARDS IN THE HELLS CANYON REGION OF IDAHO, OREGON, AND WASHINGTON

By

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INTRODUCTION

This report describes potential geologic hazards in western Idaho, northeastern Oregon, and southeastern Washington, specifically in the Hells Canyon region (Figs. 1 and 2). It is written mainly to help managers and planners in the U.S. Forest Service and other Federal and State agencies as they attempt to increase the recreational attributes of, and safety within, the Hells Canyon region. The report also can be used to educate visitors about the geologic hazards and the possible risks they impose. It is not meant to be comprehensive and I assume that potential geologic hazards exist in addition to those described here. I mention specific localities merely as examples, and expect the reader to recognize similar potential hazards that occur elsewhere in the region.

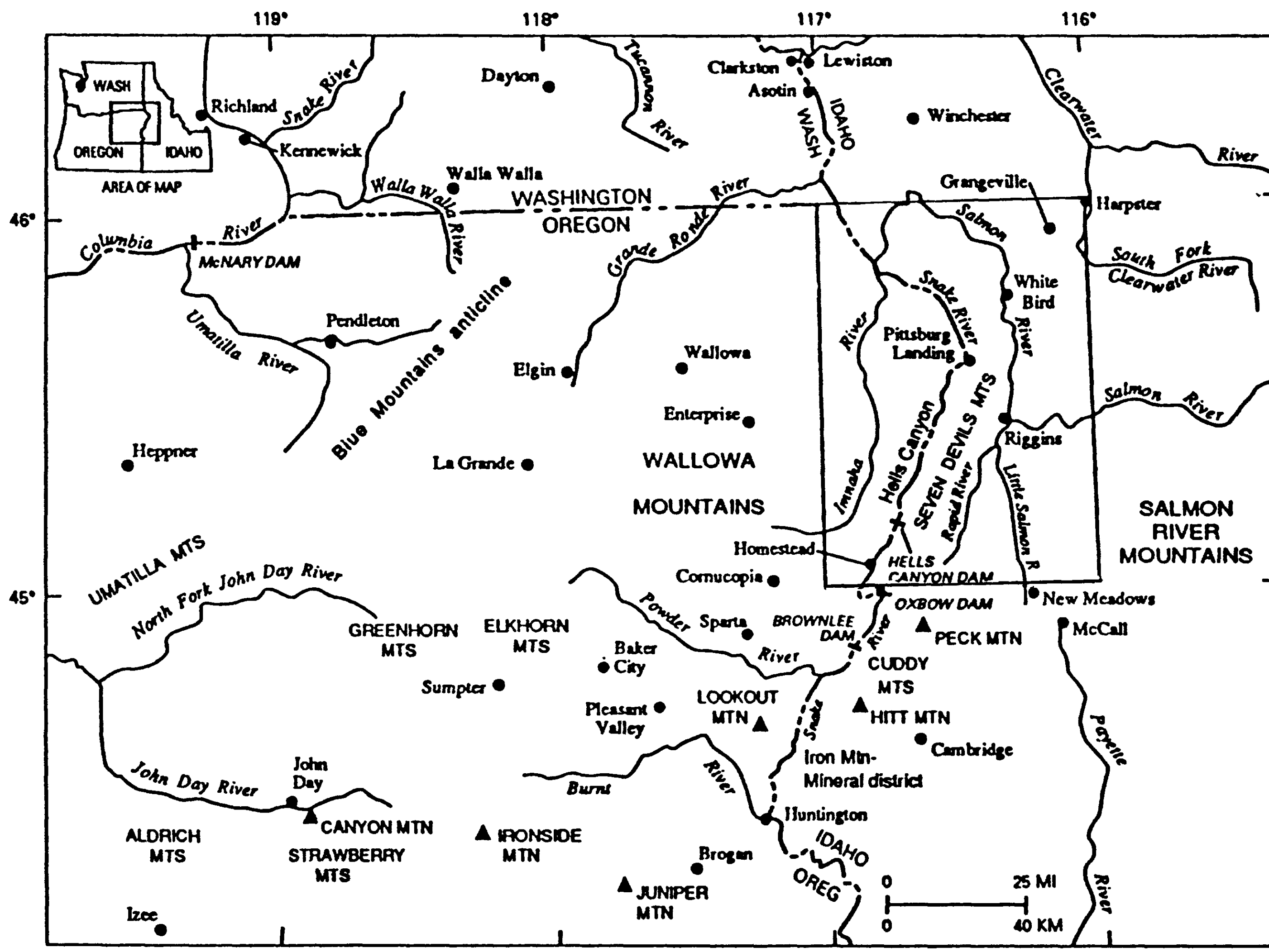

Figure 1. Map of Hells Canyon and adjacent regions of Oregon, Washington, and Idaho. Inset map shows area of Figure 2.

This report is based on field work completed during the last thirty years. My work in the Hells Canyon region has involved many diverse projects including geologic mapping, detailed stratigraphic and petrologic studies, and resource evaluation. Although I have focused on understanding the early geological evolution of the region, particularly the late Paleozoic and Mesozoic eras (i.e., 300 to 100 million years ago), I also studied the more recent (late Quaternary) landforms and the processes that are presently shaping the physiography of the Hells Canyon region. It is mainly on these latter studies that I base this report.

I define the Hells Canyon region to include the Snake River canyon and its tributary drainage areas between Oxbow Dam and the mouth of the Grande Ronde River (Figs. 1 and 2). The Hells Canyon region includes a large part of the Hells Canyon Recreation Area, most of the Hells Canyon Wilderness Area, parts of the Nez Perce, Payette, and Wallowa-Whitman National Forests, some land managed by the Bureau of Land Management, and small amounts of privately owned land. I refer to geologic processes in the Wallowa and Seven Devils mountain ranges, some parts of which are outside the Hells Canyon region, during reviews of the geologic column, glaciation, and tectonic uplift. A discussion of earthquakes includes a larger region bounded by 44°30' to 46°30' N. and 116°00' to 118°00' W.

A geologic "hazard" as defined in this report refers both to the geologic agent and to the potential for harm caused by the agent. In contrast to a hazard, "risk" exists if something of value (human life and property) is at jeopardy by the potential hazard. In the Hells Canyon region natural geologic hazards include floods, earthquakes, and slope movements (rock, debris, and earth falls, slumps, slides, and flows). Some of these geologic hazards pose significant risk to human life and property. Furthermore, past and present human activities (such as the construction of dams and roads, digging of mines, and defoliation from grazing and fires) affect the rate of geologic processes and thereby may increase risk.

The Snake River and its tributary streams are continually trying to deepen and widen their channels and canyons. In order to accomplish this, tectonic uplift and continuous erosion, combined with a large amount of time, work together to increase both the deepening and the widening. Cataclysmic or catastrophic events such as earthquakes, floods, and landslides will hasten changes in the region, but over time ranges of thousands of years, the effects from these events can be averaged and thereby minimized. With people in the canyon, however, a cataclysmic or catastrophic event is very significant because it may jeopardize human life and property.

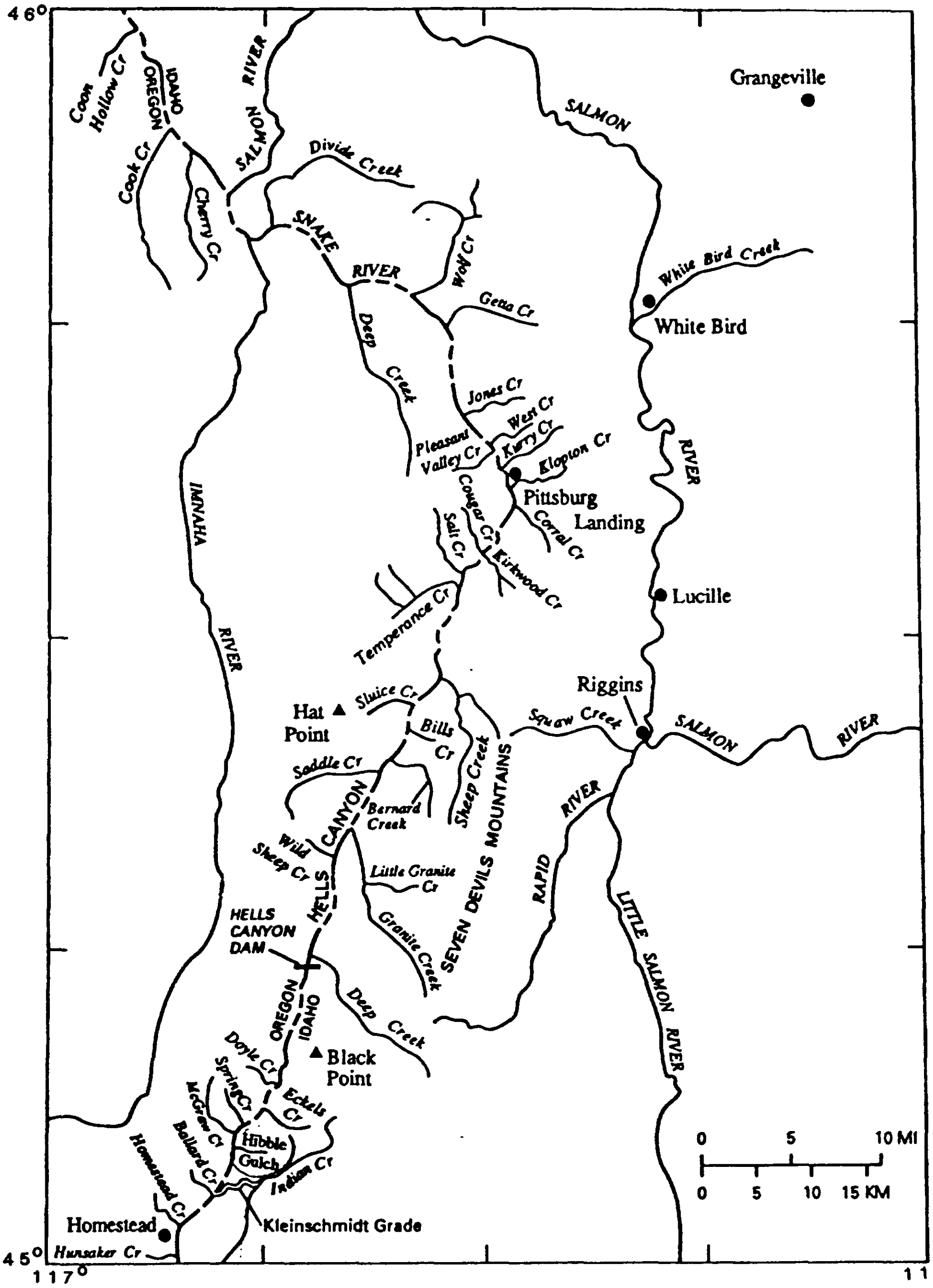

Figure 2. Map of Hells Canyon from 45° to 46° N. and from 116° to 117° W. showing most of the creeks that are discussed in this report. The reader should refer to appropriate USGS quadrangle maps for locations not shown on this figure.

In this report, I first review the general geology of the Hells Canyon region. Subsequently I discuss potential geologic hazards, specifically slope movements and earthquakes. Finally, I list some recommendations for education of the public and for further studies.

GENERAL GEOLOGY OF THE HELLS CANYON REGION

Introduction

Although geologists have been poking around Hells Canyon for more than a century, detailed studies of geology began in the early 1960's (Morrison, 1963; Vallier, 1967). Several Master's degree theses have been written, but those completed by White (1972) and Goldstrand (1987) were particularly helpful because of the included geologic maps. U.S. Geological Survey Professional Papers, compiled and edited by Vallier and Brooks (1986, 1987, 1994, and in press) and Walker (1990), contain more than forty separate chapters on the geology of the Blue Mountains, which includes the Hells Canyon region, and the mountains of west-central Idaho. Within these books, the interested reader can obtain information on the Idaho batholith of central Idaho, the Cenozoic geology of eastern and central Oregon, and the pre-Cenozoic paleontology, stratigraphy, petrology, tectonics, and mineral resources of the Blue Mountains and Hells Canyon.

Terrane Concept and Evolution of the Blue Mountains

An important contribution to understanding the evolution of rocks in the Blue Mountains region is the terrane concept. Terranes, as used in this report, refers to "tectonostratigraphic terranes" that were described by Howell et al. (1985, p. 4) as fault-bounded packages of rocks of regional extent characterized by a geologic history which differs from that of neighboring terranes. The pre-Cretaceous rocks in eastern Oregon and western Idaho were divided into five separate terranes. Silberling et al. (1984) named them the Baker, Grindstone, Izee, Olds Ferry, and Wallowa terranes. Vallier (in press) refined the boundaries (Fig. 3) and correlated the terranes to different parts of a complex island arc. Island arcs are distinctive physiographic features, particularly in the western and northern parts of the Pacific Ocean, where they form both arcuate and linear submerged mountain ranges (capped by islands) that occur above a subduction zone where two tectonic plates converge. Good examples are the Aleutian, Kurile, Bonin, Mariana, Tonga, Vanuatu, and Solomon island arcs.

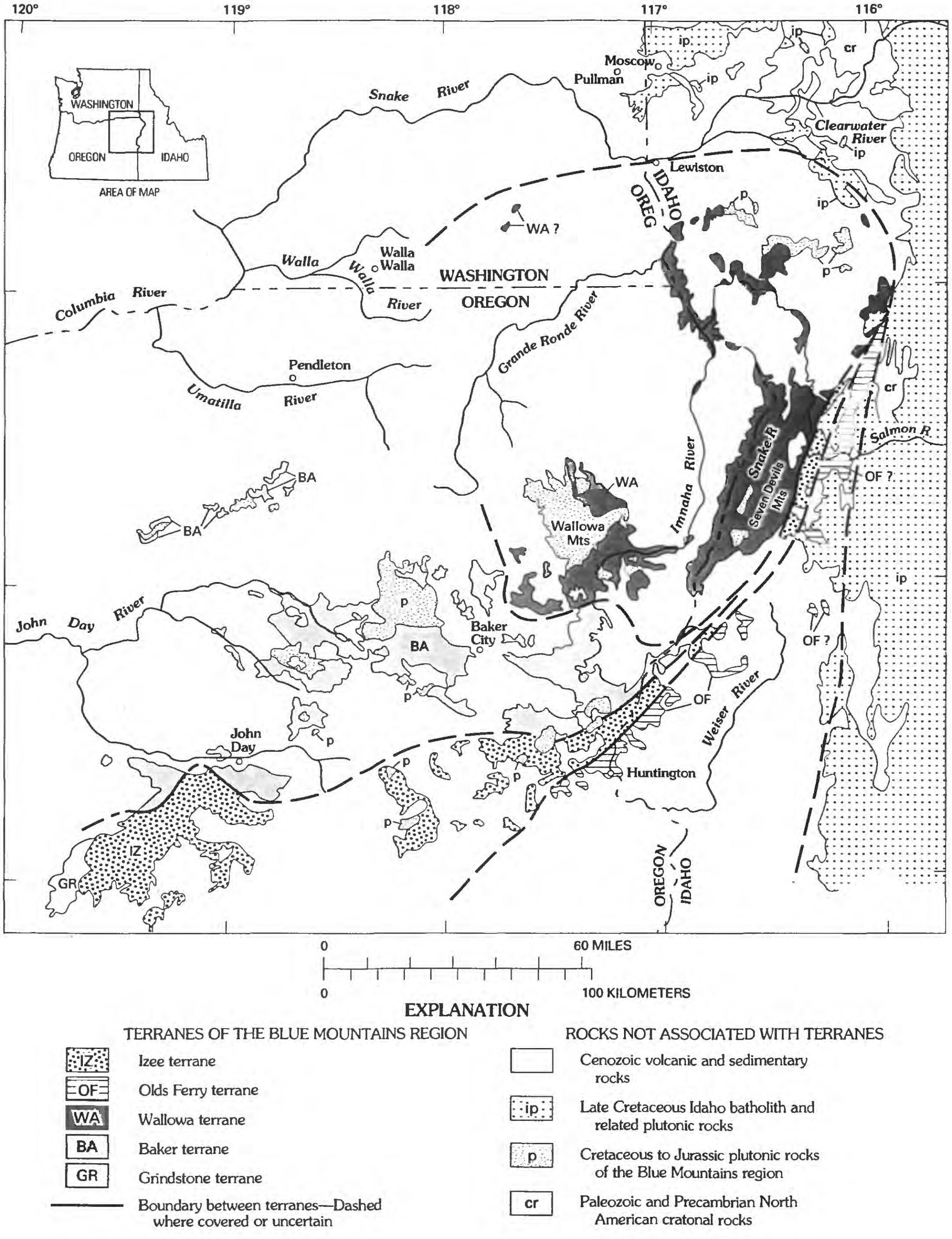

Figure 3. Terranes of the Blue Mountains region (Vallier, in press). Hells Canyon, Wallowa Mountains, and Seven Devils Mountains are in Wallowa terrane.

The Wallowa terrane, which includes the Hells Canyon region, Wallowa Mountains, and Seven Devils Mountains, formed near the magmatic axis (where volcanoes form) of an island arc. The Baker and Grindstone terranes are part of the fore-arc region (between the magmatic axis and the deep ocean basin) of the arc, and include parts of the ancient subduction zone. The Olds Ferry terrane also represents a magmatic axis of the arc. Lavas and associated plutonic rocks in the Olds Ferry terrane are somewhat younger than those in the Wallowa terrane; Vallier (in press) attributed the age and position of the terrane to renewed volcanic activity in the Blue Mountains island arc after a major change in plate tectonic vectors (direction and/or velocity). The Izee terrane is composed predominantly of sediments that were deposited in a basin that formed between the combined Wallowa and Baker terranes and the Olds Ferry terrane after that change in plate vectors had occurred. The basin was probably similar to the central basin of the Solomon Islands arc (southwest Pacific) that formed after the collision of the arc with the Ontong Java Plateau (Vallier, in press). Sediments of the Izee terrane were deposited upon older rocks of both the Grindstone and Baker terranes.

Geologic Evolution of the Hells Canyon Region, Wallowa Terrane

Rocks in the Hells Canyon region are placed in a geologic column (Fig. 4) that includes the rock unit names (formally called formations and groups) and geologic ages (Vallier, 1974; 1977; in press). The oldest known rocks in the Wallowa terrane are dikes in the Cougar Creek Complex, south of Pittsburg Landing, questionably as old as Late Pennsylvanian in age, that crystallized about 310 to 300 million years ago (Ma). Most of the rocks in the Cougar Creek Complex, however, are Early Permian (270 to 260 Ma) in age. The oldest stratified rocks (sediments, lavas, and tuffs) also are Early Permian (about 270 to 260 Ma). Rocks in the Baker terrane that crop out near Brownlee Dam, a few miles south of Hells Canyon, may be as old as 350 million years. Considering the volume of material, most volcanic activity and sediment deposition in the Wallowa terrane occurred in the Early Permian and the Middle and Late Triassic (about 235-210 Ma) intervals. Jurassic sedimentary rocks (about 190-150 Ma) record the break up, subsidence, and extensive oceanic transgression of the ancient island arc. Plutonic (coarse-grained intrusive rocks like granite) activity occurred mainly during the Early Permian, Middle and Late Triassic, and Late Jurassic-Early Cretaceous (about 145-115 Ma) intervals. Rocks older than Late Jurassic (about 145 Ma) in age are metamorphosed and deformed. The Pre-Cenozoic rocks in the Hells Canyon region are overlain unconformably by lava flows of the Miocene (mostly 17-14 Ma) Columbia River Basalt Group.

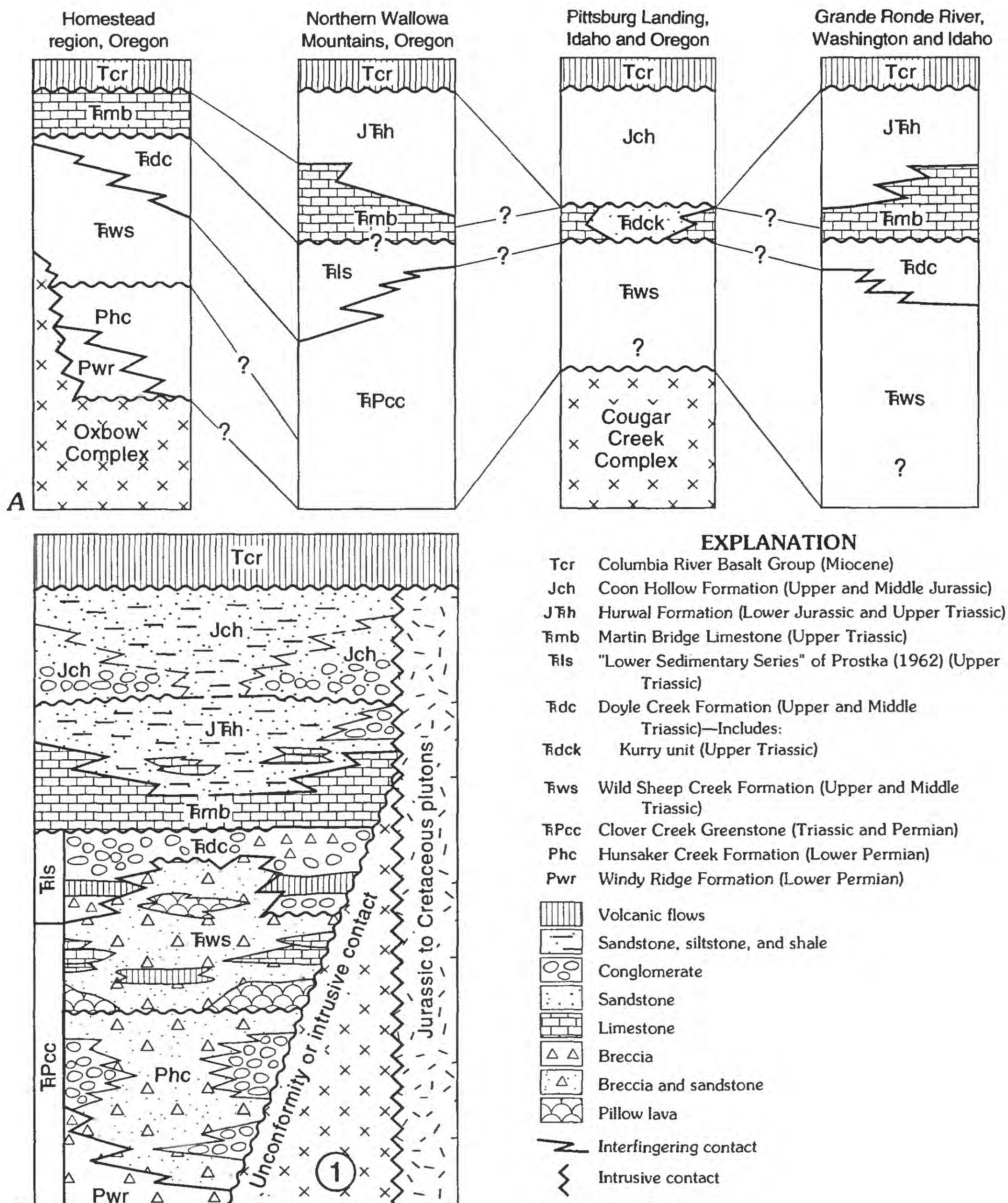

Figure 4. Geologic column for the Hells Canyon region, Wallowa terrane (Vallier, in press). The upper four diagrams show regional changes in stratigraphy.

Metamorphosed plutonic rock bodies of Permian and Triassic ages are abundant and occur throughout large parts of the Hells Canyon region. Best exposures are in the canyon south of Pittsburg Landing (Cougar Creek Complex), the Oxbow area, and between Getta Creek and the mouth of the Salmon River. Plutonic rocks also occur in the southern Seven Devils Mountains near Black Lake. Most of these coarse grained rocks range in composition from gabbro and diorite to quartz diorite. The younger, essentially unmetamorphosed, Late Jurassic and Early Cretaceous plutonic rock bodies are best exposed in the Wallowa Mountains where they comprise the Wallowa batholith.

The Cougar Creek Complex (Vallier, 1974) is a diverse assemblage of Pennsylvanian (?) and Permian dike units and small plutonic bodies that are composed of norite, gabbro, diabase, basalt, diorite, andesite, quartz diorite, trondhjemite, and rhyolite (Vallier, in press). The rocks are variably metamorphosed to the amphibolite and greenschist facies. Mylonites are common and mark zones of considerable strain related mostly to movement along strike-slip faults. Similar rocks occur in the Oxbow Complex that was mapped near Oxbow Dam (Vallier, 1967; 1974; in press).

Stratified volcanic and sedimentary rocks both overlie, and are in part intruded by, the Permian and Triassic plutonic rocks. Stratified rocks from oldest to youngest are the following (Fig. 4): Early Permian Windy Ridge and Hunsaker Creek formations; Middle and Late Triassic Wild Sheep Creek and Doyle Creek formations; Late Triassic Martin Bridge Limestone; Late Triassic and Early Jurassic Hurwal Formation; Middle and Late Jurassic Coon Hollow Formation; and the Miocene Columbia River Basalt Group. Gravels of probable Eocene (about 55 to 40 Ma) age occur on high structural terraces above the mouth of the Grande Ronde River.

Unconformably overlying the pre-Miocene (mostly Permian, Triassic, and Jurassic) rocks in the Hells Canyon region are flows of the Columbia River Basalt Group. These flow rocks, mostly of Middle Miocene age (most were erupted about 17 to 14 Ma, although some flows near Asotin, Washington are as young as 6 million years old), comprise a thick volcanic pile that at one time completely covered the older rocks. The flows were extruded onto a deeply eroded landscape that had a regional relief of about 1,000 to 2,000 feet. Late Miocene through Holocene tectonic uplift and erosion stripped off the thick sequence of lava flows from the Wallowa and Seven Devils mountains and along most parts of the Snake River canyon between Oxbow Dam and Getta Creek and from a few miles east of the mouth of the Imnaha River to the mouth of the Grande Ronde River. During uplift the Snake River and its tributary streams cut deep canyons. Large uplifted blocks, bounded by faults, became the Wallowa, Cuddy, and Seven Devils mountain ranges.

Quaternary Geology

Quaternary (last 1.8 million years) geology includes both the Pleistocene (greater than about 12,000 B.P. (Before Present)) and the Holocene (approximately the last 12,000 years). The Quaternary epoch was the time of extensive continental glaciers throughout the world's northern hemisphere. Holocene is the time after the retreat of the last great North American continental ice sheet and also marks the time of human migration into western North America. Most Quaternary sediments in the Hells Canyon region were deposited in the very late part of the Pleistocene and Holocene (throughout the last 20,000 to 15,000 years). Glaciers, floods, and volcanic eruptions from Cascade volcanoes have been significant factors in the evolution of late Pleistocene landforms, particularly those that occur along the river and at the mouths of tributary streams.

Glaciers. There are at present no glaciers in the region, but mountain glaciers occurred in both the Wallowa and Seven Devils mountain ranges during the last ice age. Some geologic processes were intensified during glaciation. For example, as the glaciers of central Idaho melted, increased volumes of water flowed through the Snake River and many of its tributaries. Wide U-shaped valleys, similar to the valley in the upper part of Granite Creek of the Seven Devils Mountains, were carved into the mountain sides by the glaciers.

Continental glaciers covered large parts of North America at least four times during the Pleistocene. Deposits left after the melting of these glaciers are well exposed along road cuts and stream banks in the midwestern states of Nebraska, Kansas, Iowa, Illinois, Minnesota, Wisconsin, and Indiana. Alpine glaciation, prevalent in the mountainous areas of the western U.S., did not leave a similar sedimentary record because high erosion rates, that are common to such rugged regions, destroyed the older deposits before the growth of the next glacier. I have not mapped glacial deposits older than the last glacial stage (Wisconsin) in the Hells Canyon region, but I suspect that some exist.

Alpine glacial deposits occur in many of the valleys that incise the Seven Devils Mountains. The upper parts of Granite, Little Granite, and Sheep Creeks show both erosional (U-shaped valleys) and depositional (moraine materials) results from alpine glaciers. Upper reaches of the Imnaha River and some of its tributaries in the southern Wallowa

Mountains also show the effects from glaciers. The most spectacular features of alpine glaciation in the region, however, are the lateral and terminal moraines that bound Wallowa Lake near Joseph, Oregon and the deep U-shaped valleys that cut through the steep escarpment bounding the northern Wallowa Mountains.

The effects of glaciation on the Snake River and its tributaries are important because melt waters must have hastened the widening of the canyon and greatly modified its channel, particularly during stages of melting. Landslides and debris flows probably dammed the river and its tributaries. When those temporary dams broke, floods must have cascaded through the canyons. The climate also was modified during the glacial stages; at times increased rainfall sent more water down the streams for a significant length of time, possibly for hundreds of years.

Bonneville Flood and Other Floods. The Bonneville Flood (Malde, 1968) was probably the most spectacular geologic event that occurred in the Hells Canyon region during the last 15,000 years. Ancient Lake Bonneville (ancestral Great Salt Lake) discharged about 4,750 km^3 of water over the divide at Red Rock Pass into a tributary of the Snake River about 14,500 years B.P. (O'Connor, 1990). Peak discharge was approximately 1×10^6 m^3/sec at the outlet point. Downstream in Hells Canyon peak discharge decreased to less than 0.6 million m^3 per second. The flood left many erosional and depositional features along the Snake River canyon. One spectacular erosional feature in Hells Canyon is near upper Pittsburg Landing where a wind gap (wind now blows through the slot where water previously flowed) nearly 600 feet above the river marks the upper level of the flood waters. At the Oxbow, two wind gaps (west gap has the Brownlee-Oxbow road running through it) indicate that Bonneville Flood waters overflowed the peninsula-like prong that juts out to the northeast.

O'Connor (1990) divided the Snake River canyon below Hells Canyon Dam into three segments and estimated the mean depths, discharges, and velocities of the Bonneville Flood (as noted above, flood water discharge was approximately 1×10^6 m^3/sec at the spillover):

Segment 1. *Bills Creek to Pittsburg Landing* (river miles 234-214); depth, 170 meters (557 feet); discharge, 0.57×10^6 m^3/sec (20×10^6 ft^3/sec); velocity, 13.8 m/sec (30.8 m.p.h.).

Segment 2. *Pittsburg Landing to Salmon River* (river miles 214-188); depth, 187.6 m (615 feet); discharge, 0.57 x 10^6 m^3/sec (20 x 10^6 ft^3/sec); velocity, 15.9 m/sec (35.6 m.p.h.).

Segment 3. *China Garden to Lewiston* (river miles 176-141); depth, 114.4 m (375 feet); discharge, 0.57 x 10^6 m^3/sec (20 x 10^6 ft^3/sec); velocity, 14.5 m/sec (32.4 m.p.h.).

Maximum Snake River flood discharges in historic time are estimated to have been about 100 x 10^3 ft^3/sec before the dams were built (compared to a maximum discharge of 20 x 10^6 ft^3/sec for the Bonneville Flood in Hells Canyon--about 200 times greater). The velocity of 7 to 8 m.p.h. during historic floods is slow compared to the 30-35 m.p.h. velocity calculated for the Bonneville Flood.

Other floods have greatly affected the Columbia Basin of eastern and central Washington. Geologists who studied effects of the Missoula Flood (also referred to as the Spokane and Bretz floods) suggest that at least 40 cataclysmic floods swept across large parts of the Columbia River drainage basin after the Bonneville Flood, but prior to about 12,800 years B.P. (Allen and Burns, 1986). Good evidence for one or more of the floods entering the Snake River canyon can be seen in the gravel quarry along Snake River Avenue near Hells Gate State Park just a few miles south of Lewiston where sand and silt deposits from the Missoula Flood overlie Bonneville Flood boulders, cobbles, and gravels. The older Bonneville Flood deposits dip steeply downstream, whereas beds of the overlying Missoula Flood sediments dip upstream, showing that the currents were flowing south. According to Gary Webster (oral commun., 1990), Missoula Flood waters probably flowed southward into the Snake River canyon as far upriver as Pittsburg Landing.

The Missoula and Bonneville floods aren't the only floods that affected the Snake River canyon. Glaciers and slides (rock and debris) dammed the river and many of its tributaries, particularly during the times of glacier melting, thereby making temporary dams that subsequently broke and flooded the stream channels. This will happen again in the region.

Mazama Ash. Mazama ash is a direct result of the cataclysmic eruption of Mt. Mazama in the Cascade mountain range about 6,800 years ago (Bacon, 1983). The mountain top collapsed after the eruption and the resultant deep caldera holds Crater Lake. The eruption of Mt. Mazama was at least ten times more powerful than the 1980 eruption of Mt. St. Helens.

White and beige Mazama ash deposits are easily recognized in the Hells Canyon region. The deposits are particularly noticeable on alluvial fans where the ash was concentrated by debris flows after it had been eroded from the surrounding hillsides. Older volcanic ash deposits probably occur in the canyon, but I have not yet observed two ashes in any one outcrop that would indicate an eruption older than Mazama.

Volcanic ash accumulates on hillsides like snow. Subsequent (and contemporaneous) rains erode these deposits, which flow down the intervening streams. In places, the ash might temporarily dam the stream channels. After the dams break, resultant flows of mud and other debris cascade down the channels and spread out on alluvial fans where the stream gradients are reduced. If the main stream channel of an alluvial fan is filled with ash, the stream may cut a new route, thereby abandoning the original filled channel and preserving the ash deposit. Many of the thick ash deposits on alluvial fans in the Hells Canyon region were formed and preserved by these processes.

When one of the Cascade volcanoes (probably Mt. Hood or Mt. Ranier) explodes violently like Mt. Mazama, the Hells Canyon region will once again be cloaked with ash; water-saturated flows of ash and other debris will cover alluvial fans and choke tributary stream channels. Large eruptions from these ominous volcanoes will happen, but we are not able to predict when they will occur. However, volcanic ash definitely is a potential geologic hazard in the Hells Canyon region.

The Erosion of Hells Canyon

Wheeler and Cook (1954) concluded that at one time the Snake River was a tributary of the Salmon River. According to their interpretation, the Snake River eroded headwards and captured an ancient lake (Lake Idaho) that from about 8 Ma to 2 Ma covered most of the Snake River plain; the resultant flood from this capture made the Snake River the major river and Salmon River became a tributary. If their scenario is correct, then this capture took place about 2 million years ago (equivalent to the youngest deposits of old Lake Idaho). Therefore, the Snake River as the dominant river of the region is about 2 million years old. I suspect that much of the present depth of the canyon was cut during the last 2 million years, but there definitely was a Snake River canyon of some kind before then. I presume that the river eroded the canyon during the last 6 million years, but that most erosion occurred during the last two million years.

GEOLOGIC HAZARDS

Although floods and volcanic ash are potential geologic hazards, slope movements and earthquakes are the major geologic hazards in Hells Canyon. The effects from slope movements and earthquakes include the damming of streams (with subsequent floods), inundation of campgrounds by rock and mud debris, ground shaking, and abrupt rupture of rocks. These potential geologic hazards pose risk to both the lives and the properties of visitors and residents within Hells Canyon and along the river below it.

Slope Movements

"Slope movement" is used as a general term to describe all types of mass wasting. In general, slope movement includes the down-slope movement of material that ranges from fine-grained, sediment-loaded streams, to rock falls. The most easily recognized slope-movement process is landsliding. There are several methods used for classifying slope movements and landslides. In this report I use a modified version (Table 1) of the widely accepted classification of Varnes (1978). The complete classification is more cumbersome than some and I recommend that concerned engineers and managers consult the original article for more details. As described in this report, the various types of slope movements are very significant present-day hazards in the Hells Canyon region.

Table 1. Classification of Slope Movements (modified from Varnes, 1978). The original classification of Varnes (1978) under "Types of Movements" includes other types that did not seem necessary to discuss in this report. For example, the category "Topples" appears between "Falls" and "Slides".

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Coarse	Fine
FALLS		Rock Fall	Debris Fall	Earth Fall
SLIDES	*ROTATION*	Rock Slump	Debris Slump	Earth Slump
	TRANSLATION	Rock Slide	Debris Slide	Earth Slide
FLOWS		Rock Flow	Debris Flow	Earth Flow
COMPLEX		Combination of Two or More Types of Movement		

Rock and Debris Falls. A rock fall (Table 1) will occur when the large rock mass finally gives way that is hanging precariously above the river in Oregon near what is locally called the Eagle's nest (Fig. 5). Altered rocks around the base of the rock mass suggest that it could occur at any time. Another precarious rock mass hangs above the boat ramp below Hells Canyon Dam in Idaho (Fig. 6).

All steep canyon walls are susceptible to rock and debris falls, whether they lie along the river and reservoirs or bound the tributary streams. Rock and debris fall occur with surprising regularity. Their abundance can be assessed by traveling the Idaho Power Company road between Oxbow, Oregon and Hells Canyon Dam. Nearly every morning rocks on the road indicate that they had fallen during the preceding night. Deep indentations in the asphalt testify to the large size of some boulders.

Particularly susceptible to rock and debris falls are the abrupt and sheer canyon walls on the Idaho side of the reservoir from Limepoint Creek on the south to a point north of Hells Canyon Dam, approximately as far as Brush Creek. In many places, the deeply weathered strata dip 30^{o} or more toward the reservoir; they could abruptly move downslope, particularly when bedding planes are saturated with water. Furthermore, wherever the Idaho Power Company road is cut deeply into the steep walls and cliffs (e.g., just south of Eagle bar and between Limepoint Creek and Kinney Creek), the likelihood for rock and debris falls to occur is increased. Below the dam in Oregon, steep slopes and cliffs bound the road that leads to the USFS Hells Canyon visitor center. Along this road rock and debris falls should be expected. Sustained rainfall and (or) earthquakes will encourage abrupt slope failures and lead to a plethora of rock and debris falls.

Rock and Debris Slumps and Slides (Landslides). Landslides (both rock slides and debris slides) are a significant geologic hazard in the Hells Canyon region. The steep walls of the Snake River canyon and its tributary canyons indicate that landslides have occurred in the past and that they should be expected in the future. In addition, shaking induced by earthquakes and times of increased rainfall will influence the frequency of landslides. The difficulty, however, is predicting when and where they will occur.

An outstanding example of a rock and debris slide (in part a rotational slump) occurs along Oregon State Highway 86 between Halfway and Baker City, Oregon (Jacobson et al., 1985). During earthquakes in 1984, the north wall of Powder River canyon failed. Lava flows of the Columbia River Basalt

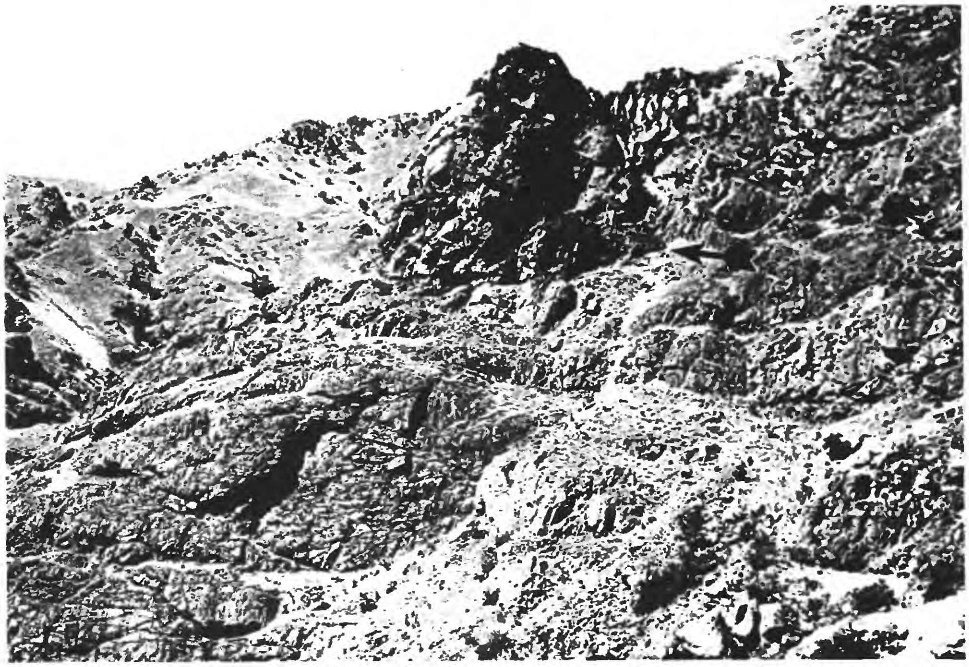

Figure 5. Large rock body hangs precipitously above the trail near Eagle's nest in Oregon. Rocks under the rock mass are highly altered. Arrow points to slip plane.

Figure 6. Large rock mass hangs above the boat launch area below Hells Canyon Dam. Bedding planes parallel the slope and dip towards the river.

Group broke loose and slid downward along a water-saturated surface that exists between the younger basalt flows and the older plutonic rocks of the Sparta complex.

Evidence of past rock and debris slumps and slides (landslides) give us a glimpse of what will occur in the future. Vallier and Miller (1974) discussed some ancient and modern landslides along the Snake River between Huntington, Oregon and the Hells Canyon Dam. A very significant landslide deposit, for example, lies along the Snake River south of the Hells Canyon Dam at Big Bar. This landslide deposit is almost entirely covered by waters of the Hells Canyon Dam reservoir; a small island marks the top of the landslide. Large landslide features also occur elsewhere in Hells Canyon. In Hells Canyon between Marks Creek and Waterspout Creek a large slump (and landslide) moved down slope; parts slid into the river from the Oregon side and apparently dammed the river. Some of the rock debris still exists on the Idaho side, at least 200 feet above river level, and debris that remains in the river forms Waterspout rapids. An eroded terrace far above the river marks an ancient slump scar. Its presence confirms that the area could move down slope again.

Large landslide deposits occur along the Snake River at Rush Creek (Fig. 7) and on the Idaho side of the river at upper Pittsburg Landing (White and Vallier, 1994). Smaller landslide deposits are at Johnson Bar south of Sheep Creek and at High Bar just north of Willow Creek. At High Bar the landslide deflected the river channel to the west. A landslide deposit forms a base for the abandoned hay fields and pastures of Walter's ranch in the upper reaches of Big Canyon Creek a few miles northeast of Pittsburg Landing.

Pre-historic landslides are difficult to date. The most precise method for determining landslide ages in Hells Canyon would be through use of the radiocarbon method, which is fairly reliable to about 65,000 years B.P. Suitable carbon for dating, however, is extremely difficult to find in these features and, to my knowledge, the method has not yet been used for dating the landslides. Therefore, I have relied on relative methods of dating. In the Hells Canyon region, two fairly well-understood and regionally dated (radiocarbon methods used elsewhere in the Pacific Northwest) events assist in the interpretations. The Bonneville Flood occurred about 14,500 years ago (O'Connor, 1990) and left gravels and boulders in terraces deposits along the banks of Snake River. The cataclysmic eruption of Mount Mazama took place about 6,800 years ago (Bacon, 1983) and left ash beds on landslides and within alluvial fans; some are well preserved.

Therefore, if Bonneville Flood waters overtopped and rounded a landslide feature (e.g., Big Bar, High Bar, and the large landslide near upper Pittsburg Landing in Idaho), I conclude that the landslide occurred more than 14,500 years ago. If landslide deposits occur between Bonneville Flood sediment deposits and Mazama ash (e.g., landslide deposit at Rush Creek), then the down-slope movement occurred between 14,500 and 6,800 years ago. If the landslide deposit was not rounded off by Bonneville Flood waters and there is no Mazama ash on the deposit, then the landslide probably occurred during the past 6,800 years.

Landslide potential exists in many places along the Snake River and its tributary canyons. Places for particular monitoring from south to north along the canyon are the following: 1) the Woodhead Park area near the Brownlee Dam where a one-meter scarp marks the beginning of a landslide (Mann, 1989); 2) at Big Bar (Vallier and Miller, 1974) along the Hells Canyon Dam reservoir where an oversteepened canyon wall in Oregon has strata dipping steeply towards the river; 3) the area between Eagle Bar and Brush Creek in Idaho south of Hells Canyon Dam where steeply dipping strata hang precipitously above the Idaho Power company road and the Hells Canyon Dam reservoir; 4) the area between Marks and Waterspout creeks in Oregon, already greatly weakened by a large slump, could fail again during a strong earthquake; 5) the Bills Creek to Sheep Creek area in Idaho where an ancient thrust fault deformed and weakened the rocks, thereby making them susceptible to downslope movements (Rush Creek and Johnson Bar landslides are the result), and 6) the upper Pittsburg Landing area in Oregon across from the mouth of Klopton Creek where present-day downslope movements are apparent.

Rock and Debris Flows. Rock, debris, and earth flows probably are the prevalent and, therefore, the most hazardous type of slope movements. They can form in a variety of ways. For example, abundant rain falling on easily eroded soil can trigger a debris or earth flow when the rocks and soils become water-saturated. This often happens during heavy and persistent rains after forest and grass fires. In places, oversteepened canyon walls of a tributary stream may slough off into the channel and form a temporary dam. When the dam breaks, the increased volume of water erodes the bottom and sides of the channel, carrying large amounts of rocks and other debris. Unfortunately, these rock and debris flows do not form only during a rain storm or the rapid melting of snow. A rock fall or slide may form a temporary dam at any time. A possible triggering mechanism, besides excess moisture, is a strong earthquake. An earthquake of large magnitude, in fact, could cause temporary damming of several streams.

Results of a rock flow can be observed between Whitebird, Idaho and Pittsburg Landing where the road descends through a series of switch backs into the Pittsburg Landing area. Loose, angular boulders of basalt hug the steep sides of the roadway and threaten the integrity of the road. The rock flow cascaded downslope from the rugged, and deeply weathered, outcrops of Columbia River Basalt flows that still loom ominously far above the road.

Many rapids in the Snake River were formed by rock and debris flows. Water-saturated debris (rocks and soils) cascaded down canyons of tributary streams, crossed the alluvial fans, and either partially or totally filled the Snake River channel. In most places where rapids are near the mouth of a tributary stream, the boulders that produced the rapids reached the river channel as either a rock flow or a very coarse-grained earth flow. Rock and debris falls in tributary canyons probably generated the flows that subsequently cascaded down the valleys, across the alluvial fans, and into the river. These water charged rock and debris flows are commonly referred to as "waterspouts" and "blowouts." In August, 1993 a debris flow plunged down Quartz Creek (major creek just south of Temperance Creek in Oregon) and reached the Snake River. Steep walls and highly altered rocks (note the orange and ocher colors) along the north side of Quartz Creek make future debris flows probable.

Most alluvial fans in the canyon formed by deposition of materials from rock, debris, and earth flows. During these cataclysmic events a debris-filled stream channel loses velocity and momentum as it reaches the top part (apex) of the alluvial fan, because the gradient of the channel is dramatically reduced at that point. The pre-existing main channel across the alluvial fan may be too small to contain the debris and thereby overflows. The flow subsequently spreads across the fan and, consequently, a new channel in the fan may be eroded. A good example of an alluvial fan with a deep stream channel, eroded after one or more major debris flows, is at Wild Sheep Creek (Fig. 8).

Debris and rock flows are potentially one of the most dangerous geologic hazards in the canyon because campers and boaters use alluvial fans for picnics and overnight stays. A water-saturated debris flow, traveling at a speed of 10 to 20 miles per hour, could arrive at an alluvial fan in only a few seconds after its initiation. There would be no warning except for a loud roar just before it hits the camp. Particularly during earthquakes and times of excessive rain, rocks could cascade off steep canyon walls of the tributary streams and form a rapidly moving rock flow.

Figure 7. Looking south at the river terraces near Johnson's Bar. Arrow points to landslide remnant at Rush Creek.

Figure 8. Alluvial fan at the mouth of Wild Sheep Creek. Deep channel is cut into the debris-flow fan.

Earthquakes

A thorough discussion of earthquakes is beyond the scope of this report and the reader is encouraged to seek textbooks and journal articles for a better understanding. A recent contribution on seismicity in the region (Zollweg and Wood, 1993) presents a thorough review. Their report contains earthquake tables, figures, and maps that are not duplicated in this report. I suggest that the interested reader obtain a copy of that report either from the authors or from the Idaho Power Company.

This section on earthquakes is designed to familiarize the reader with some of the measurements of earthquake intensities and magnitudes and with the possible risk that earthquakes pose in the Hells Canyon region. Expected damage (and risk) generally is related to the magnitude (strength) of the earthquake. However, the total time period of shaking is important as is the strength of the rocks and sediments through which earthquake waves pass.

Definition and Measurement. An earthquake occurs when the ground noticeably trembles or shakes. The origin of an earthquake may be either natural or man-made. We discuss only the natural earthquakes, although such events as sonic booms, dynamite explosions, and nuclear blasts can also cause earthquakes.

The relative strength (energy) of an earthquake is measured by two methods: intensity (I) and magnitude (M). Intensity is a qualitative measurement based on a XII point scale (the modified Mercalli Intensity Scale of 1931 is the one most widely used) that is related to the amount of shaking and damage. Intensity measurements are based on happenings during an earthquake and are based on the qualitative judgments of observers. Magnitude, as explained below, is a quantitative method of measuring the size or strength of an earthquake.

Although seismometers have been used to describe ground motion for more than 100 years, it has been only since C.F. Richter designed a logarithmic scale in 1935 that we've been able to precisely measure the size (or magnitude) of an earthquake. The magnitude (M) of an earthquake, as originally defined, is derived from a simple formula using the logarithm of the maximum amplitude (A) on a seismogram trace + 3 times the logarithm of the distance (D) to the epicenter in kilometers - 3.37; i.e., $M = \log A + 3 \log D - 3.37$. Now, however, the measure of magnitude has become more sophisticated and seismologists measure magnitudes of surface waves (M_S), body waves (M_B), and moment (deformation at earthquake source, M_W). In most case, these three are similar. Intensities and surface wave magnitudes can be roughly correlated using a formula $M_S = 1.3 + 0.61I$. An approximate correlation of Intensity and magnitude (M_S) is given in Table 2.

Table 2. Approximate Correlation of Intensity and Magnitude (modified from Reiter, 1990).

Intensity	Effects	Magnitude (M_S)
III	Felt noticeably indoors; standing cars move	3.0
IV	People awakened; windows rattle	3.75
V	Windows are broken, pendulum clocks stop	4.35
VI	Felt by everyone; many frightened, objects are upset	5.0
VII	Everyone runs outdoors; felt in moving cars	5.5
VIII	General alarm; damage to weak structures; monuments and walls fall down	6.0

There are many problems in locating earthquakes and in measuring their intensity and (or) magnitude. In western Idaho and eastern Oregon, for example, there is an insufficient number of seismograph stations. Incorrect velocity models, used for calculating travel times, are often used in a geologically complex and rugged terrain like the Hells Canyon region. In addition, there just haven't been very many people living close to the epicenters for recording the intensity of shaking when an earthquake occurs. For example, if an earthquake of magnitude 3 to 4 were to occur in the Seven Devils or Wallowa Mountains in the winter, it probably would not be reported because the distance to a ranch or town would be great enough to dampen the earth movements such that they would not be felt.

History of Earthquakes in the Hells Canyon Region. Several earthquakes have been recorded in the Hells Canyon region (Fig. 10). Particularly abundant are those in the Cuddy Mountains, Oxbow, and Pine Valley areas (Mann, 1989; Mann and Meyers, 1993; Zollweg and Wood, 1993). Some earthquakes are associated with movement along faults that may be related to the Olympic-Wallowa Lineament (OWL) of Raisz (1945) which can be traced as a linear feature from western Idaho through northeastern Oregon, south-central Washington, and possibly through Seattle. The Olympic-Wallowa Lineament is a wide zone of northwest-trending faults and is associated with several pull-apart basins, that include

Pine Valley, Baker Valley, and the Grande Ronde Valley (Mann and Meyers, 1993). Without a doubt, however, the most susceptible area for earthquakes in the Hells Canyon region (Zollweg and Wood, 1993) is in a northwest-trending zone between Cambridge, Idaho and Halfway, Oregon (area defined approximately by Sturgill Peak, Cuddy Mountains, Oxbow Dam, Brownlee Dam, and Pine Valley near Halfway, Oregon).

Table 3 lists earthquakes that have been reported through 1992. It is incomplete and additional data can be found in the report by Zollweg and Wood (1993), who added a large amount of data from records of the Blue Mountains Observatory (near Sparta) in the 1962-1967 time interval..

The Pine Valley-Cuddy Mountain region has experienced many earthquakes during this century (Figs. 9 and 10). The largest earthquakes have Intensities of V and VI (comparable to magnitudes of 4.0 to 5.0) and measured magnitudes of 4.2 and 4.3. The 1913 earthquake centered near Cuprum, just north of Oxbow, caused moderate damage (Mann, 1989). Two earthquakes of Intensity V occurred along the sides of the Pine Valley pull-apart basin. A swarm of M=2.8-3.3 earthquakes occurred in the Brownlee Reservoir area between November, 1989 and January 4, 1990. After reports of earthquakes by residents near Brownlee Dam in November and December of 1989, we set out a six-instrument portable seismograph net that recorded three well-located microearthquakes; although the positioning of the seismographs were not sufficient to accurately pinpoint the epicenter, two epicenters are located close to the Brownlee fault, just east of Brownlee Dam (Mann and Meyers, 1993).

Identification of "Active Faults". I consider faults to be "active" if either earthquakes have occurred along them in the historic past (about last 100 years) or it can be shown that displacement along the fault took place during the Holocene (approximately the last 12,000 years). In order to demonstrate that faults have been active during the Holocene, it generally is necessary to either show that there is an escarpment associated with the fault's last movement, or demonstrate that sediments of Holocene age have been offset along the fault trace. In very rugged areas, fault scarps can be eroded in only a few hundred years. Furthermore, many suspected "active faults" have no Holocene sediments along their trace. This is particularly true in areas like Hells Canyon where rugged relief promotes erosion rather than deposition and preservation of sediment bodies. In addition to radiometrically dated carbon that might be found in sediments along a fault trace, well-dated volcanic ash also can be very useful. For example, if Mazama ash is offset by a fault, we can conclude that the fault moved within the last 6,800 years.

Table 3. Partial list of earthquakes recorded by observers (Intensities) and on seismic nets (Magnitudes) in northeastern Oregon and western Idaho, 1913 through 1992, bounded by 44.5° to 46.5° N. Latitudes and 116° to 118° W. Longitudes. Data were provided by Loudon Stanford (Idaho Geological Survey). Depths are very poorly constrained. See Zollweg and Wood (1993) for additional data.

Year	Date	Time	Latitude (N.)	Longitude (W.)	Depth (km)	Magnitude/ Intensity
1913	14-Oct	0230	45.70	117.10	unknown	IV
	14-Oct	2300	45.10	116.70	unknown	VI
1917	1-Jun	1035	46.10	116.40	unknown	IV
1927	9-Apr	0500	44.88	117.20	unknown	V
	9-Apr	0700	44.83	117.32	unknown	IV
	9-Apr	0930	44.82	117.08	unknown	IV
	9-Apr	1400	44.75	117.23	unknown	IV
1931	6-Jan	2100	44.90	116.20	unknown	IV
1933	20-Apr	2025	44.70	116.10	unknown	IV
1935	31-Oct	1500	46.40	116.60	unknown	II
1941	23-Dec	1748	44.75	117.00	unknown	IV
1942	12-Jun	0930	44.92	117.00	unknown	V
	14-Jun	0600	44.83	116.92	unknown	III
1943	14-Apr	0953	46.40	117.00	unknown	V
1944	25-Jul	0000	46.10	116.40	unknown	IV
1949	15-Mar	2053	44.80	116.60	unknown	III
1955	31-Mar	2335	44.70	116.70	unknown	IV
1963	6-Sep	1924	44.80	117.10	unknown	IV
1965	7-Nov	1642	44.97	116.93	5	4.3
1966	25-Feb	1457	44.70	116.10	33	3.5
	30-Dec	0351	44.87	116.94	10	4.2
1967	10-Oct	0000	46.40	117.00	unknown	IV
1971	13-Jul	2329	44.83	117.90	33	3.9
1977	27-Nov	0925	44.58	116.27	5	4.5
1981	29-Sep	0539	44.69	116.99	5	3.6
1983	29-Mar	0137	44.79	116.88	5	3.4
1984	31-Jan	0529	45.58	116.57	5	3.5
	10-Aug	0727	44.99	116.95	5	3.8
	19-Sep	0132	45.08	116.77	5	3.8
1985	24-Aug	0153	46.22	117.91	unknown	3.8
1986	16-Jul	2238	46.49	117.17	20	2
	20-Jul	1905	44.46	116.03	5	3.6
	17-Dec	2247	46.54	117.81	unknown	2.1
1987	26-May	1611	45.38	116.23	17	4.3
	27-Dec	0951	44.51	116.14	8	3.6
1988	1-Mar	2142	45.50	117.74	unknown	1.8
	23-Dec	2131	46.19	117.99	unknown	1.6
1989	30-Mar	0853	45.32	116.11	5	3.1
	27-Jun	2337	46.47	117.63	6	1.9
	11-Aug	0234	45.55	117.86	53	2.6
	20-Dec	0852	44.62	117.07	5	3.2
1990	4-Jan	0221	44.77	117.63	5	3

	4-Jan	1801	45.02	117.05	unknown	3
1991	1-Sep	1129	45.44	116.79	10	2.9
	4-Oct	0210	46.60	117.37	unknown	2.3
1992	26-Jan	0535	45.02	116.74	6	3.2
	4-Jun	0054	46.32	117.57	9	2.7
	6-Jun	2031	44.83	117.00	unknown	3.6
	17-Sep	2124	45.43	117.60	26	1.7

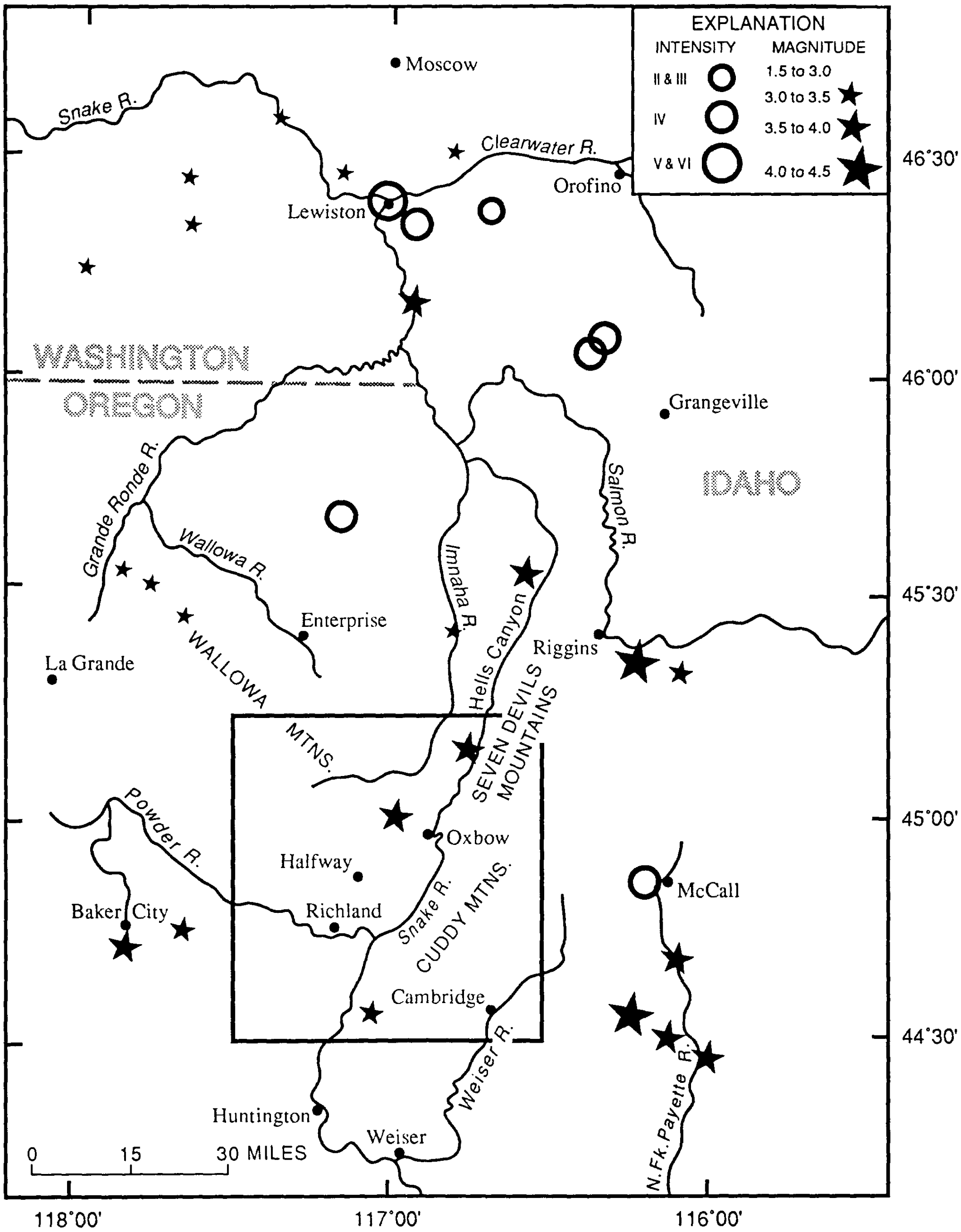

Figure 9. Approximate locations of earthquakes recorded in the region from 1913 to 1992. Small inset shows area of Figure 10. Additional data are in Zollweg and Wood (1993).

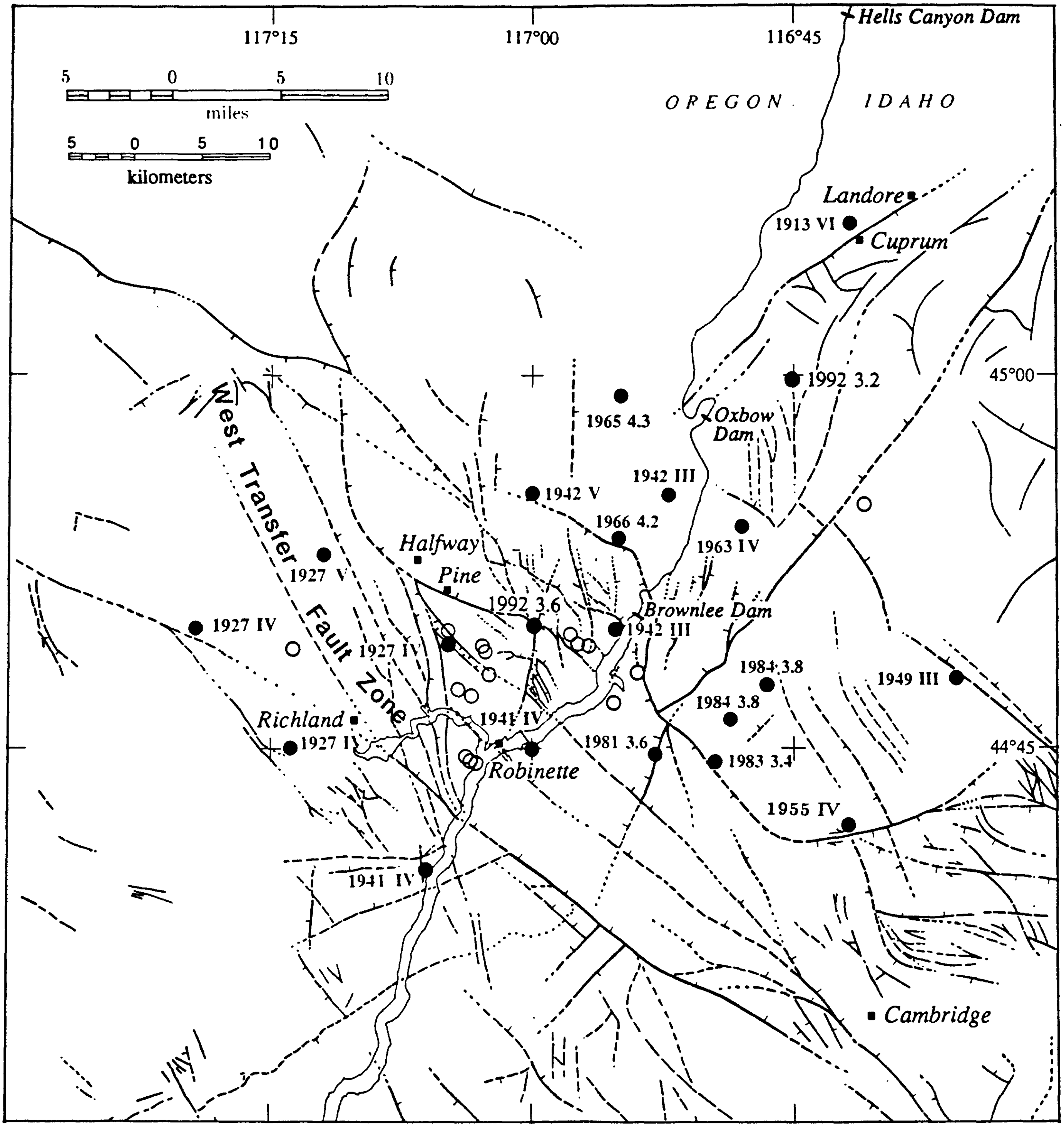

Figure 10. Late Cenozoic faults with earthquake epicenters in the Cuddy Mountains-Pine Valley area (from Mann and Meyers,1993). Open circles are micro-seismic epicenters.

Are there "active faults" in the Hells Canyon Region? Yes. Historic earthquakes in the region record movement along active faults. However, without earthquakes to mark the movement, other tools have to be utilized to document the activity along a fault. Active faults are particularly difficult to identify in the mountains, where no or very little Holocene sediments are preserved because of rapid erosion. I have no doubt that active faults occur in the region, which have not been identified. I suspect that some straight segments of the Snake River canyon follow active faults. The longest straight segment in Hells Canyon below the Hells Canyon Dam is between Wild Sheep Creek and Saddle Creek, a distance of about 5 miles. There are several other linear segments four to five miles in length.

The length of a fault greatly influences the expected magnitude of an earthquake during rupture (Table 4). If active faults do occur in the Seven Devils Mountains, I expect them to be relatively short and probably no longer than 15 miles, which is the approximate length of the main uplifted segment of those mountains. I suspect that maximum lengths of faults in Hells Canyon are 10 to 15 miles.

Table 4. Rupture length of faults and possible magnitude of earthquakes generated (Bolt et al., 1975, p. 27).

Rupture Length (km)	Rupture Length (miles)	Magnitude
5-10	3-6	5.5
10-15	6-9	6.0
15-30	9-19	6.5
30-60	19-37	7.0
60-100	37-60	7.5

An especially intriguing fault is the Wallowa fault which marks the spectacular escarpment along the north side of the Wallowa Mountains. It has been traced for about 35-40 miles. "Activity" along the fault during the Holocene has not been demonstrated, although I suspect that repositioning (because of poor seismograph coverage) of the three small earthquake epicenters that form a row just south of the fault (Fig. 9) will show that they are related to small movements along the Wallowa Fault. Jim Zollweg (oral communication, March, 1994) reported that some low-amplitude earthquakes occurred along the Wallowa fault during the last four years. If one fault runs the entire length of the Wallowa fault, and it ruptures, an earthquake with a magnitude of at least 7.0 (Table 4) might occur, which is enough to damage many of the buildings in the area. The structural integrity of Wallowa Lake (a moraine-dammed lake of Holocene age) may be at risk during a large magnitude earthquake.

Limekiln fault, the major fault that crosses Snake River near the mouth of the Grande Ronde River, is another structure that could cause damage if it ruptures. Its length, at least 20 miles (Newcomb, 1970), suggests a potential 6.5-magnitude tremor. The fault runs directly into the Craigmont monocline, which continues northeastward for another 20 miles. If the monocline is underlain by the fault, then the combined structure is much longer; its rupture could generate an even larger earthquake.

Hazards Influenced By Human Activities

Dams. Man-made dams are a definite hazard in Hells Canyon and to the communities that lie downstream. I don't know, however, if they pose a significant risk and I am not trained to evaluate the engineering factors that were used during construction to ensure their safety. Personnel from the Idaho Power Company (1987) published a report on the consequences of a Brownlee Dam failure. Failure of the Brownlee Dam would cause the failure of all dams that are downstream on the Snake River. The report shows expected heights of the resultant flood water, velocities of water flow, and times when the water would reach certain locations along the river. For example, flood waters would reach Lewiston in as few as 6.5 hours and peak in 9.5 hours at an elevation of 803 feet above sea level, which is about 80 feet above the present river level.

Mines. Mine portals dot the sides of Hells Canyon. Some are dug into the hillsides greater than half a mile (Irondyke mine near the old town of Homestead). Many mine tunnels are at least 200 feet long, but most tunnels were dug into the canyon walls for only a few tens of feet. Each, however, poses a potential hazard. Rock falls are common in mines and timbers, if used, rot and fall, thereby causing walls and ceiling to slough off into the tunnel. Animals also may be hazards in abandoned mines. Snakes often live near the portal entrances and large mammals have been known to inhabit the tunnels.

Defoliation. Defoliation, by whatever means, can increase the possibility for rock and soil failure, thereby increasing the potential for rock and debris flows. Particularly susceptible are slopes that are subjected to rapid erosion after a forest fire.

DISCUSSION AND CONCLUSIONS

There are many potential geologic hazards in the Hells Canyon region including floods, slope movements, and earthquakes. Visitors in the canyon should be aware of these hazards and be able to evaluate the risk that they impose. Communities along the rivers should be educated about the risk associated with dam (both natural and man-made) failures.

The U.S. Forest Service and all other Federal and State agencies that have jurisdiction and responsibilities in Hells Canyon should, within their budget and time constraints, educate visitors about these hazards and prepare for them where it is reasonable. I suggest that some detailed studies be started in selected areas. Education and preparation can include, but not be limited to, the following:

1) Study the campsites in light of the possibility that rock and debris flows could destroy them. Each campsite should be evaluated for a catastrophic slope movement event. Perhaps picnic tables can be removed from some of the alluvial fans.

2) Assure that the seismic network, funded by Idaho Power Company and currently being monitored by James Zollweg of Boise State University, is kept in place and that the network is expanded to include all of Hells Canyon and the Wallowa, Elkhorn, and Seven Devils mountains.

3) Obtain an updated assessment from Idaho Power Company concerning the risks that are associated with the Brownlee and other dams, particularly with regards to potential damage related to earthquakes and landslides. Advise visitors and people in river communities about the risk associated with dam failure, particularly if a large-magnitude earthquake occurs. If not currently in place, design an emergency evacuation plan.

4) Study selected areas in Hells Canyon to evaluate landslide potential and possible risk. In particular, the area between Bernard Creek and Sheep Creek should be monitored, particularly after long periods of rain.

5) Have geologists and engineers study the imposing rock masses above the Eagle's nest (Fig. 5) and Hells Canyon launch site (Fig. 6) to evaluate their potential for catastrophic failure. Study other steep canyon walls, both along the rivers and the tributary streams to evaluate potential failure. Warn visitors at the Hells Canyon visitor center near Hells Canyon dam about the dangers of rock falls, particularly if they park vehicles along the road. I have some concern about the visitor center itself because of the possibility

that rock falls and rock and debris flows, generated in Hells Canyon Creek, could form a temporary dam which would back up water and other debris. The subsequent rupture of the temporary dam would release a large volume of water and rock debris that would inundate the parking lot and endanger the building, visitors, and employees.

6) Educate visitors about the risks associated with mines. And, if risks seem high at any mine, take appropriate measures for reducing that risk. An inventory of all mines is suggested. The inventory could include such things as the mine's history, minerals found, depth of the tunnel or shaft, and potential for rock falls, etc. Some portals may need to be closed.

7) Encourage the search for "active" faults in the Hells Canyon region. Studies of satellite data in several frequency bands may help identify active faults (influence on water and vegetation can be very evident on these satellite images). Detailed geologic mapping, particularly between the peaks of the Seven Devils Mountains and the Snake River, would be worthwhile to identify the late Quaternary (and possibly Holocene) faults.

8) In a more regional sense, faults associated with the Olympic-Wallowa Lineament and the Wallowa and Limekiln fault systems should be evaluated for earthquake potential. The maximum magnitude earthquakes that can be generated along active faults throughout the region should be calculated.

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REFERENCES CITED

Allen, J.E., and Burns, Marjorie (with S.C. Sargent), 1986, Cataclysms on the Columbia: Timber Press, Inc., Portland, Oregon, 211 p.

Bacon, C.R., 1983, Eruptive history of Mount Mazama and Crater Lake caldera, U.S.A.: Journal of Volcanology and Geothermal Research, v. 18, p. 57-116.

Bolt, B.A., Horn, W.L., Macdonald, G.A., and Scott, R.F., 1975, Geological Hazards: Springer-Verlag, New York, 328 p.

Goldstrand, P.M., 1987, The Mesozoic stratigraphy, depositional environments and tectonic evolution of the northern portion of the Wallowa terrane, northeastern Oregon and western Idaho: Bellingham, Western Washington State University, M.S. thesis, 200 p.

Howell, D.G., Jones, D.L., and Schermer, E.R., 1985, Tectonostratigraphic terrar of the Circum-Pacific Region, *in* Howell, D.G. (ed.), Tectonostratigraphic Terranes: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, vol. 1, Houston, Texas, p. 3-30.

Idaho Power Company, 1987, Emergency action plan for Brownlee Dam and power plant, Hells Canyon Hydroelectric Project #1971, 79 p.

Jacobson, R., Milne, W., Brooks, H., and Brandsdottir, B., 1985, The 1984 landslide and earthquake activity on the Baker-Homestead highway near Halfway, Oregon: Oregon Geology, v. 47, p. 51-57.

Malde, H.E., 1968, The catastrophic Late Pleistocene Bonneville flood in the Snake River Plain, Idaho: U.S. Geological Survey Professional Paper 596, 52 p.

Mann, Gary M., 1989, Seismicity and late Cenozoic faulting in the Brownlee Dam area--Oregon-Idaho: A preliminary report: U.S. Geological Survey Open-File Report 89-429, 46 p.

Mann, G.M., and Meyers, C.E., 1993, Late Cenozoic structure and correlations to Seismicity along the Olympic-Wallowa Lineament: Geological Society of America Bulletin, v. 105, p. 853-871.

Morrison, R.K., 1963, Pre-Tertiary geology of the Snake River canyon between Cache Creek and Dug Bar, Oregon-Idaho boundary: Eugene, University of Oregon, Ph.D. dissertation, 290 p.

Newcomb, R.C., 1970, Tectonic structure of the main part of the basalt of the Columbia River Group, Washington, Oregon, and Idaho: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-587.

O'Connor, J., 1990, Hydrology, hydraulics, and sediment transport of Pleistocene Lake Bonneville flooding on the Snake River, Idaho: Tucson, University of Arizona, Ph.D. dissertation, 192 p.

Prostka, H.J., 1962, Geology of the Sparta Quadrangle, Oregon: Oregon Department of Geology and Mineral Resources Geologic Map GMS-1, on sheet, scale 1:62,500.

Raisz, E., 1945, The Olympic-Wallowa Lineament: American Journal of Science, v. 243A, p. 479-485.

Reiter, Leon, 1990, Earthquake hazard analysis: Columbia University Press, New York, 254 p.

Silberling, N.J., Jones, D.L., Blake, M.C., Jr., and Howell, D.G., 1984, Lithotecton terrane map of the western conterminous United States, Pt. C, *in* Silberling, N.J., and Jones, D.L., eds., Lithotectonic terrane maps of the North American Cordillera: U.S. Geological Survey Open-File Report 84-523, 43 p.

Vallier, Tracy L., 1967, The geology of part of the Snake River canyon and adjacent areas in northeastern Oregon and western Idaho: Corvallis, Oregon State University, Ph.D. dissertation, 267 p.

_______, 1974, Preliminary report on the geology of the Snake River canyon: Oregon Department of Geology and Mineral Industries, GMS-6, 29 text pages, map scale 1:125,000.

_______, 1977, The Permian and Triassic Seven Devils Group, western Idaho and northeastern Oregon: U.S. Geological Survey Bull. 1437, 58 p.

________, in press, Petrology of pre-Tertiary igneous rocks in the Blue Mountains region of Oregon, Idaho, and Washington: Implications for the geologic evolution of a complex island arc, *in*, Vallier, T.L., and Brooks, H.C., (eds.), Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: Petrology and Tectonic Evolution: U.S. Geological Survey professional Paper 1438, Chapter 3.

Vallier, T.L., and Miller, V.C., 1974, Landslides in the Grand Canyon of the Snake River, Oregon and Idaho: Terre Haute, Indiana State University, Department of Geography and Geology, Professional Paper 4, p. 9-28.

Varnes, D.J., 1978, Slope movement and types and processes, in, Landslides, Analysis and Control: Transportation Research Board, National Academy of Sciences, Washington, D.C., Special Report 176, Chapter 2.

Wheeler, H.E., and Cook, E.F., 1954, Structural and stratigraphic significance of the Snake River capture, Idaho-Oregon: Journal of Geology, v. 62, p. 525-536.

White, D.L., 1972, Geology of the Pittsburg Landing Area, Snake River canyon, Oregon-Idaho: Terre Haute, Indiana State University, M.S. thesis, 98 p.

White, David L., and Vallier, T.L., 1994, Geologic evolution of the Pittsburg Landing area, Snake River canyon, Oregon and Idaho, *in,* Vallier, T.L., and Brooks, H.C., (eds.), Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: Stratigraphy and Resources: U.S. Geological Survey Professional Paper 1439, U.S. Government Printing Office, p. 55-73.

Zollweg, J.E., and Wood, S.H., 1993, Faulting relationships, seismicity, design earthquakes, and peak ground accelerations at hydroelectric facilities in Hells Canyon of the Snake River, Idaho-Oregon: Idaho Power Company (Consultant Report), Boise, Idaho, 158 p.