TRANSPORTATION DEPARTMENT

Research Project No. 79

By

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Consulting Seismologist

IDAHO

Reprint

RESEARCH SECTION

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MAXIMUM PROBABLE EARTHQUAKE

ACCELERATION ON BEDROCK

IN

THE STATE OF IDAHO

Research Project No. 79

By

Roger W. Greensfelder
Consulting Seismologist

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for

Idaho Department of Transportation
Division of Highways

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ADDENDUM AND ERRATUM

Dr. David Blackwell (personal communication, September 1976) has kindly provided detailed information concerning heat flow in and adjacent to the western Snake River Plain (west of Hagerman). Contrary to the statement on page 13 of this report, heat flow averages nearly 1.7 HFU (Heat Flow Units) near the axis of the plain; the higher values reported by Brott and Blackwell (1975), averaging about 3 HFU, apply only to the margins of the western SRP. In the eastern SRP, thermal disturbances due to flow of shallow ground water prevent reliable interpretation of available shallow temperature gradient data near the axis of the plain, but limited data indicate high values along its margins, as in the western SRP.

Blackwell has constructed an elaborate model to explain the observed heat flow pattern, including the following elements: a large mafic intrusion beneath the SRP and adjacent areas at depths greater than 10 km (6 mi.); thermal conductivity one-half normal in the top 10 km of crust beneath the SRP; radiogenic heat production of zero within this crustal segment, but normal in adjacent granitic segments; constant heat flow of 1.4 HFU from the upper mantle across all of southwestern Idaho. By assuming the intrusion was emplaced 10 million years ago at a temperature of 1350°C, the model fits the observational data quite well. Although the model does not include a plot of crustal isotherms, it clearly indicates that temperatures in the crust beneath the western SRP are considerably higher than average for the Cordilleran region. In the top 10 km (6 mi.), temperatures would appear to be nearly twice average, because heat flow is nearly the Cordilleran average despite half-normal conductivity and the absence of radiogenic heat production.

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Special thanks are due Donald Cox (Chief of Highway Operations) who authorized and encouraged the study over a period of 1½ years.

INTRODUCTION

Our ability to predict in detail the course of events in large, open natural systems is still in its infancy. Processes that govern the occurrence of earthquakes are still not well understood, and they involve a great many variables. In order to make accurate deterministic predictions of earthquakes one would need detailed knowledge of the mechanical properties of crustal rocks, strain rates throughout the crust and upper mantle, location of faults and fracture systems, and pore pressure of water. Most of these factors are only known at shallow depths and in very few places. Therefore, earthquake risk prediction on a regional scale generally assumes a random distribution of seismicity in time and space; however, in some areas, mapped faults may be assumed to control the geographic distribution of the larger, potentially destructive earthquakes.

In making the present study, it became abundantly clear that only a careful synthesis of both geologic and seismologic data could provide a realistic prediction of future seismicity and attendant ground motion in Idaho. Seismicity data for the Idaho region are of poor quality for all but the last 12 years, and cannot be considered, in and of themselves, to form a representative sample of long-term earthquake occurrence. Therefore, it has been necessary to interpret long-term seismicity from the Quaternary tectonics and crustal structure of the region. In other words, the true distribution of earthquakes in time and space has been considered as governed by apparent tectonic (mechanical) behaviors which characterize large portions of the crust. Then, the degree to which limited seismicity data represent a given tectonic province could be assessed. In an order-of-magnitude way, the differences of observed seismicity seem to fit tectonic patterns in the study region. But significant discrepancies do exist, and could only be resolved by a careful weighing of the geologic and seismologic evidence of seismicity.

Unlike that of California, the distribution of known late Quaternary faulting in Idaho and adjacent regions is much too limited to form a sufficient basis for describing the distribution of future large shocks and ground shaking. Nevertheless, it was desired to have the seismic risk analysis fully account for known active faults. Therefore, it has been necessary to use a hybrid method, wherein earthquake risk in the vicinity of active faults is derived in a semi-deterministic manner, while in other areas it is derived assuming a completely random distribution of seismicity.

To do this, it was necessary to adopt an explicitly probabilistic approach, in order that predicted accelerations for earthquakes occurring both randomly and along known faults would have a comparable probability of occurrence. In other words, while spatial probability density was allowed to vary, probability of occurrence in time was held at a constant level across the study region. It is felt that this procedure affords the fullest and most balanced description of earthquake risk that may be derived from available information.

A famous statistician named Gumbel, who developed the theory of extreme values, once said, "It is impossible that the improbable will never happen." Although this might sound a bit simple, it is too easily forgotten that 100-year, even 10,000-year, events do happen occasionally, and sometimes much sooner than anyone would expect. With this word of caution, one may appreciate the uncertainties of the present study, and of the data on which it was necessarily based.

PRE-CENOZOIC HISTORY

Situated within the Cordilleran mountain system of western North America, most of Idaho was a region of miogeosynclinal deposition from later Precambrian through early Mesozoic time. The westernmost part of the state was eugeosynclinal and a narrow strip along the Wyoming border received intermittent continental-shelf deposits (figure 1). Several orogenic episodes, beginning with the Antler orogeny in early Mississippian time and ending with the Nevadan orogeny in the Jurassic, affected the eugeosyncline.

The Nevadan orogenic belt comprises metamorphic and plutonic rocks of Jurassic and Cretaceous age, which form the basement complex of west-central Idaho, including the great Idaho Batholith. Structural trends in these rocks describe a great S-curve between the Klamath Mountains of California and the Cascade Range in northern Washington (figure 1); the sharp bends have been called the Mendocino and Idaho oroclines. The possible importance of these features in the Cenozoic tectonics of the region is discussed in the following section.

Paleozoic and Mesozoic miogeosynclinal rocks are widely exposed in the fault-block mountains of east-central and southeastern Idaho. The Sevier orogeny, of early Cretaceous age, is expressed in the Bannock thrust belt of southeastern Idaho. Marine sedimentation in the western Cordillera ended approximately with the Sevier orogeny.

Clastic sediments, both marine and continental, were deposited in the Rocky Mountain geosyncline, on the relatively stable continental platform, from Cretaceous through Paleocene time. Lower Cretaceous sediments of this geosyncline are found in southeastern Idaho. The Laramide orogeny, ending in Paleocene time, effectively terminated all geosynclinal conditions in the Cordillera.

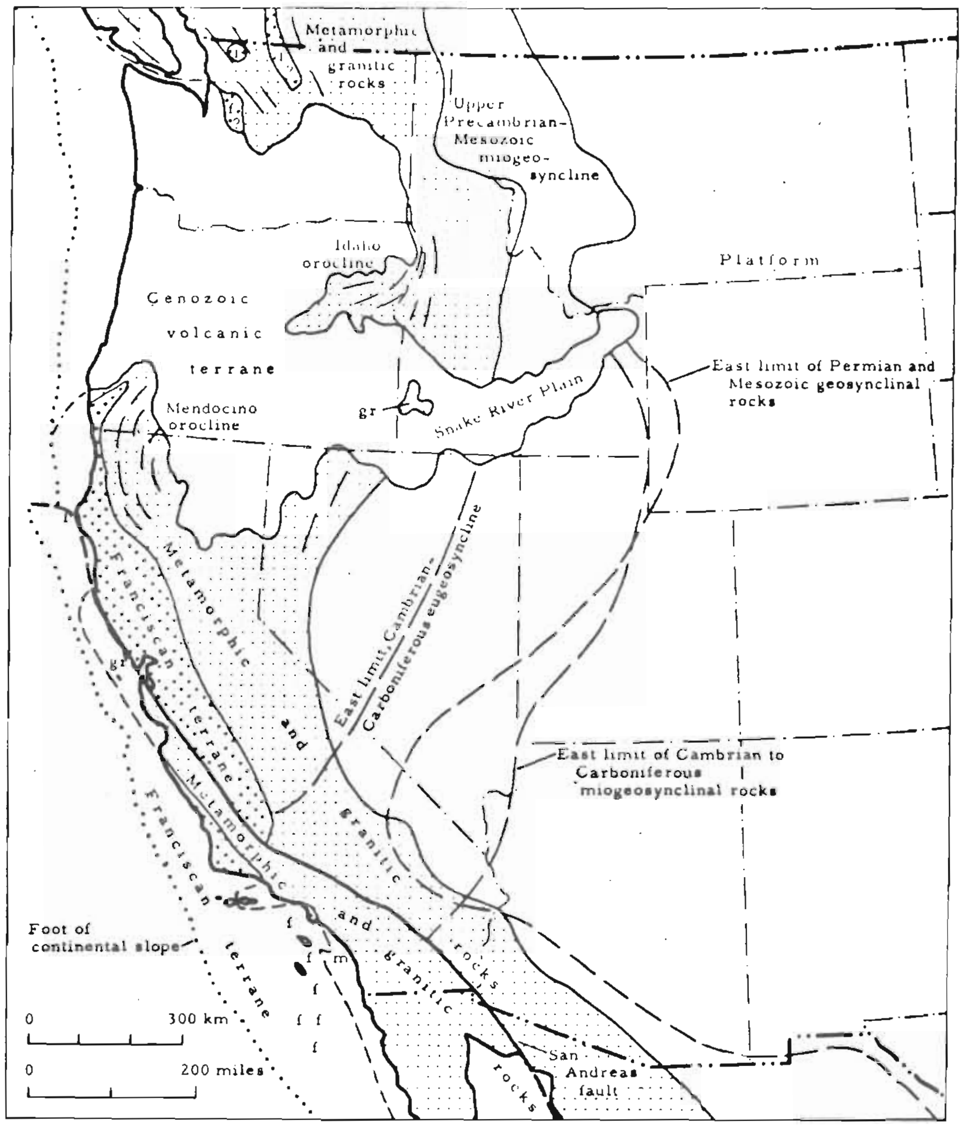


Figure 1. Major Paleozoic and Mesozoic complexes of the western United States. Small and offshore areas are marked by letters: f, Franciscan terrain (and similar rocks in Washington); gr, granitic rocks; m, metamorphic rocks.

(from Hamilton and Myers, 1966)

North of the Idaho batholith, Precambrian rocks of the Belt supergroup comprise essentially all basement rock, except for a few small Cretaceous plutons.

Cenozoic normal faulting locally may have been guided by preestablished planes of weakness. This relationship seems most evident in the southeastern part of the state.

CENOZOIC TECTONO-VOLCANIC EVOLUTION,
CRUSTAL STRUCTURE, AND SEISMICITY

BACKGROUND

Hamilton and Myers (1966) states their belief that the various patterns and types of later Cenozoic faulting in the Cordillera fit an overall system of northwestward drift, decreasing from southwest to northeast. This model explains right-slip on northwest-trending faults, normal dip-slip on northeast-trending faults, and oblique slip on north-trending faults. They, and others before, have estimated total extension accompanying block faulting and volcanism in Nevada and Utah as up to 300 km (190 miles). The Snake River rift was said to have formed as a result of northwestward drift of the Idaho batholith, which moved as an unbroken plate. Throughout much of the Cordillera, basaltic volcanism served to rebuild the crust as it was thinned and fragmented by tensional faulting. The tectonic provinces as defined by Hamilton and Myers are shown in figure 2.

Although this model fits the Basin and Range province and tectonic provinces of California quite well, it seems too great an oversimplification for the region to the north. While tensional faulting is widespread in the Pacific Northwest, there is evidence to show that this has not been due chiefly to northwest-directed crustal extension. Distributed right-lateral shear may have been important in the evolution of the Volcanic Rift Province; the Idaho batholith has experienced significant late Cenozoic normal faulting suggesting west-directed extension; and the region of basin-range structure east of the batholith appears to have undergone both northeast-directed extension and north-oriented right slip.

Space-time variations in volcano-tectonic activity indicate major regional differences in both the evolution and present day nature of tectonic forces operating in the Northwest. These factors and their implications for expected seismicity are discussed in the following sections.

OVERVIEW

Early Cenozoic tectonics and volcanism in the Cordillera were the manifestation of east-west compression which resulted from continuing convergence of the Pacific and North American tectonic plates. Subduction was accompanied by widespread extrusion and intrusion of intermediate-composition magmas in Eocene and Oligocene time. In Idaho, these are represented by the Eocene Challis Volcanics and associated small plutons intruding the Idaho batholith.

Lipman and others (1972) have interpreted the configuration of early Cenozoic subduction zones in the Cordillera from the geographic distribution of the percentage of K_2O in volcanic rocks. Among other things, they deduced that the cessation of andesitic volcanism in the interior of the Pacific Northwest was caused by a steepening of the subduction zone about 40 million years (m.y.) ago (late Eocene).

A profound change in the tectonics and volcanism of the interior Cordillera began about 25 m.y. ago (early Miocene). This involved a shift from compressional to tensional deformation (e.g. Basin-and-Range block faulting), and from intermediate to fundamentally basaltic volcanism (Christiansen and Lipman, 1972). The transition appears to have begun in southern Arizona and New Mexico and to have migrated northwestward into northern Nevada by late Miocene time. The cause of this shift appears to have been the annihilation of the West Coast subduction zone, which progressed northwesterly with the Mendocino triple junction and formation of the San Andreas fault (Christiansen and Lipman, 1972). As the trench was destroyed, compressive stress was released in the interior of the

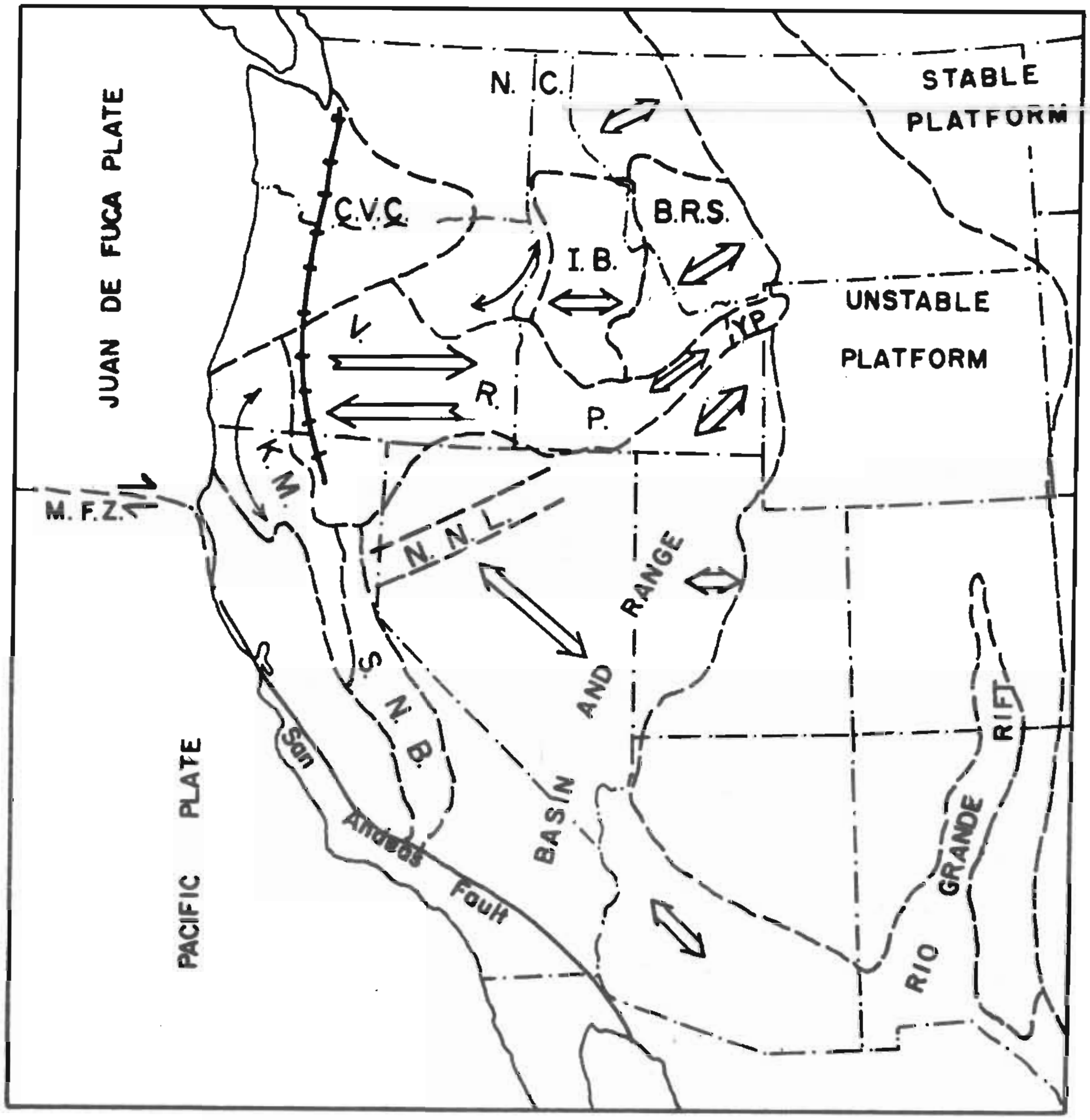


Figure 2 - Late Cenozoic tectonic features of the Pacific Northwest (tectonic provinces after Hamilton and Myers, 1966)

BRS - Basin-Range Structure
IB - Idaho Batholith
MFZ - Mendocino Fracture Zone
NNL - Northern Nevada Lineament
VRP - Volcanic Rift Province
CVC - Cenozoic Volcanic Crust
KM - Klamath Metamorphic Terrain
NC - Northern Cordillera
SNB - Sierra Nevada Batholith
YP - Yellowstone Plateau

Cascade Subduction Zone

Mendocino and Idaho Oroclines

region of distributed right-lateral shear

direction of crustal extension

Cordillera, giving rise to tensional faulting and basaltic volcanism (Scholz et al, 1971).

The inception of basaltic volcanism in the Columbia and Oregon plateaus about 21 m.y. ago (early Miocene) was probably related to changes in the Cascade subduction zone, and is comparable to regions of extension found behind western Pacific island arcs. In any case, the timing and tectonic aspects of the transition in this area indicate a process substantially different from that of the Basin and Range province.

In Idaho, post-Eocene volcanism was confined essentially to the Volcanic Rift province, which includes the Snake River Plain and the Owyhee Mountain uplands in the southwestern corner of the state. It appears that late Cenozoic volcano-tectonic activity in southwestern Idaho and eastern Oregon began in early Miocene time (about 21 m.y. ago) with the eruption of the Columbia River basalts and the rifting that continued to form the Snake River Plain. This was followed by the eruption of the silicic Idavada Volcanics (lower Pliocene), basalts of the Snake River Group (late Pleistocene). The eruptive centers of these units shifted progressively eastward with time, suggesting that rifting followed a similar path.

The Quaternary volcanics of the Yellowstone Plateau are a bimodal basalt-rhyolite series (fundamentally basaltic in nature), and represent the latest stage of volcano-tectonic migration in the Snake River region. The predominant rock types of the Yellowstone Plateau are of rhyolitic composition, and basalts of the Snake River Group form only a thin covering over the rhyolitic materials of the Island Park Caldera. On this basis, it has been suggested that silicic igneous activity has predominated throughout late Pliocene and Quaternary time in the eastern Snake River Plain. (Christiansen, 1975)

Several investigators have theorized that the eastern Snake River

Plain represents the track of a mantle plume overridden by the southwest-moving North American plate; this plume is now thought to lie beneath the Yellowstone Caldera. Smith and Sbar (1974) have embellished this hypothesis in order to explain the tectonics of the Intermountain Seismic Belt. In their model, the subcrustal spreading produced by the plume drives the Northern Rocky Mountain and Great Basin subplates westward, away from the stable part of the North American plate. In addition, it is supposed to drive the two subplates apart in a north-south direction. Smith and Sbar admit that their model doesn't really fit earthquake mechanism and Quaternary tectonic data very well.

VOLCANIC RIFT PROVINCE

Structures and volcanism of the Snake River Plain (SRP) indicate a complex tectonic evolution of this area since early Miocene time, and that the western (northwest-trending) and eastern (northeast-trending) portions of the SRP are fundamentally different.

The western SRP appears to have formed by long-continued injection of basalt along en echelon faults and fissures, and by major subsidence along bounding faults. According to Malde (1959), progressive movement on high-angle faults along the northeastern margin of the plain has relatively dropped the lower Pliocene Idavada Volcanics some 2700 meters (9,000 feet). However, it should be noted that much of this displacement may be due to uplift of the Idaho batholith. On the southwest edge of the plain, downdropping has occurred along a series of en echelon faults with unknown displacements.

Seismic refraction data (Prodehl, 1970) indicate that the crust is quite anomalous in this region: the sial is not more than 8 km (5 mi.) thick, and the sima is about 34 km (21 mi.) thick. In terms of proportion of mafic constituents, this crustal section has a nearly oceanic character. Gravity data (Hill, 1963) suggest that a 10 km (6 mi.) zone of basalt-filled fissures may form the upper crust along the axis of the plain. Therefore, it would seem that magmatic injection of fissures has been the dominant process in the formation of the western SRP; its graben-like character seems relatively insignificant.

In eastern Oregon, geologic features suggest a structural development and character similar to that of the western SRP, except that no major subsidence has been noted there. Miocene basalts are cut by en echelon northwest trending faults with apparently minor displacements.

Regionally, the en echelon normal faults of eastern Oregon and the western SRP indicate slight extension in a northeast direction, and the lack of significant fault displacements in most of the area suggests that large-scale crustal extension was not their cause.

On a larger scale, the Mendocino and Idaho oroclines indicate plan rotations of some 60° or more. According to Hamilton and Myers (1966), paleomagnetic declinations in Miocene lavas show 20° clockwise and counterclockwise rotation in the Mendocino and Idaho oroclines, respectively.

The above features may be explained by broadly distributed right lateral shear, which might be called "transform shearing," acting in an east-west direction, as shown in figure 2. This phenomenon would seem logically necessary to explain the fact that east-west crustal extension has been much greater in the Basin and Range province than to the north of it. The continuation of subduction beneath the Cascade Range into Quaternary time is a possible explanation for the relatively low rate of crustal extension north of the Basin and Range province. Therefore, the region of distributed shear may be considered a zone of adjustment between two extensional regimes. Perhaps the migrating mantle plume, described above, served to create a a belt of hot, soft, plastic crust which localized the zone of adjustment.

The evolution of the western Snake River Plain can be reasonably well explained in terms of the above model. Normal faults and fissures of the western SRP trend northwesterly, and it appears that Plio-Pleistocene basalts generally erupted through and filled northwest-trending fissures. Regionally distributed right-lateral shear may have served to open fractures continually in Plio-Pleistocene time, providing the necessary volcanic conduits. This long-continued injection of basalt has considerably augmented the crust.

The western Snake River Plain is part of an area of highly anomalous continental crust. This is characterized by a thin sialic and thick mafic layer, high heat flow, and an absence of seismicity and later Quaternary faulting. In these ways, it is distinctly different from surrounding areas.

The eastern Snake River Plain appears as a more discordant structure, relative to surrounding areas, than does the western SRP. No bounding faults have been identified, and basin-range fault blocks, which strike towards each other from opposite sides of the plain, appear to have subsided and been covered by young volcanic materials. However, gravity data (LaFehr and Pakiser, 1962) suggest that as much as 1500 meters (5,000 ft.) of structrual relief may occur beneath the area, and that basalts are much less voluminous than in the western SRP. Furthermore, the available data (from geology, gravity, and resistivity) suggest the presence of thick deposits of silicic volcanics, and perhaps a crust more normal than that of the western SRP. In the eastern SRP, as in the western part, late Pleistocene volcanism has comprised basaltic eruptions from fissures. However, fissures of the eastern SRP trend considerably more to the north than those of the western part.

Based on the foregoing, it appears that the eastern SRP did not begin to form until long after the western part - perhaps not until late Pliocene time. Furthermore, it seems to have formed by a process involving substantial melting of crustal material, producing the silicic volcanics of the Yellowstone Plateau; Christiansen (1972) suggested that a series of granitic plutons may underlie the eastern SRP. Thus, intense igneous activity may have consumed the older crust of this area in quite recent geologic time.

The entire SRP is a region of very high heat flow, perhaps averaging more than 2.5 HFU (Brott and Blackwell, 1975). Further, it is apparent that the eastern SRP is hotter than the western part, based on volcanic history. From available data, the Volcanic Rift province, and especially the Snake River Plain, appears to be a zone of crust-mantle decoupling wherein the lower crust is abnormally soft on account of its elevated temperature. If correct, this model predicts that major tectonic stresses cannot exist in or be transmitted through the crust of this province. Therefore, Quaternary tectonics and present seismicity may reasonably be expected to differ considerably across such a crustal discontinuity, as they apparently do.

BASIN AND RANGE PROVINCE

The tectonics of the Basin and Range province were largely covered in the section entitled "Overview," but certain additional points should be made.

Scholz and others (1971) proposed that the shift from compressional to tensional tectonics that began in the Basin and Range province about 25 m.y. ago was accompanied by the development of a mantle diapir. This is supposed to have risen and spread rapidly away from a north-trending axis, providing an active source of crustal tension. As the diapir continued to spread, basaltic volcanism and tensional faulting remained concentrated over its edges, where tensional stresses were greatest. Quaternary and historic faulting, volcanism and seismicity are concentrated along the west and east margins of the province, indicating the present extent of the diapir. The existence of the diapir is supported by a combination of geophysical anomalies, including: high heat flow, averaging nearly 2 HFU (Thompon and Burke, 1974); low seismic velocities just below the Moho, averaging 7.8 km/sec. (25,600 ft./sec.); thin crust, averaging about 28 km (17 mi.) in thickness (Prodehl, 1970).

This model is essentially adequate, but it fails to explain the late Cenozoic tectonic belt that trends at about N 55° E across northern Nevada - the "northern Nevada lineament" of figure 2. Along this belt, many range-bounding normal faults trend northeasterly, and the ranges themselves seem to have been offset in a right-lateral sense. The lineament manifests an abundance of thermal springs, late Quaternary faulting, and historic seismicity. Late Quaternary faulting dies out rapidly going northward from the lineament, and historic seismicity is essentially absent immediately north of it, as well as north of its projection into the northeasternmost Basin and Range province in Idaho. Finally, it appears to be the transition zone between the very distinct crustal structures which characterize the Basin-Range and Volcanic Rift provinces. On this basis, it is proposed that the lineament may be an important Quaternary and present-day tectonic boundary, separating regions of high and low activity.

In southeastern Idaho, range-bounding normal faults trend generally north-northwest, parallel to the strike of Laramide thrusting. Thus pre-Miocene planes of weakness may have localized later block faulting. Historic seismicity has been almost entirely confined to the Wasatch Front, Cache Valley, and Bear Lake-Soda Springs fault zones. Fault-plane solutions for earthquakes in this region indicate east-west extension.

BASIN-RANGE STRUCTURE

Located in eastern Idaho and western Montana, this tectonic province (figure 2) appears as a northern extension of the Basin and Range province across the Snake River Plain. It extends northward from the north edge of the Snake River Plain to the north edge of the Idaho batholith, and eastward from the east margin of the batholith to the Big Belt Mountains and the Abasaroka Range. It is characterized by Late Cenozoic faulting and a number of range-front fault segments have been active in Wisconsin, Holocene, and historic time. However, it differs from the Basin and Range province in that the majority of normal faults trend northwesterly, rather than from north to the northeast. As in southeastern Idaho, pre-Miocene bedding and thrust faults have probably guided normal faulting.

Concerning the Idaho portion of this province, Ruppel (1964) states that the broken pattern of offset ranges and frontal faults indicates a number of north-striking right-lateral faults. These lie in a 80 kilometer-wide (50 mi.) north trending belt about 240 km (150 mi.) in length. While most strikeslip displacements probably occurred in Miocene and Pliocene time, those on several faults near Leadore may have begun in early Pleistocene. These are marked by brecciated zones, drag folds, and unstable slope deposits; aggregate displacement may reach 6.5 km (4 mi.)

The pattern of faulting described above is different in nature from that of northern Nevada. That of northern Nevada is well-explained by northwest oriented tension, but that of east-central Idaho suggests both northeast oriented tension and north-striking right-lateral shear, probably not acting concurrently. Northward movement of the Idaho batholith in Miocene and Pliocene time, accompanying widening of the western Snake River Rift, may have produced the right-lateral faulting. Ruppel's (1964) assignment of Pleistocene age to the youngest strike-slip faults is here considered highly speculative, and is discounted. Late Quaternary and Holocene normal faulting clearly indicates that northeast extension acting along northwest-trending faults characterizes recent and contemporary deformation in this region.

In the southeasternmost corner of the basin-range structure province, bordering the Yellowstone Plateau, are a series of east-trending structures that cut across older northwest-trending ones. The Centennial Valley and Centennial fault and related features extend east to Hebgen Lake, across the Madison Range. These faults exhibit dip-slip movement of Holocene age, and appear to be part of a belt of east-west structures that began to form in late Quaternary time (Myers and Hamilton, 1964).

The 1959 Hegben Lake earthquake, accompanied by subsidence of up to 7 meters (22 ft.) over an east-trending area of some 1550 sq. km (600 sq. mi.), may have been a manifestation of this new tectonic system. However, normal faulting that accompanied this earthquake trended northwest. Fault-plane solutions for earthquakes on the north side of the Yellowstone Caldera indicate north-south extension along this trend (Trimble and Smith, 1975). These data suggest that the axis of tension in the Centennial Valley-Yellowstone region might have rotated from northeast to north during Quaternary time.

Historic seismicity has been confined essentially to the east margin of this province, although Quaternary faulting is rather evenly distributed throughout its southern portion.

IDAHO BATHOLITH

This large granitic body has been referred to as an "unbroken plate" (Hamilton and Myers, 1966). However, significant Quaternary and older faulting indicates that it is indeed broken, albeit much less so than the region immediately to the east.

The Challis Volcanics (Eocene), which cover much of the batholith's eastern portion, are faulted in a number of places. In its southern portion, the batholith is cut by several north-trending normal faults of probable late Pliocene and early Pleistocene age; only two late Wisconsin or Holocene scarps are documented in this area. Geothermal activity and seismicity in and near the Stanley Basin (Sawtooth Valley) graben indicate minor active faulting at depth in this area.

Detailed geologic mapping of the batholith is far from complete. Therefore, Quaternary faulting there may be considerably more abundant than is presently known. Available data suggest that east-west extension has predominated in Quaternary time in this area.

Crustal structure of this province is not well known. However, gravity data (Bonini, 1963) show Bouguer anamaly values close to those of the high, southern portion of the Sierra Nevada batholith. This has a crust from 40 to 50 km (25-30 mi.) thick. Therefore, by analogy, one might assume a comparable crustal thickness for the Idaho batholith.

NORTHERN CORDILLERA

The Northern Cordillera province in Idaho comprises the western margin of the Idaho batholith, overlapped by Miocene basalts and younger sediments, and the Rocky Mountains to the north (figure 2).

Miocene basalts along the western margin of the batholith have been tilted gently westward, and are broken by a number of north-trending normal faults. Displacements on these faults may reach to over 900 meters (3,000 ft.), and probably occurred during uplift of the batholith. Rocks of the Plio-Pleistocene Idaho Group are much less tilted and faulted than the Miocene basalts, indicating that the rate of uplift has decreased since early Pliocene time.

that normal faulting continued into at least early Quaternary time, but no Wisconsin or Holocene movements have been well documented. However, there are reports of possible Holocene faulting along the Squaw Creek fault, which will be dealt with in a later section. Minor seismicity has been reported in the area.

North of the batholith lies the Precambrian terrain of the northern Rocky Mountains, where there are few documented Cenozoic features. The Osburn and Hope faults, in Idaho, probably haven't moved since late Miocene time (Gilluly, 1963). In Montana, the Rocky Mountain trench is a structure of uncertain origin and nature, but some Quaternary faulting is associated with it. Late Quaternary faulting has been reported near the Purcell Mountains. Seismicity is very low in this region, except in the vicinity of Flathead Lake.

LATE QUATERNARY FAULTING AND SEISMICITY

METHODS OF ANALYSIS

In the western United States, one generally may observe a very close relationship between the distributions of late Quaternary faulting and of historic seismicity. Almost invariably, larger earthquakes (magnitude above 6-1/2) of the West have been accompanied by surface faulting. These major events, as well as most smaller earthquakes, have occurred in or along tectonic belts or fault systems marked by late Quaternary activity. This observation is good reason to predict that the preponderance of large and destructive earthquakes will continue to occur in such active zones.

Where one or more destructive earthquakes or many moderate shocks have occurred, earthquake risk has generally been recognized. However, some regions with late Quaternary faulting exhibit very little siesmicity, and risk in these areas is generally underestimated, or at least unevaluated. In order to evaluate earthquake potential in such areas, it is useful to interpret the maximum rupture lengths and, where feasible, the recurrence interval of surface faulting events. This is a difficult task, and available data generally do not permit better than order-of-magnitude estimates of recurrence. Underlying this procedure is the fundamental belief that the presence of late Quaternary faulting is much more representative of long term (and future) earthquake risk than is a lack of historic seismicity. This belief is borne out by historical records from Asia, which show that, in some active regions, major earthquakes may be separated by 200 to 1,000 or more years of seismic quiescence. Therefore, we in the western United States should be very cautious when interpreting our 50-200 years of earthquake history.

Not all earthquakes are associated with late Quaternary surface faulting. Many low-magnitude (less than 5) shocks occur as swarms, probably associated with the release of localized stress concentrations. In the western United States, swarm activity tends to occur in areas of geothermal manifestations and in connection with the filling of reservoirs.

In the following discussion, general relationships between earthquakes and faulting are described. The most important factors considered are: maximum size and recurrence of surface faulting events; magnitude versus frequency of occurrence of earthquakes; and earthquake magnitude versus fault length.

INTERPRETATION OF FAULTING

The numbers and lengths of late Quaternary fault offsets of various ages can be a useful indicator of maximum magnitude and frequency of occurrence of large earthquakes in a given region. While these data are often considered more representative of long-term seismic hazard than are historic seismicity data, they are not entirely satisfactory either.

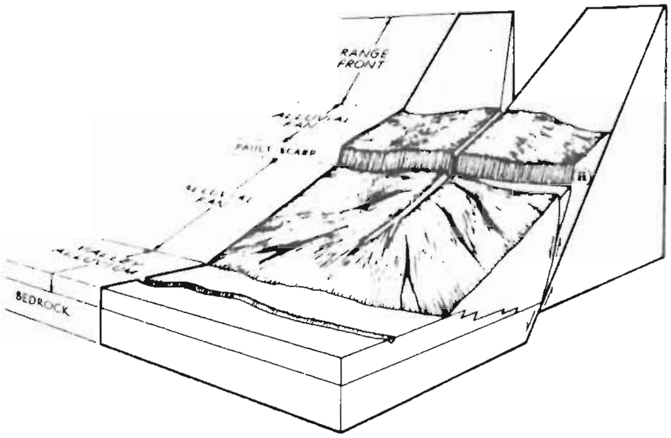
Knowledge of young fault displacements is certainly incomplete, especially in remote, little-investigated regions. In alluviated areas, erosion and deposition may be so active that scarps or other offsets of geomorphic features will be largely destroyed within a few centuries. On the other hand, bedrock topography may be so rugged as to make identification of fault-related features extremely difficult, if not impossible. It is important to bear these factors in mind when analyzing young faults.

If the lengths, magnitudes, and approximate ages of recent fault displacements were thoroughly known in a given region, then one could make a quantitative estimate of the frequency of occurrence and magnitudes of the associated earthquakes. However, such data are generally quite incomplete, and reliable age estimates of fault movements are essentially non-existent. For Idaho, available data are considered generally adequate for determining maximum credible events; but data supporting recurrence calculations are limited to the southern part of the Basin-Range Structure province.

Within the region under study, Quaternary faulting appears to be characterized almost entirely by dip-slip movements on normal faults that bound block-faulted mountains. As presently known, practically all such faulting is confined to the Basin and Range province and the Basin-Range Structure province. In these areas, late Quaternary fault scarps are generally found in alluvial fans at the foot of the upthrown block.

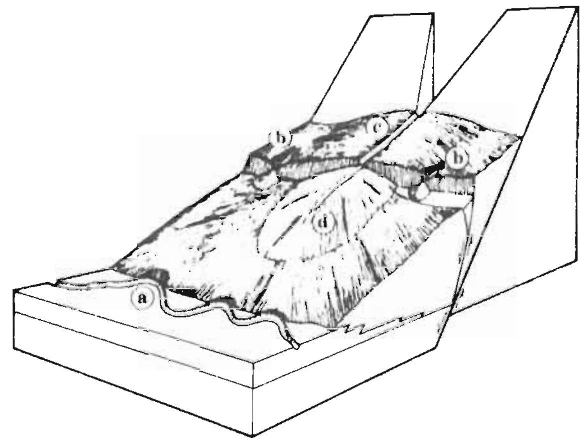
Typical erosional and depositional changes that accompany the ageing of such scarps are shown in figure 3. Not shown in the replacement of the original scarp face, with initial slopes of some 50° - 70°, by a stable debris-slope (30°-37°). This occurs in a few thousand years, and the debris-slope may then persist for a few hundred thousand years (Wallace, 1975). The time scale given in figure 3 is only tentative, because rates of erosion and deposition may vary widely depending upon climate, stream gradient and watershed area, and the makeup of the alluvial-fan debris.

For this study, the age of most recent faulting has been classified as Holocene (last 10,000 years, including historic time), Wisconsin (last 100,000 years), Quaternary (last 2,000,000 years), and older. These classifications are somewhat arbitrary, but convenient; they are thought to be the best that the available data will allow. Faulting assigned to Holocene time is characterized by highly continuous, little-eroded scarps in alluvium; they may cut stream deposits no older than the Pluvial period of about 11,000 years ago. Fault scarps assigned to the Wisconsin glacial epoch are more or less discontinuous, eroded, and may be locally covered by new alluvial cones, while most such scarps are believed to represent movement during Wisconsin time, some may be a few hundred thousand years old. The faults



SKETCH 1

The existing fans are offset by fault movement. The new break refracts up through the gravels above the bedrock fault. A fault line graben is formed at point (a). The position of the mountain stream and the creek in the valley are shown at the time of surface fault displacement.



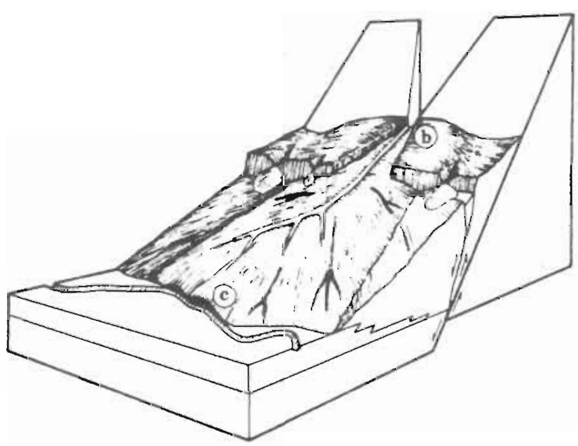
SKETCH 2

(a) Lowering the valley block causes the stream to shift to the low side of the valley. Scallop-like erosional escarpments form at the toe of the fan.

(b) Notches and colluvial cones form slowly away from drainages from the mountain valleys.

(c) Along valley drainage, downcutting proceeds rapidly on the 'mountain' side of the fault.

(d) Much of the material eroded uphill from the fault is deposited downhill as a secondary fan.

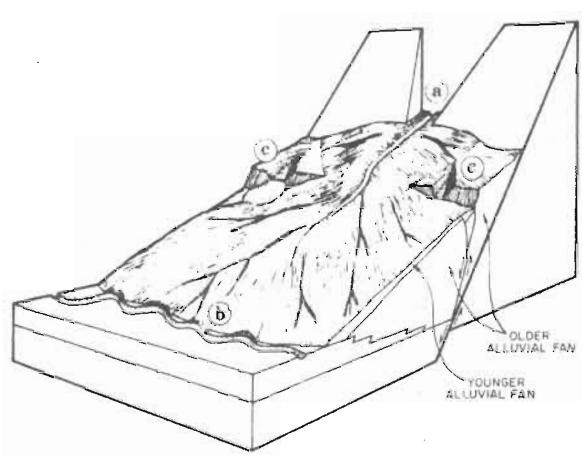


SKETCH 3

(a) By erosion uphill and deposition downhill, the stream establishes a new temporary gradient from the mountains to the creek.

(b) Uphill from the escarpment, the mountain stream cuts laterally building erosional escarpments from the fault scarp back to the range front.

(c) The lower part of the fan pushes the creek back toward the center of the Graben Valley.



SKETCH 4

(a) The fan builds upward and back into the mountain valley. The fan builds over and buries the fault scarp.

(b) The creek and the fan reach an equilibrium point with a few erosional escarpments, most of the contact is gradational.

(c) Most of the surface which was exposed at the time of fault movement is buried by the new fan deposits. Only discontinuous fragments of the scarp remain.

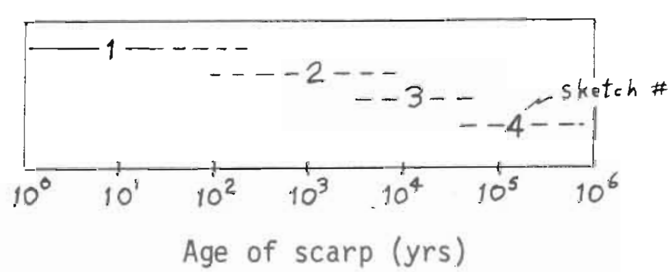


Figure 3. Geomorphic changes in normal fault scarps with age. (sketches from Woodward-Clyde Consultants, 1975)

simply designated as "Quaternary" are expressed as bedrock faultline scarps, along which erosion, and therefore rates of offset, have varied widely. It was generally not feasible to assess relative age of these scarps.

EARTHQUAKE MAGNITUDE VERSUS FAULT LENGTH

In order to estimate earthquake potential from surface fault data, it is necessary to know the relationships between fault dimensions and magnitude. Many theoretical papers have dealt with this fundamental aspect of earthquake mechanics; for our purposes these are not particularly useful. Rather, we shall rely on empirical curves relating these parameters.

Empirical curves relating magnitude to fault rupture length and to displacement have been developed by a number of workers. For both fault length and displacement, there is a great deal of scatter in the data points, but it is less for length than for displacement; figure 4 shows fault length versus magnitude.

EARTHQUAKE MAGNITUDE VERSUS FREQUENCY

It is universally observed that the frequency of occurrence of tectonic earthquakes is an exponential function of their magnitude. The frequency-magnitude function is expressed by the equation:

$$\log N = a-b(m-M_0)$$

where N is the average number of earthquakes of magnitude M or greater, per unit time; the constants "a" and "b" are determined from the observed distribution of earthquakes in magnitude intervals for some period of time; and M_0 is the minimum magnitude treated.

The constant "b" has a worldwide average of about 0.9, making a sevenfold decrease in frequency for each unit increase in magnitude; in the western United States, "b" ranges from about 0.6 to 0.9. The constant "a" varies widely from area to area, and may be considered a basic index of seismicity. It may be reckoned as the logarithm of the number of shocks of magnitude M_0 <u>or greater</u> per unit time (usually per year).

Another way of stating earthquake statistics is in terms of recurrence interval, which is simply the reciprocal of frequency. This is convenient in discussing larger earthquakes, which may occur only once in several hundreds or thousands of years in some regions.

Experience has shown that earthquake statistics representative of long-term seismicity can only be obtained from a time-area sample of sufficient size. This may be of the order of at least 10^7 square kilometer years, e.g. 100,000 km^2 (40,000 $mi.^2$) for 100 years. Because the effective record of seismographically recorded earthquakes in the western United States is only about 40 years long, we infer that here the minimum valid sample area is about 250,000 km^2 (100,000 $mi.^2$) within the same tectonic province. This is roughly the area of the entire State of Idaho; therefore, observed differences in seismicity between sub-areas of Idaho might not be statistically valid.

GENERAL FEATURES OF STUDY AREA

Plate 1 shows the location and relative ages of Quaternary faulting as presently known in Idaho and adjacent areas. The criteria used in making age classifications were described above.

Generally it may be seen that faults exhibiting Wisconsin and Holocene (includes historic) movement are limited to the southeastern portion of Idaho and adjacent parts of Montana, Wyoming, and Utah. All are normal faults which bound fault-block mountains chiefly within the Basin and Range province and area of basin-range structure north of the Snake River Plain. This pattern is impressively interrupted by the SRP, as is that of historic seismicity within the Intermountain Seismic Belt (figure 5 and plate 2).

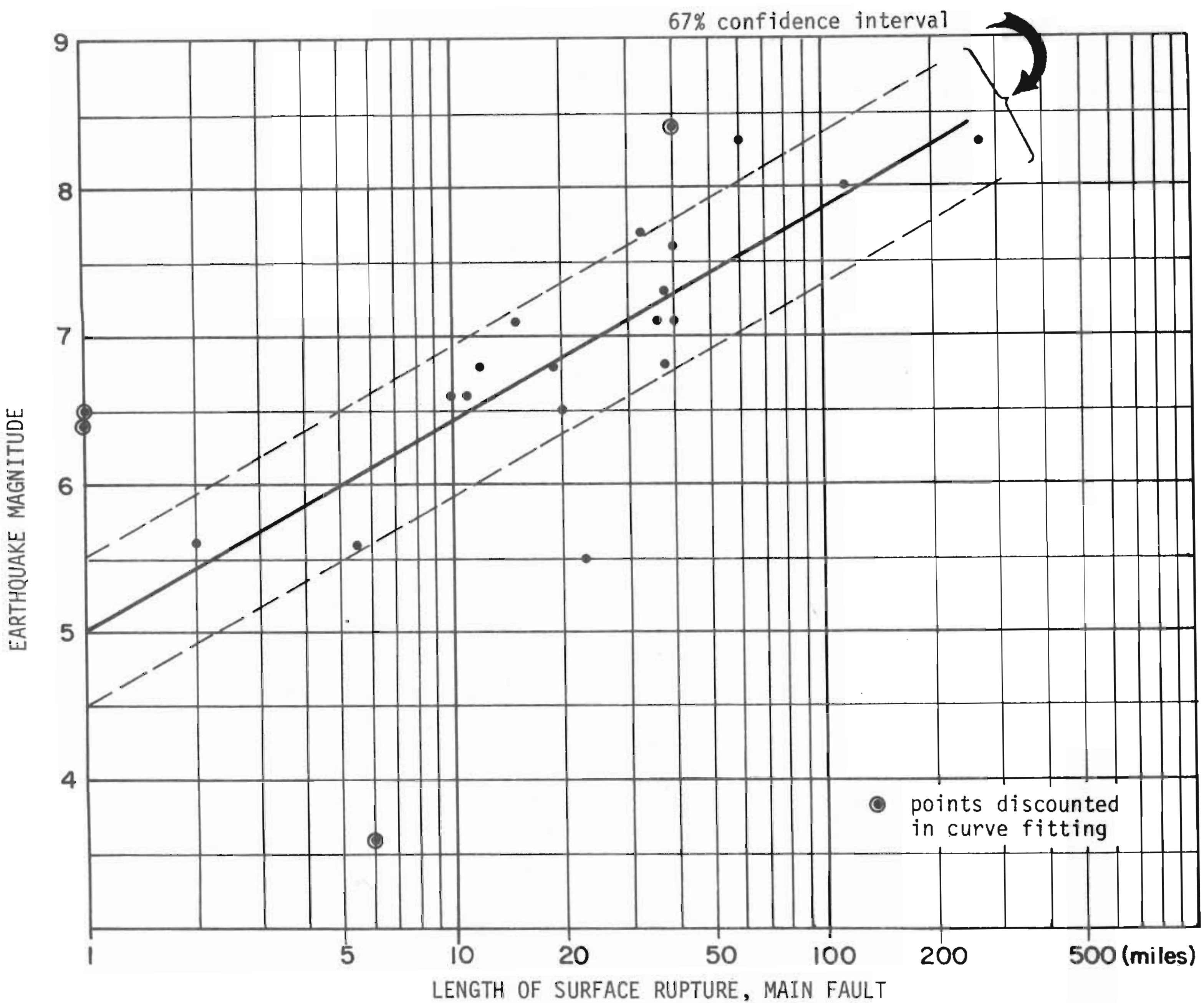


Figure 4 - Earthquake magnitude versus fault rupture length (data from Bonilla, 1970).

The Intermountain Seismic Belt (ISB) shown in figure 5, extends along the west margin of the unstable continental platform (figure 2), and includes southeasternmost Idaho as well as adjacent areas of Utah, Wyoming, and Montana. It is roughly coincident with the belt of late Quaternary faulting just described. Excepting the Idaho Batholith, nearly all historic seismicity of Idaho falls within the ISB.

The frequency of occurrence of earthquakes observed in the entire ISB is considered representative of long-term seismicity within various portions of it, on a pro-rata basis. Magnitude versus frequency of occurrence in the ISB, for the years 1932 through 1961, is plotted in figure 6. Because smaller earthquakes were not fully reported in this region before 1963, the b-slope shown (0.61) is probably too small. However, the curve is considered adequately representative of magnitudes greater than 5. It shows that the recurrence interval for M = 7 or larger shocks is about 10 years. On a pro-rata basis, this may be expressed as about one M= 7 or larger shock per 350 years per 10,000 km^2 (4000 $mi.^2$); for magnitude 6 shocks, recurrence is about 85 years per 10,000 km^2. This rate of seismicity is considered to be the <u>maximum</u> that affects Idaho.

The largest historic earthquake that has occurred in the ISB is the Hebgen Lake event of August 17, 1959, with a magnitude of 7.1. Other large shocks have had magnitudes in the range 6-1/2 to 7, mostly about 6-1/2. Except for the Hebgen event, no earthquake within 80 km (50 mi.) of Idaho or in Idaho has had a magnitude above 6-1/2. Thus, M = 7 is considered the maximum credible earthquake that can be expected in the study area. Lengths of individual Holocene scarps do not exceed 15 km (10 mi.) in Idaho, indicating a maximum credible magnitude of 6-1/2 in the state.

In the Idaho Batholith, documented Quaternary faulting is very sparse; however, this could be partly accounted for by a lack of recognition. Seis-

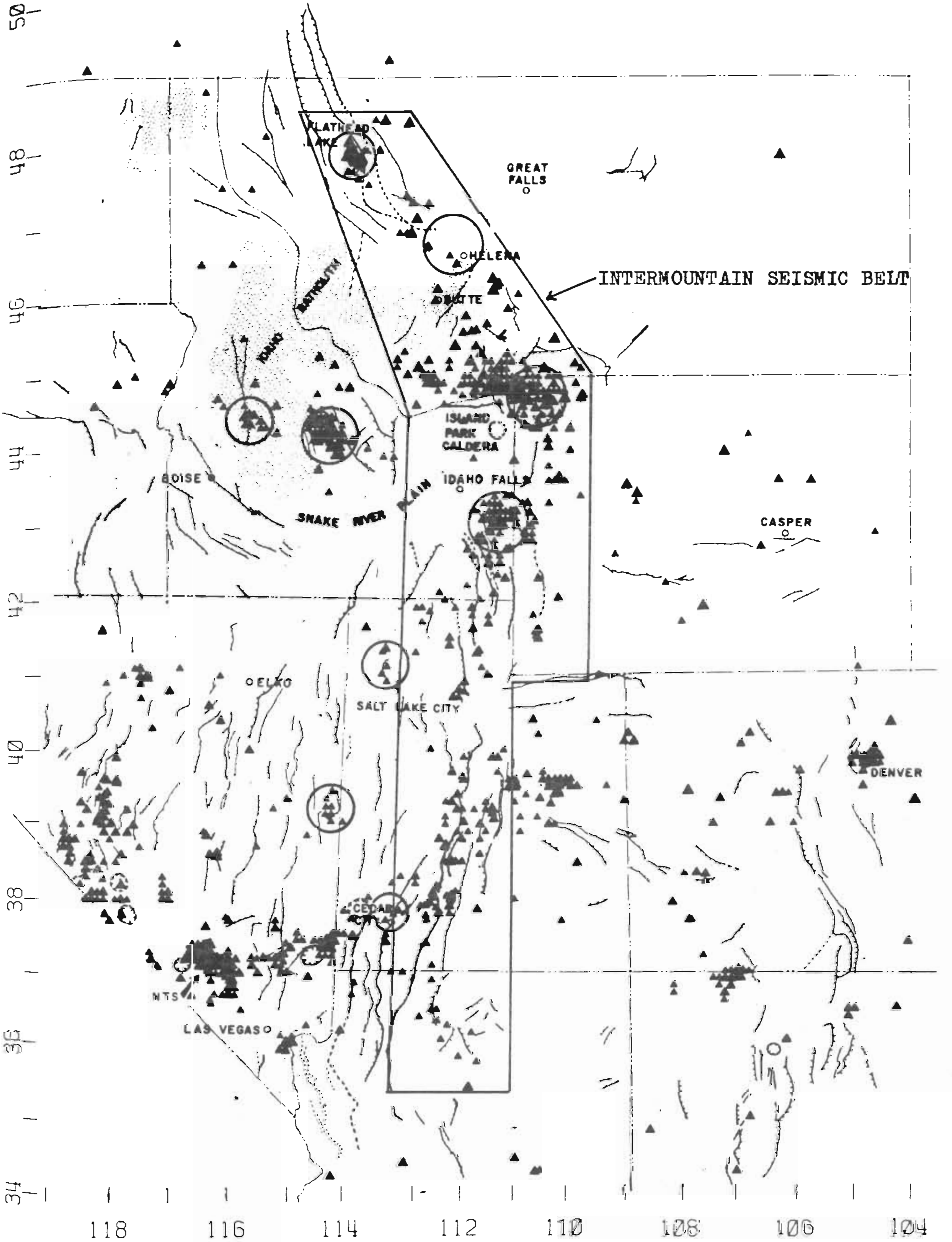


Figure 5. Seismicity of interior Cordillera, 1961-1970, and location of Intermountain Seismic Belt. Circles mark locations of earthquake swarms. (adapted from Smith and Sbar, 1974)

micity is in part characterized by swarm activity, involving large numbers of small shocks, apparently associated with geothermal activity. Two larger earthquakes, of magnitude 6, occurred in 1944 in the vicinity of recent faulting.

The area of late Quaternary faulting just east of the southern part of the batholith is noteworthy for its lack of historic seismicity. This absence of seismicity is misleading, as will be demonstrated in the following section of the report.

Throughout the rest of the state, the relationship between early Quaternary faulting and sparse historic seismicity is unclear. Based on the lack of late Quaternary faulting and historic earthquakes, we may conclude that long-term seismicity in the Snake River Plain and Northern Cordillera is a few orders of magnitude lower than in the ISB.

In the following section, faulting and seismicity are interpreted in greater detail.

INTERPRETATION OF DATA

Information Sources

Faults. A series of three Quaternary fault maps, for Idaho, western Montana, and western Wyoming, covers most of the study region (Witkind, 1975). The maps are at a scale of 1:500,000, and appear to provide a reasonably complete description of the locations of known Quaternary faulting, as well as some of Mio-Pliocene age. The present study relied upon them for fault locations. Also shown on these maps are the ages of youngest beds broken by the faults.

A catalog accompanying each map supplies comments and references for each faults; however, the given data are insufficient to support the age classifications. Thus, it was necessary to further investigate recency

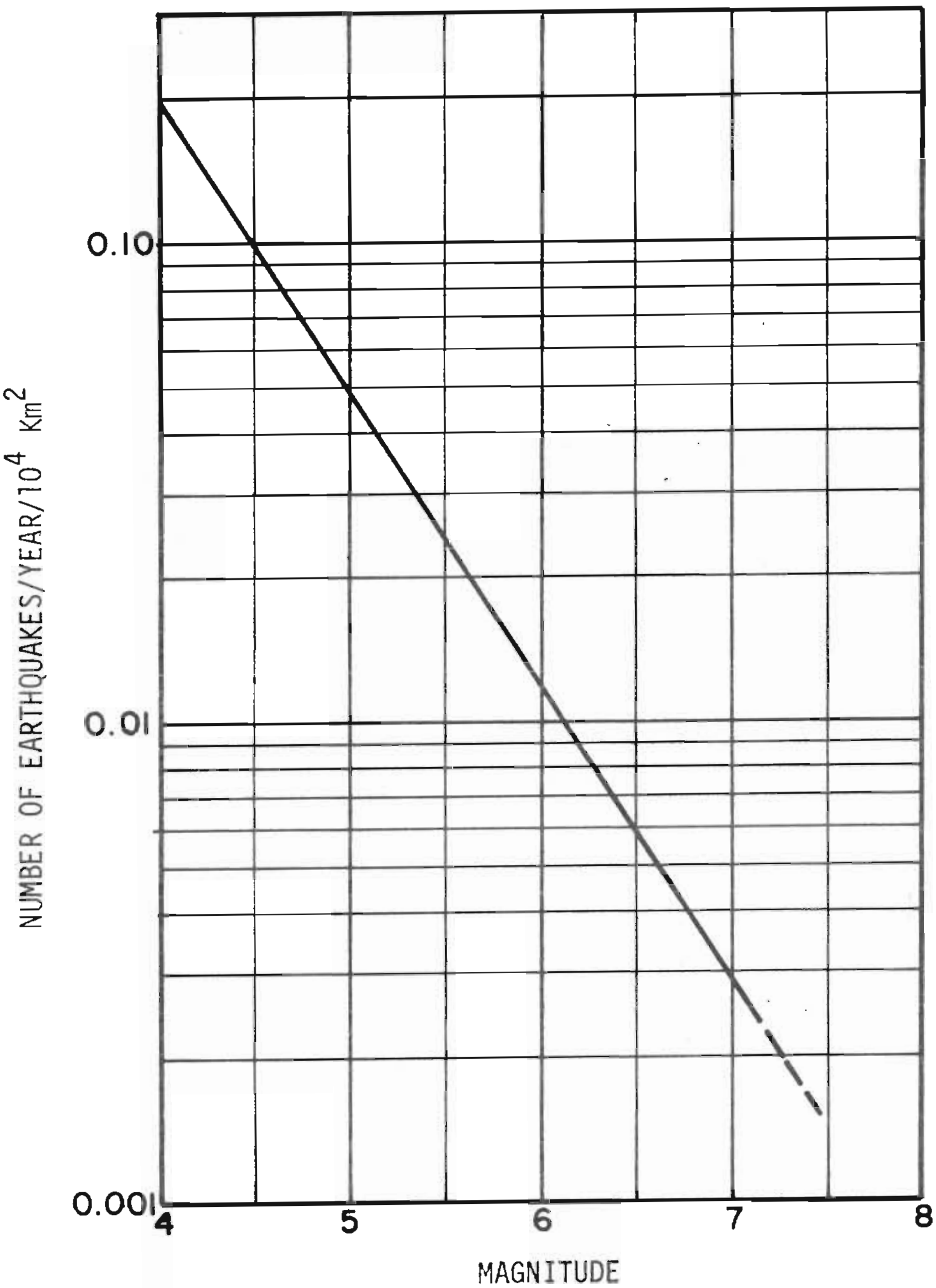


Figure 6 - Frequency of occurrence versus magnitude for earthquakes of the Intermountain Seismic Belt, 1932 - 1961 (see fig. 5 for area covered)

of faulting. This involved checking the geological literature, viewing aerial photographs, and making an aerial reconnaissance. Based upon this investigation, a number of significant changes and refinements were made, as described below. Still, many uncertainties remain. Except as noted below, Witkind's age classifications have been adopted in this study.

Earthquakes. For the period preceding about 1932, earthquake data for the United States are based almost entirely on felt and damage reports, from which intensities and approximate epicenters were derived. Preinstrumental epicenter locations may easily have errors of 30 km (20 mi.) or more, depending upon population distribution, vast numbers of small-moderate shocks (magnitude less than 4-1/2) were never reported. In the early 1930's, the U. S. Coast and Geodetic Survey began installation of a number of seismographic stations, which, in combination with university-operated stations, provided reasonably complete reporting of earthquakes with magnitudes greater than 4-1/2 ± 1/2, depending upon their location. Epicenters located using these stations were generally better than before, but errors still could be up to 30 km (20 mi.) or sometimes more. Instrumental magnitude data were rarely reported until 1962. Beginning in about 1962, seismographic coverage in the western U. S. was vastly improved as a result of Defense Department sponsorship of many new stations. Since that time, detection and reporting of earthquakes of magnitude greater than 3-1/2 has been complete, epicenter locations are now probably accurate to within about 15 km (10 mi.).

Before 1962, reporting of earthquakes in the Idaho region was poorer than average, first on account of sparse population, and later because of weak station coverage. Throughout the period 1932 - 1962, no stations operated in Idaho, and for much of this time the nearest stations were at Spokane, Butte, Salt Lake City, and Mt. Lassen. Since 1962, many seismograph stations have been installed in northern Nevada and Utah, Yellowstone Park, eastern Oregon, and the eastern Snake River Plain.

The effect of these changes can readily be seen in the NOAA (National Oceanic and Atmospheric Administration) earthquake records for the study area (epicenters are plotted on plate 2). While only 75 earthquakes are reported from 1904 to 1963, 265 are reported from 1963 to early 1975, for the area south of latitude 45-1/2° N. This represents a 20-fold increase in the rate of reporting. Simple magnitude-frequency calculations using this ratio show that detection and reporting of earthquakes in Idaho before 1963 was quite incomplete for magnitudes less than 5.

Basin and Range Province

In the southeastern corner of Idaho, the bulk of young faulting appears to have occurred along three fault zones. From west to east these are: the Wasatch front system, extending northward from Salt Lake City, Utah to Malad City; the west and east Cache Valley faults, extending from the vicinity of Logan, Utah to Oxford and Preston, respectively; the Bear Lake graben, extending northward from the Utah border to the vicinity of Soda Springs.

In Utah, the Wasatch and Cache Valley faults exhibit abundant scarps in alluvial fans (Woodward-Lundgren and Associates, 1974). While most of these are probably Wisconsin or older, some are very likely Holocene in age. In Idaho, these two fault zones seem to be less active: associated bedrock scarps are lower and more eroded, and alluvial scarps, if they exist, are not prominent. Neither inspection of aerial photographs nor aerial reconnaissance (air reconnaissance) substantiated the existence of alluvial fault scarps, as mapped by Witkind (1975). However, marked seismicity along the Utah border does indicate that these faults are active.

The Pocatello Valley earthquake (magnitude 6.1, March 28, 1975) and numerous after shocks occurred just a few miles west of the Wasatch fault. Just south of Pocatello Valley, the Hansel Valley earthquake (M = 6.6) produced surface faulting in 1934. North of Malad City, there is no evidence of either late Quaternary faulting or historic seismicity.

The Bear Lake graben fault system is definitely active. A 16 km (10 mi.) long late Holocene scarp in bedrock north of Montpelier was highly visible in air-recon., and many very fresh scarps break Wisconsin-age basalts north of Soda Springs. Although young scarps were not evident along the west side of the graben, faults there should also be considered active, on the basis of structural relations and seismicity.

Grand Valley graben, east of Idaho Falls, exhibits tall but rather eroded bedrock fault scarps (spur facets), and no scarps in alluvium. Witkind (1975) mapped a series of short Wisconsin faults in alluvium on the valley floor, but these could not be substantiated, perhaps because extensive plowing has obliterated them. Gravity data indicate several thousand feet of displacement on the faults bounding on the graben.

Diffuse swarms of small earthquakes recorded near the south end of Grand Valley, beneath the Caribou Range, appear to be related to changing water levels in Palisades Reservois (Schleicher, 1975; Sbar et al, 1972). Similar phenomena noted at many reservoirs indicate that changing loads can trigger release of tectonic stress; earthquakes with magnitude up to 6-1/2 may have been so triggered. Holocene fauting is reported in Star Valley, Wyoming, on trend with Grand Valley. Thus, it is concluded that the Grand Valley faults should be treated as potentially active.

The Heise fault, on trend with the Grand Valley structure on the north, forms a high scarp in late Quaternary Snake River basalts. Because of its structural relationship with the graben, it too is considered potentially active.

In adjacent Wyoming, several faults are mapped as Holocene by Witkind (1975), and in any case they are certainly major-displacement Wisconsin faults. Thus, they are considered as active.

West of the Bear Lake graben - Soda Springs fault system, many early Quaternary or older normal faults are mapped (Witkind, 1975). Aerial reconnaissance showed that these are expressed by highly eroded, subdued, bedrock fault-line scarps. No seismicity has been reported in their vicinities. Therefore, they are considered inactive.

Magnitude-frequency data for this area (figure 7) indicate a recurrence interval of approximately 250 years for M = 6.5, per 10^4 km^2 (4000 $mi.^2$).

No earthquake larger than M = 6.6 has been recorded in this region. Documented Holocene scarps which may represent just one event range in length from 15 to 35 km (9-22 mi.) indicating a maximum credible magnitude of approximately 7; in Idaho, the Montpelier fault has the longest Holocene scarp 15 km (10 mi.), indicating a magnitude of about 6-1/2. Thus, M = 6-1/2 is considered the maximum credible magnitude in this part of Idaho.

Basin-Range Structure Province

The concentration of Holocene-and Wisconsin-age fault scarps in the southern part of this province is impressive. These are located in southeastern Lemhi, eastern Custer, and Butte Counties, Idaho, and adjacent parts of Montana, including areas north of Clark and Fremont Counties. In the Montana portion of this area, major historic seismicity is recorded, but only a few small shocks (M less than 4) are recorded in Idaho. That this seismicity "hole" is probably misleading is demonstrated below.

Classic basin-range structure, characterized by tilted fault blocks

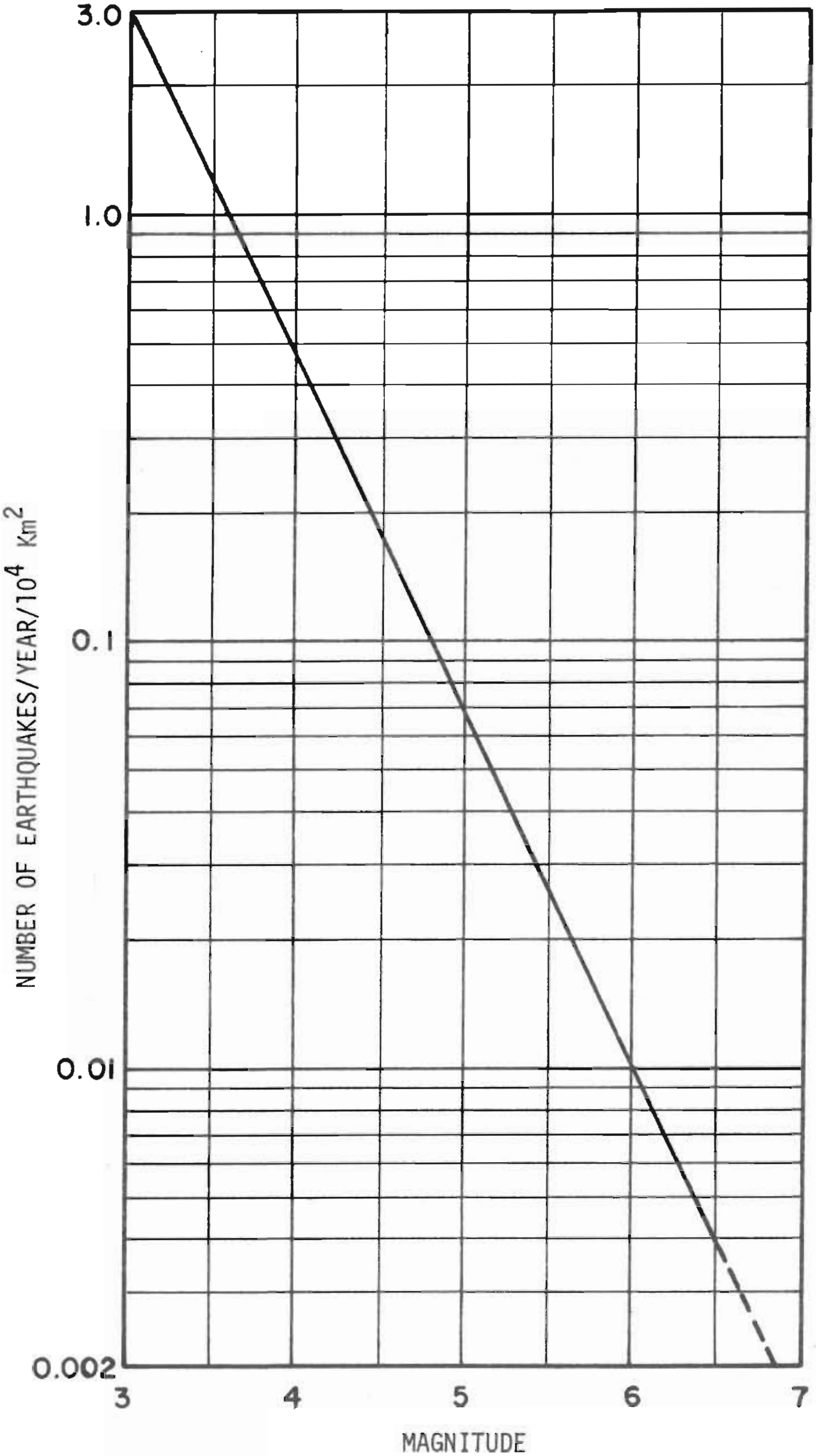


Figure 7 - Magnitude versus frequency of occurrence of earthquakes in the Basin and Range province in Idaho and adjacent area, 1932 - 1975

separated by broad, alluviated basins, occurs between the Idaho Batholith on the west, and the Madison Range on the east. The Centennial Mountains and Valley, separated by a late Wisconsin-age fault, form an anomalous east-trending structure, described in the first major section of this report. Cumulative displacements along these normal faults reach several thousand feet, a large part of which has occurred in Quaternary and latest Quaternary time.

North of latitude 45-1/2°, Quaternary faulting is very sparse, and no scarps of Wisconsin or Holocene age are documented within Idaho or 50 miles east of the Montana border. No earthquakes are reported in this same area. Because of the combined lack of young faulting and seismicity, this area is believed to have very low earthquake risk.

Idaho Portion. Late Quaternary faulting occurs along the west sides of the Lost River, Lemhi, and Beaverhead Ranges. Much of this is as young as Wisconsin, and some is as young as Holocene age. Generally, youngest faulting occurs in the southeastern half of the area comprised by the three ranges.

Because of their proximity to the Idaho National Engineering Laboratory (INEL) facilities at Arco, considerable attention has been given these faults. Malde (1971) made a very detailed analysis of scarps in alluvial fans along the Arco and Howe faults, at the south end of the Lost River and Lemhi Ranges, respectively. Deep trenches dug across the scarp indicated displacements of gravel horizons totalling 12 to 15 or more meters (40-50 ft.). On the South Howe scarp, 12 meters (40 ft.) of cumulative offset, which probably occurred in four or more separate events, pre-date unbroken buried caliche soils, tentatively dated at 30,000 years; at least 3 meters (10 ft.) of movement post-dates this horizon. Along the Arco scarp, 12 meters (40 ft.) of cumulative offset pre-dates the caliche soils, and indicates 2 or 3 separate faulting episodes. In both cases, uncertainties of soil stratigraphy allow that movements could have occurred from 4,000 to 10,000 years ago.

More recently, Woodward-Clyde Consultants (1975) made aerial and ground reconnaissances of faulting in this area, the results of which have been corroborated by study of aerial photographs and air reconnaissance conducted for the present study.

Witkind (1975) has shown all of these faults as Wisonsin, based apparently on scarce published data. Age designations shown on plate 1 represent the writer's interpretation.

As shown on plate 1, some 142 linear km (88 mi.) of probably Wisconsin-age faulting and 29 km (18 mi.) of Holocene faulting are considered fairly well substantiated. Although shown as Wisconsin on plate 1, the fault segment between Nicholia and Blue Dome may actually be Holocene, according to data presented by Woodward-Clyde. In addition to the 171 km (106 Mi.) of Wisconsin-Holocene faulting, some 190 km (118 mi.) of bedrock scarps were observed. Some of these are marked by well-developed spur facets indicating late Quaternary displacements totalling several hundred meters.

Although reliable estimates of scarp heights are not generally available for this area, it is estimated that those of Wisconsin age are generally from 6 to 12 meters (20-40 ft.) high; those of Holocene age, generally from 3 to 5 meters (10-15 ft.). It can be assumed that, on the average, a 1.2 meter (4 ft.) normal-fault displacement is accompanied by a magnitude 6.5 earthquake (Bonilla, 1967). If so, then on the average, Holocene scarps represent from 2 to 3 and Wisconsin scarps from 5 to 10 shocks of M = 6.5. It may also be assumed that each M = 6.5 event is accompanied, on the average by 15 linear kilometers (10 mi.) of faulting. Thus, the observed scarp mileages imply the occurrence of between 50 and 100M = 6.5 shocks. Based upon their relative heights and appearance and the assumption of a rather constant level of activity, most of the observed scarps probably record offsets less than 100,000 years old. Therefore, the fault data suggest a recurrence interval of from 1,000 to 2,000 years for M = 6.5 shocks in the area comprising the three range fronts.

A nine-month long microearthquake survey was conducted in this area in 1969 (Pitt and Eaton, 1971). The station network had a sensitivity sufficient to record magnitude 1 shocks within 100 km (60 mi.) but did not detect a single shock in this region. Since July 1973, the INEL at Arco has operated a high-gain seismograph network of four stations in the area of the eastern Snake River Plain. By September 1975, the net had detected several dozen small shocks (M = 1 to 3) in and near a triangular area with vertices at Salmon, Challis, and Leadore. The majority of these occurred near the frontal faults along the Lemhi and Beaverhead Ranges near Patterson and Leadore, respectively. No shocks were located more southerly than about 25 km (16 mi.) south of Leadore.

Therefore, earthquake recurrence estimated from faulting seems reasonable as it does not conflict with the low-level of observed seismicity, but still indicates a significant rate of fault activity. It is noted that the computed recurrence of M = 6.5 events is from 1/4 to 1/8 that of the adjacent Intermountain Seismic Belt, on a per-area basis.

Montana Portion. From the Tendoy Mountains to the vicinity north of Yellowstone Park, several late Quaternary faults are documented. Of these, the Centennial and Madison Range frontal faults are impressive for their length and youthful scarps.

A number of earthquakes have been recorded in the vicinity of the Madison and eastern Centennial faults. The August 17, 1959 Hebgen Lake earthquake, M = 7.1, was accompanied by 24 km (15 mi.) of faulting, and most seismicity occurring since that time, within 30 km (20 mi.) of the main shock, seems to comprise aftershocks of it. Before 1959, only eight earthquakes large enough to be felt were reported in this area; the largest of these, M = 6-1/4, occurred on November 23, 1947, with epicenter located a few kilometers north of Centennial Valley. Another group of epicenters lies scattered across Beaverhead County; the largest earthquake here had M = 5.1.

Only about two dozen earthquakes in the area can be easily distinquished from the many aftershocks of the Hebgen Lake earthquake. This is insufficient data on which to base magnitude-frequency analysis. Therefore, the area is assumed to have seismicity characteristic of the Intermountain Seismic Belt.

Idaho Batholith

Only three late Quaternary fault scarps are mapped within this province: two branching faults along the Deadwood River, and a very short scarp in southern Sawtooth Valley, break Wisconsin glacial deposits. Although limited data suggest that swarm activity may characterize the seismicity of the batholith, the occurrence of two magnitude 6 earthquakes (in 1944 and 1945) suggests significant tectonic stress. One of these shocks had its epicenter on the Deadwood Creek fault; the other was located 24 km (15 mi.) to the north, on trend with the same fault. Since 1963, six smaller shocks (M = 3.5 - 4.3) have had epicenters within 24 km (15 mi.) of the fault.

Practically all of the remaining recorded shocks have occurred as part of a diffuse swarm centered east of Sawtooth Valley; this began in 1963 and most activity ceased in June 1969. Some 50 shocks of magnitude 3.1 to 4.9 had epicenters in a zone 70 km (45 mi.) long and 40 km (25 mi.) wide, extending southeasterly from Sunbeam. Some of this spread represents epicenter location error. A microearthquake survey in 1964 located epicenters near a major zone of hot springs in the Sunbeam district and along a contact between granitic and Paleozoic sedimentary rocks (Smith and Sbar, 1974). The b-value (magnitude-frequency) for this swarm was 1.3, which is farily typical of swarms.

Although the causes of swarms are not well known, they are frequently associated with geothermal and volcanic activity, and may be caused by release of localized stress along fractures subjected to unusually high pore pressure of fluids. While a majority of swarms have maximum magnitudes less than 5, they sometimes occur as foreshocks preceding M = 6 to 7 earthquakes. However, foreshock swarms seem to be limited to areas of major contemporary tectonism, such as the Imperial Valley and Japan. Therefore, it is believed that swarms in the Idaho Batholith are of the ordinary, non-foreshock type.

Fault and earthquake data for this area are ambiguous. It is probable that some known and unknown faults have had significant but undetected Quaternary movement. Earthquake data are too sparse to construct a magnitude-frequency curve, except for the above-described swarm (figure 8); this probably does not represent the entire batholith.

Late Cenozoic faulting and crustal extension has certainly been greater in the adjoining region of basin-range structure than in the batholith, and it is assumed that this represents relative present-day tectonism in the two regions. It has already been calculated that the recurrence interval of M = 6.5 shocks in the adjoining Basin-Range structure province is of the order of 1,000 years. This is thought to represent a minimum for the entire southern part of the batholith (south of 45-1/2° N). Interestingly, this is near the value obtained by extrapolating the magnitude-frequency curve representing 1963-1970 swarm activity east of Sawtooth Valley.

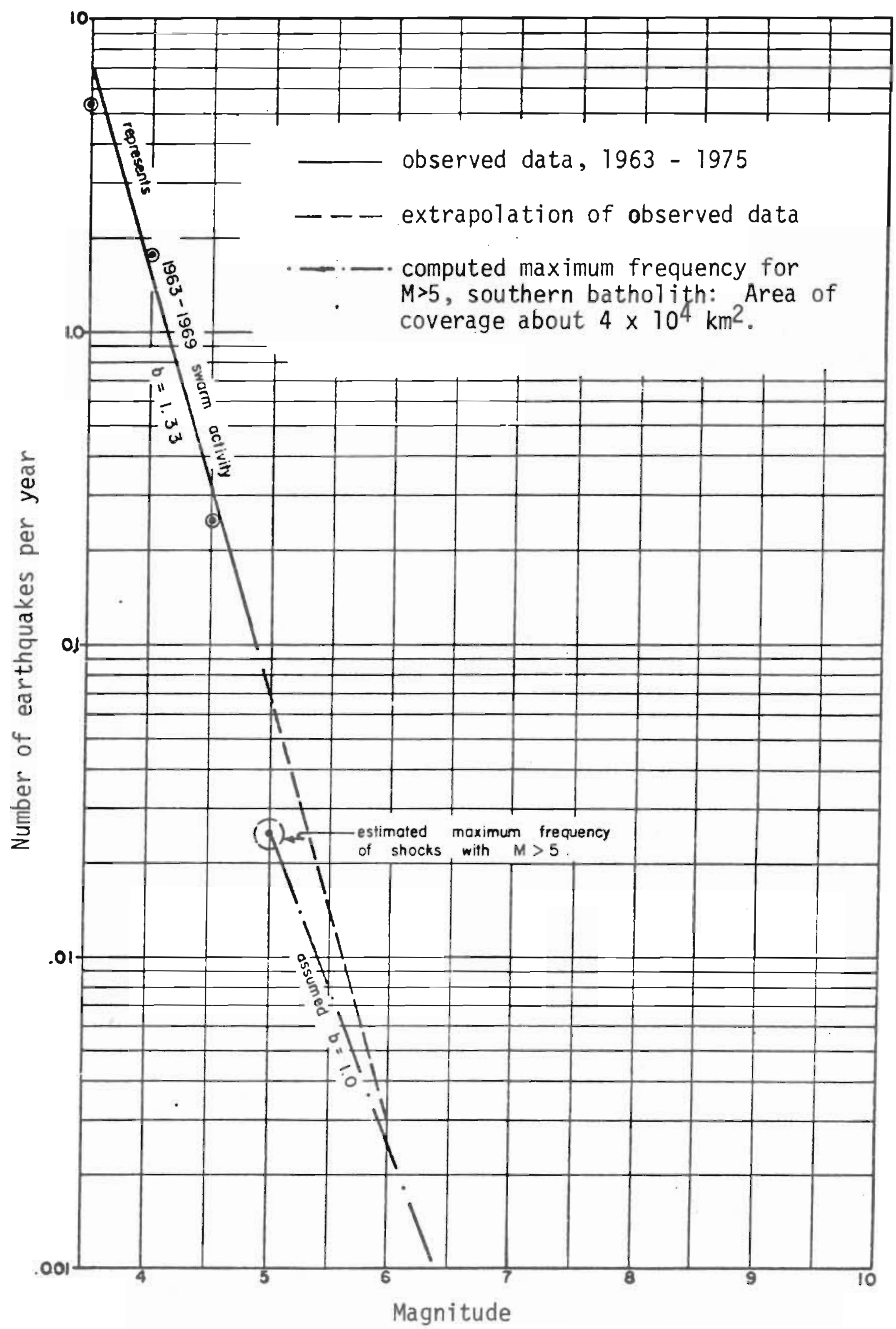


Figure 8 - Magnitude versus frequency of occurrence for the Idaho Batholith

These results imply two things. First, it seems that the swarm activity of 1963-1970 could be nearly representative of the entire southern part of the batholith. Second, the two M = 6 shocks near the "Deadwood" fault should be considered as a single double-shock event, with an average recurrence interval of at least 300 years. The fact that no shocks of magnitude 5.0 to 5.9 have been reported during the 40 year period since 1935 strongly supports this notion. It implies that the maximum frequency of occurrence for $M > 5$ is .025/year. Assuming a reasonable b-slope of 1.0, one may draw a curve through this point, predicting maximum frequency of earthquakes of greater magnitude (see figure 8). This indicates a recurrence interval for M = 6.5 of at least 1,000 years for the southern portion of the batholith, in agreement with the tectonic hypothesis.

Distribution of hot springs, as well as that of seismicity, suggests that the area north of latitude 45-1/2° is much less active than that to the south. Although profuse south of that latitude, documented hot springs are non-existent to the north (White and Williams, 1975). The complete lack of seismicity, documented Quaternary faulting, and hot springs indicates that, north of latitude 45-1/2°, the batholith should be considered as nearly aseismic.

Northern Cordillera

Northern Region. North of latitude 45°, only six small shocks have been reported in Idaho; within 80 km (50 mi.) of the border, only six. The largest of these occurred just west of Pend Oreille Lake in 1942, with intensity VI (no damage reported at nearby Sandpoint). The nearest area of significant seismicity is around Flathead Lake, Montana, where a swarm occurred in 1964, with magnitudes up to 4.8; two larger events (intensity VII-VIII) have also occurred in this area. Except for the Flathead Lake area, the entire region of eastern Washington, Idaho and far western Montana north of latitude 45° is almost aseismic. Furthermore, no Quaternary faulting is documented in this region. Therefore, seismic risk is considered negligible here.

Western Region. North-trending normal faults are abundant along the western margin of the batholith, and seem to have formed chiefly as a result of uplift of the batholith in Pliocene time. Although tilting of early Quaternary strata seems to have accompanied continuing uplift, there is no definite evidence of late Quaternary faulting in this area; however, one report of a young scarp in alluvium is discussed below.

Minor seismicity has been reported in the vicinity of Cascade Reservoir. The NOAA file (see plate 2) shows three small shocks, one with magnitude 3.5, one with intensity IV, and another of unreported size. A microearthquake survey by Dr. James Applegate of Boise State University revealed a number of small shocks at Cascade Reservoir in early 1976. Immediately west of the Snake River, in Oregon, three shocks have been reported, the largest of which had magnitude 4.3.

On May 12, 1916, a rather large earthquake affected western Idaho, and had a maximum reported intensity of VII at Boise. Although the NOAA file locates the epicenter at Boise (see plate 2), the actual felt reports demand that the epicenter be located considerably north, and perhaps west, of Boise. Observers at the Reno and Spokane seismograph stations estimated that the epicenter was 640 km (400 mi.) north of Reno and 130 km (80 mi.) southwest of Spokane. Although these distances don't overlap, together they indicate a location from 100 to 320 km (60-200 mi.) north of Boise. Woodward-Lundgren and Associates (1972) have speculated that the epicenter may have been along the Cascade-Sweet fault, but this is purely a matter of conjecture.

Young faulting has been reported along the Cascade-Sweet fault along Squaw Creek, between the settlements of Sweet and Ola (Woodward-Lundgren and Associates, 1972). Based on aerial and ground reconnaissance, fault scarps are said to break stream alluvium along Squaw Creek, and along the flank of the mountains immediately to the west; Dr. Gary Carver, who was responsible for that portion of the 1972 Woodward-Lundgren report, has recently confirmed (personal communication, 1976) the valley-bottom scarps' existence, but allowed that those on the mountain-flank may not actually be fault scarps.

In aerial reconnaissance flown over this area a few hours before sundown, the writer was unable to find the aforementioned - or any other - young fault scarps. Along the flank of the range just west of Squaw Creek, a series of discontinuous, scarps appeared to have been formed by differential erosion of tilted basalt layers. Actually, the highly subdued nature of apparently very old bedrock fault scarps was quite striking in the larger region extending from Squaw Creek to the Snake River.

To conclude, the available data suggest that the potential for large earthquakes is quite low in this region, in comparison with the batholith, the Basin and Range Province, and the Basin-Range Structure province.

<u>Volcanic Rift Province</u>

The almost total tectonic and seismic quiescence of this region, which includes the Snake River Plain (SRP), in late Quaternary and present time is one of the most striking features of the Pacific Northwest. General aspects of volcano-tectonic history, crustal structure, and seismicity, as well as a model explaining them, have already been discussed. Certain additional details are presented below.

Since July 1973, the INEL at Arco has operated a high-gain four-station seismograph network in the eastern SRP. This appears to provide fairly reliable reporting of shocks of magnitude 2 or greater as far west as Shoshone. In two years of recording, only one shock was located in the Snake River Plain; this had a magnitude between 1-1/2 and 2-1/2, and occurred about 15 km (10 mi.) east of Shoshone. In the western SRP, Pennington and others (1974) operated portable 4-station networks at four locations for periods totalling 21 days, and they recorded no shocks at all.

While the above data strongly point to an aseismic condition for the entire Snake River Plain, there is one possible anomaly in the historic record. This is a rather strong shock on November 11, 1905, which had intensity VII at Shoshone. The epicenter of this earthquake is shown by the NOAA file to be at Shoshone (see plate 2). However, given the scarcity of felt data to support it, this location is considered unreliable. To compound the problem, there is significant unresolved disagreement among published earthquake catalogs (Townley and Allen, 1939; NOAA, 1973) and newspaper accounts (Idaho Daily Statesman, Nov. 12, 1905) concerning the time of occurrence of felt shocks for this date and region. Available data suggest that two, or even three, distinct earthquakes occurred in the southern Idaho-northern Utah region on the date in question, and that the largest one was probably centered within 24 km (15 mi.) of Shoshone - perhaps in the Bennet Hills to the north, or perhaps south or east of the town.

Although Late Quaternary faulting, as such, is unknown on the Snake River Plain, fissuring has accompanied recent volcanism in the eastern SRP. Fissures of the Idaho Rift system (plate 1) have been well-documented by Prinz (1970). The system is some 100 km (62 mi.) in length, and extends south-southeastward from the Craters of the Moon. Open fissures up to 250 meters (800 ft.) deep and 2.5 meters (8 ft.) wide characterize the system, and lacking signs of anything but pure pull-apart motion, they must have been formed by purely horizontal, uniaxial tension. A radiocarbon date from oldest lavas along the system indicates that the rifts opened some 2,100 years ago.

It is expected that similar fissures will be formed during future volcanism to be expected in the eastern SRP, and small earthquakes should accompany this. Based upon observations in Hawàii (Fiske and Koyanigi, 1968) and in Iceland (Tryggvason, 1973), earthquakes accompanying such fissuring are unlikely to have magnitudes exceeding 4, but might reach nearly 5.

Finally, we must mention the Boise fault, which forms the northern boundary of the Snake River Plain. A detailed investigation of this fault, conducted by Woodward-Lundgren and Associates (1972), revealed that no displacement has occurred during the last 1/2 million years. Furthermore, no seismicity is associated with the fault. Therefore, it is considered inactive.

Summary of Seismicity

In the preceding, magnitude-frequency curves were plotted for the Intermountain Seismic Belt, Basin and Range province, and the Idaho batholith (southern part). Recurrence intervals for M = 6.5 (designated $T_{6.5}$) and 100 -yr. maximum probable magnitudes (M_{100}), both per $10^4 km^2$ (4,000 $mi.^2$) may be read from the curves; they are listed in table 1.

Values of $T_{6.5}$ and M_{100} have been estimated for the northern Cordillera, northern batholith, Basin Range Structure province in Idaho, and Volcanic Rift province; these are also listed in table 1. The 'b' - slopes for these areas (in table 1) were assumed to be either 0.83 or 1.0, depending on tectonic characteristics. As b-values generally tend to be 0.8 to 0.9 for the more tectonically active areas of the western United States, b = 0.83, which characterizes the Basin and Range province in the study area, was assumed for the southern Basin-Range Structure province. Otherwise, b-values of 1.0 were assumed in areas believed to be tectonically less active. The 'a' - values were estimated either by counting shocks of intensity V to VI, assumed to represent M = 4 to 4-1/2 shocks, or by extrapolation of recurrence of M = 6.5 shocks; the latter was done only for the southern Basin-Range Structure province in Idaho.

MAXIMUM PROBABLE ACCELERATION IN BEDROCK

METHODS OF ANALYSIS

All methods for regional mapping of maximum probable ground motions require that the parameter of ground motion be defined in terms of earthquake magnitude and hypocentral or fault distance. Some mapping techniques are statistical, others deterministic in nature. Generally, earthquake risk maps have been based strictly upon broad generalizations of historical seismicity, and have made little use of relevant geological data.

Because our knowledge of earthquake mechanism and of actual conditions that govern earthquake occurrence is incomplete, no mapping technique should assume a wholly deterministic approach. On the other hand, a probabilistic approach which assumes all events to be randomly located unnecessarily ignores significant geologic information - especially the locations of known and probably active faults, and boundaries of tectonic provinces. In some regions, the future occurrence of large earthquakes may be assigned to known faults with a fair degree of confidence. But in areas where neither large earthquakes nor geologically recent faulting have been observed, a random distribution of potentially destructive shocks has to be assumed.

In the present study, probabilistic and deterministic techniques are combined in order to account for data available from both geology and seismology. Thus, what is known of Quaternary tectonics and the distribution of active faults has been used to guide the interpretation of seismicity data. This was done in the preceding section, although certain additional interpretations are made below.

Relationships between acceleration, magnitude, and hypocentral (or fault) distance, as well as techniques of computing maximum probable acceleration used herein, are described in the following.

Magnitude, Distance, and Acceleration

A number of empirical curves relating magnitude (m), distance (R), and acceleration (a) have been published in recent years. Because the data manifest a great deal of scatter, various investigators have come up with widely differing curves to describe them. None can be considered "right"; all are crude approximations, having probable errors ranging to ± 100%, or even more.

For the present investigation, the empirical curves of Schnabel and Seed (1972) were interpolated to 1/2-magnitude intervals and adopted for use (figure 9). These curves are considered more realistic than most others which have been published, and as good as any.

Earthquake mechanism studies, both theoretical and applied, have shown that magnitude is well correlated with both radiated energy and duration of recorded trains. They also have shown that magnitude is poorly correlated with the source parameter of stress drop, related to predominant period of wave motion, and with length of faulting (Thatcher and Hanks, 1973). Evidently magnitude is not a direct measure of source parameters, such as acceleration, but is a good measure of the crust's response to a given input of elastic wave energy. For example, recent observations have revealed accelerations exceeding 0.5 g for M = 3-1/2 to 4-1/2 events, recorded at hypocentral distances of only a few kilometers. Therefore, it is not surprising that much scatter is seen in data relating magnitude, acceleration, and distance.

Maximum Probable Acceleration: Random Source

Cornell (1968) has developed a closed-form solution for maximum prob-

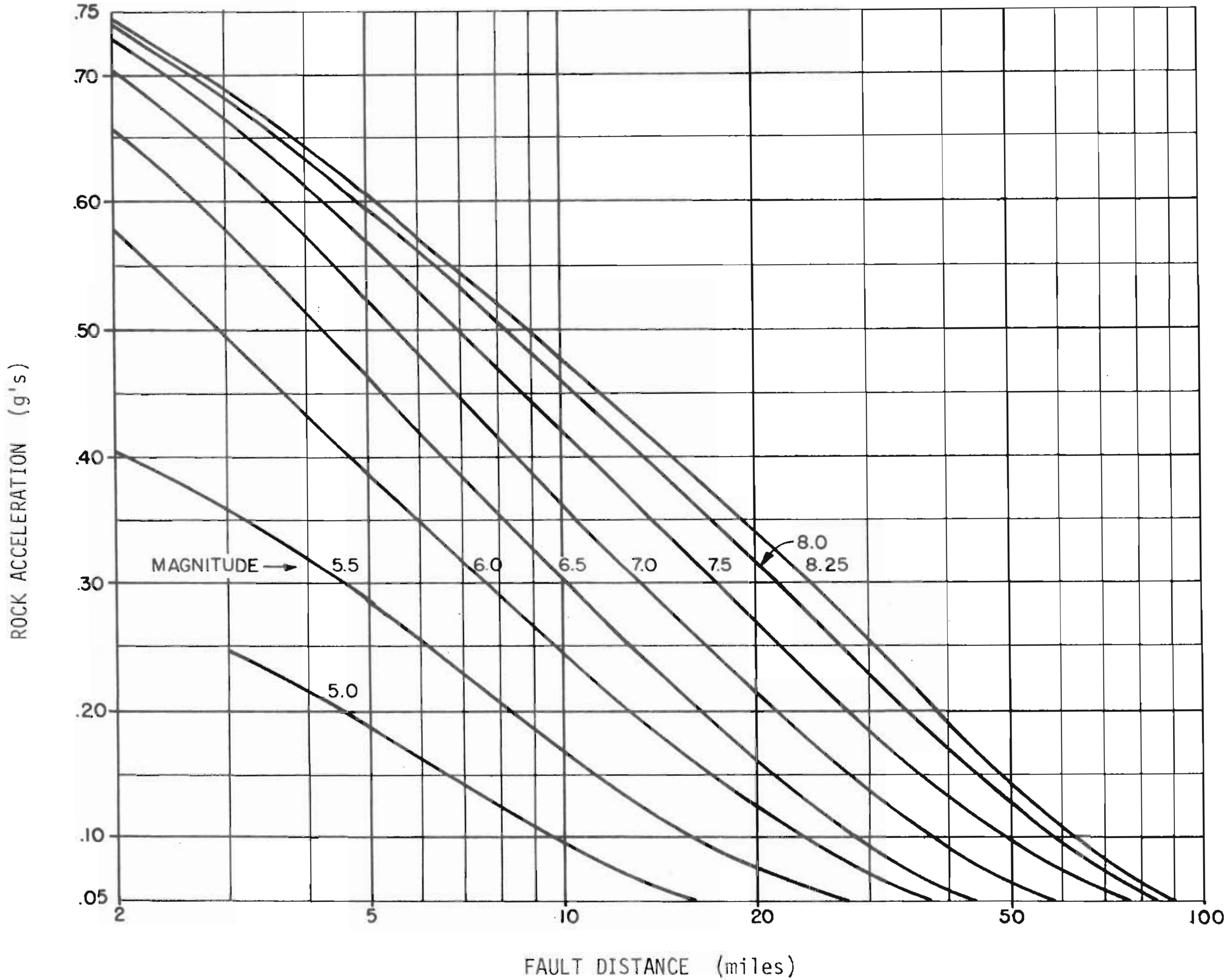


Figure 9 - Rock acceleration versus fault distance and earthquake magnitude (after Schnabel and Seed, 1972).

able ground motions at a point location. Essentially, his method assumes a Poisson distribution for earthquakes of interest (i.e. above some threshold magnitude), and derives an extreme-value distribution (Gumbel type I or type II) for ground motion. It allows the source region to be defined in a number of ways: line sources (faults) and randomly located events on a plane are easily handled. For this study, only the case of random events occurring in a plane circular region about a point was handled by this method.

In Cornell's procedure, acceleration must be expressed in the form

$$A = b_1 \, e^{b_2 M} \, R^{-b_3},$$

where A is in units of cm/sec^2, and b_1, b_2, and b_3 are constants that must be adjusted to give the best fit to the empirical acceleration data. Here, the acceleration curves of figure 9 have been rather well fit over the ranges $5 \leq M \leq 7$ and $10 \leq R \leq 40$ km by taking $b_1 = 28$, $b_2 = 0.8$, and $b_3 = 1$. It is noted that use of these constants results in accelerations which become unrealistically high if $R < 10$ km, reaching up to 5 g for R = 4 km, M = 7.5.

The T-year maximum probable acceleration A_T (units of cm/sec^2) is given by:

$$A_T = \left[\bar{\nu} \; C \; G \; T \right]^{b_2/\beta}$$

where $\beta = 2.3 \, b$

$\nu = N_{m_o}$, the number of shocks with $M \geq m_o$/km^2/yr

$C = e^{\beta m_o} \, b_1^{\;\beta/b_2}$

$$G = \frac{2\pi}{(\gamma - 1) \, d^{\gamma - 1}} \left[1 - \frac{r_o}{d}^{\;-(\gamma - 1)} \right]$$

$$\gamma = \beta \frac{b_3}{b_2} - 1$$

d = depth to assumed plane of seismicity

r_o = limiting radius of area treated.

The values of β and $\bar{\nu}$ are computed from the "a" and "b" values of magnitude-frequency curves. In this analysis r_0 = 40 km; setting d = 10 km eliminated the potential problem of accelerations being grossly overestimated for R < 10 km. Trial calculations, fitting the acceleration curves at $2 \leq R \leq 10$ and using d = 2, were within about 10% of those presented here. Thus, one may have confidence in the results.

Maximum probable acceleration (MPA or A_T) is defined as the modal (i.e. most probable) acceleration for any given T-year period. According to extreme value theory, this event has a 63% probability of being exceeded in any given T-year period. The probability that this value will be exceeded in some shorter period, t, is given by

$$P\left[a_t > A_T\right] = t/T, \text{ where } t << T.$$

In the following discussion, MPA values are designated by their annual probabilities of exceedence, P. These are equivalent to A_T where T = 1/P.

Results of calculations for the various tectonic provinces of Idaho are given in Table 1. MPA values for annual probabilities of exceedence of 10^{-4}, 10^{-3}, and 10^{-2} are shown. For the sake of comparison, maximum probable acceleration (MPA) has been computed for all tectonic regions, even those which will be treated as fault-source controlled.

The wide variation in seismic risk from one province to another is well expressed by these data. For example, they show that, at all probability levels, MPA in the Basin and Range province is at least 3 times that in the southern batholith, 4 times that in the northern Cordillera/northern batholith, and 100 times that of the Volcanic Rift Province. Based on all available information, this seems quite reasonable.

Table 1. Recurrence intervals, 100-year magnitudes, and maximum probable bedrock accelerations for earthquakes occurring in tectonic provinces of Idaho.

TECTONIC PROVINCE	b	$T_{6.5}$ (yrs)	M_{100}	MPA_4 (g)	MPA_3 (g)	MPA_2 (g)
Basin and Range	0.83	250	6.0	0.75	0.29	0.11
Basin-Range Structure: Southern, Idaho	0.83*	$\geq$1,000	$\leq$5.3	$\leq$0.42	$\leq$0.16	$\leq$0.06
Basin-Range Structure: Southern, Montana	0.83*	170	6.1	0.78	0.30	0.12
Idaho Batholith: Southern	1.0*	$\geq$4,000	$\leq$4.8	$\leq$0.22	$\leq$0.10	$\leq$0.05
Northern Cordillera Idaho Batholith: Northern	1.0*	$\sim 10^4$	$\sim$4.4	$\sim$0.16	$\sim$0.07	$\sim$0.03
Volcanic Rift Province	1.0*	$>10^5$	$<$3.3	$<$0.07	$<$0.03	$<$0.01

EXPLANATION

b = slope of magnitude-frequency curve; * means assumed, rather than observed

$T_{6.5}$ = most probable recurrence interval for $M \geq 6.5$ per 10^4 km^2

M_{100} = maximum probable magnitude per 100 yrs. per 10^4 km^2

MPA_n = maximum probable rock acceleration at any location for random distribution of seismicity

MPA_2 - probability of exceedence = 10^{-2}/yr.

MPA_3 - probability of exceedence = 10^{-3}/yr.

MPA_4 - probability of exceedence = 10^{-4}/yr.

Maximum Credible Acceleration: Faults

It was desired that the MPA map clearly reflect the presence of known active and probably active faults. Therefore, where known young faulting appears an adequate basis for localization of future earthquakes, maximum credible acceleration was mapped by contouring accelerations expected for the maximum-credible-magnitue (MCM) is 6.5, as previously explained. However, a few faults in Idaho are too short to generate an M = 6.5 shock, and are given smaller MCMs, as read from figure 4. In Wyoming and Montana, a few longer faults may produce M = 7. Acceleration values were read from figure 9.

Relationship of Maximum Probable and Maximum Credible Accelerations

Maximum credible and maximum probable events are relatable. The former have an associated probability of occurrence in time, as their times of occurrence must be considered random. The latter, however, reflect random distribution in both time and space. Therefore, these two types of events may be compared on the basis of their probabilities in time.

The probability of occurrence of maximum credible earthquakes on known faults may be computed as follows: In the Basin and Range province portion of the study area, late Quaternary faulting indicates that active range bounding faults or fault zones have a length totalling some 1,000 ± 100 km (600 ± 60 mi.). Seismicity data indicate a recurrence interval of about 80 years for the maximum credible earthquake (M = 6.5) in the 3×10^4 km^2 (12,000 $mi.^2$) area containing all of the faults. If each event is associated with 15 km (9 + mi.) of surface faulting, then it would take approximately 65 events to rupture the total 1,000 km (600 mi.) of fault length. Assuming a uniform distribution of activity along the faults, the average recurrence interval of faulting for any point on each fault would be 80 x 65 = 5,200 years. And, therefore, the average recurrence interval for maximum credible accelerations as mapped would also be 5,200 years. Similar calculations for the southern Basin-Range Structure province give T = 25,000 to 50,000 years. Thus the average order-of-magnitude recurrence time for maximum credible accelerations is 10^4 years, which amounts to a modal probability of occurrence of 10^{-4}/year.

In order to treat random-source and fault-source MPA values in a balanced manner, it was necessary to map both at the same probability level, i.e. at 10^{-4}/year. This has interesting implications. For example, the MPA_4 values in the Basin and Range province and Basin Range Structure province in Montana are 0.75-0.78 g, based on random sources. Since these values apply everywhere in those areas, it is seen that assuming all large events will occur only along known faults greatly reduces risk levels over most of the surrounding area. Therefore, it is clear that the use of geological data in predicting seismicity may result in a net areal reduction of risk at the $P = 10^{-4}$ level. Reasonably, the same relationship should hold at higher probability levels, although this cannot be demonstrated without actual stochastic modelling of fault sources.

MAPPING OF RESULTS

Known, potentially active faults occur in the southeastern part of Idaho and adjacent parts of Wyoming and Montana. Maximum credible acceleration values (with associated probability of 10^{-4}/yr.) in these areas have been determined by the assumption that practically all larger earthquakes will occur on the mapped faults, and that the maximum credible magnitude of such events is 6.5. It is noted that the highest acceleration contoured is 0.5 g, although peak accelerations inside that contour may rarely reach as high at 1.0 g within 1 or 2 km (.6-1/2 mi.) of faults. These higher values were not mapped because their occurrence and attenuation with distance is very poorly known. In any case, the duration of accelerations exceeding 0.5 g is expected to be less than 5 seconds, from considerations of velocity of fault-rupture propagation, which averages about 2-1/2 km/sec.

It is possible that damaging shocks (M = 5 to 6) will occur at some distance away from faults shown on plate 3. Nevertheless, it is believed that almost all such events will occur within 10 km (6 mi.) of the mapped faults, will have magnitude less than 6, and will not produce surface faults rupture. Thus, it is felt that the mapped acceleration values adequately account for practically all of the "off-fault" events.

However, one area appears to be an exception to this generalization. This lies between the north end of the Bear Lake graben, and the south end of the Grand Valley graben. Relatively intense seismicity is spread across the area, but there are no known young faults with which it can be associated. Therefore, it has been necessary to assume a random distribution of future large shocks in this area, yielding an MPA (at $P = 10^{-4}$/yr.) of 0.75 g. This is high indeed, but is considered to be consistent with the methods used here.

Throughout most of the state, the lack of known potentially active and active faults required that MPA values be determined on the basis of an assumed random distribution of seismicity. In these areas, MPA ranges from a low of less than 0.07 g in the Volcanic Rift province to a high of 0.22 g in the southern Idaho batholith (plate 3). These MPAs have an annual probability of exceedence of 10^{-4}.

The use of such a low probability level may be considered unrealistic for some engineering purposes. However, it is stressed that the use of higher probability level would be inconsistent with the occurrence of maximum credible events on known faults. An internally consistent map of MPA for probabilities greater than 10^{-4}/yr. would look quite different from plate

3. E. G., at $P = 10^{-3}$/yr., points with a fault distance of 10 km (6 mi.) might have an MPA of about 0.3 g, as compared with 0.4 g for $P = 10^{-4}$; in the Idaho batholith, MPA would be less than or equal to 0.10 g.

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GLOSSARY

WORDS & PHRASES

Aftershock - An earthquake which follows a larger earthquake or main shock and originates at or near the focus of the larger earthquake. There could be a series of aftershocks extending over a period of several months.

Antler Orogeny - An orogeny which extensively deformed Paleozoic rocks of the Great Basin in Nevada during late Devonian and early Mississippian time. Reference: Antler Peak quadrangle near Battle Mountain, Nevada. The main expression of the orogeny is the emplacement of eugeosynclinal western rocks over miogeosynclinal eastern rocks along the Roberts Mountains thrust.

Aseismic - Area not subject to earthquakes.

Basin & Range - Topography, landscape or physiographic province characterized by a series of tilted fault blocks forming longitudinal, asymmetric ridges or mountains and broad, intervening basins. In southwestern U.S. exemplified by steep eastern faces and gentler western slopes.

Block Fault Mountains - Mountains formed by normal faulting in which the crust is divided into structures or blocks of different elevations and orientations.

Bouguer Anomaly - A gravity anomaly calculated by allowing for the attraction effect of topography but not for that of isostatic compensation.

Brecciated Zone - A zone (within the fault planes) of coarse-grained clastic rock composed of large (>2mm in diameter) angular and broken rock fragments that are cemented together in a finer-grained matrix, which may or may not be similar to the composition of the fragments. The breccia fragments can be of wall-rock or be of any composition, origin or mode of accumulation. Reference: The consolidated equivalent of rubble, in which the fragment content is >80%.

Cenozoic - An era of geologic time from the beginning of Tertiary period to the present. Considered to have begun 70 million years ago.

Clastic Sediments - A sediment formed by the accumulation of fragments derived from pre-existing rocks or minerals and transported as separate particles to their places of deposition by purely mechanical agents. (ie: water, wind, ice & gravity).

Cordillera - A comprehensive term for an extensive series or broad assemblage of more or less parallel ranges, systems, and chains of mountains, valleys, basins, plains, plateaus, rivers, etc., having various trends but the mass having one general direction. ie: The great mountain region from the eastern face of the Rocky Mountains to the Pacific Ocean. Reference: A parallel chain.

Cretaceous - The final period of the Mesozoic era thought to cover a span of time between 136 to 65 million years ago. Reference: Emplacement of Idaho Batholith in Idaho, estimated 105 m.y. ago.

Diapir - A dome or anticlinal fold, the overlying of which have been ruptured by the squeezing out of the plastic core materials.

Dip-slip - Component of the movement or slip that is parallel to the dip of the fault. Reference: Movement parallel to the dip of the fault.

Eocene - An epoch of the lower Tertiary period after the Paleocene and before the Oligocene.

Eipcenter - That point on the Earth's surface which is directly above the focus of an earthquake.

Eugeosynclinal - A geosyncline in which volcanism is associated with clastic sedimentation.

Extrusion - The igneous process of emitting lava and other ejectamenta onto the Earth's surface.

Foreshock - A small tremor that commonly precedes a larger earthquake or main shock by seconds or weeks and that originates at or near the focus of the larger earthquakes.

Geomorphology - The study of the classification, description, nature, origin and development of present land forms and their relationship to underlying structure, and of the history of geologic changes as recorded by these surface features.

Geosyncline - A mobile downwarping of the crust of the earth, either elongate or basin-like, measured in scores of kilometers, which is subsiding, as volcanic or sedimentary rocks accumulate.

H F U - Heat Flow Units - A measurement of terrestial heat flow equivalent to 10^{-6} cal/cm^2/sec. Reference: Involves the measurement of the geothermal gradient of rocks, by accurate resistance thermometers, at depths >300 meters, in drill holes.

Holocene - An epoch of the Quaternary period from the end of the Pleistocene to present time. ie: Post glacial considered >10,000 yrs.

Intrusive - The process of emplacement of magma in pre-existing rock.

Jurassic - The second period of the Mesozoic era, thought to cover the time span of 195-190 and 136 million years ago.

Laramide Orogeny - A time of deformation typically developed in the eastern Rocky Mountains, whose several phases extended from late Cretaceous until the end of the Paleocene.

Mafic - Iron and magnesium - rich rocks or minerals; typical mafic rocks include basalt and gabbro.

Magma - Naturally occurring mobile rock material, generated within the Earth and capable of intrusion and extrusion, from which igneous rocks are thought to have been derived through solidifcation and related process.

Maximum Credible Earthquake - The largest earthquake that may reasonably be expected to occur in a particular region or on a particular fault, given the known geologic framework and seismic characteristics of that region or fault.

Mantle Plume - An upwelling of molten or semi-molten (partially melted) mantle rock, such a feature may explain highly concentrated volcanic activity, such as in Yellowstone Park.

Mesozoic - An era of geologic time, from the end of the Palezoic to the beginning of the Cenozoic.

Metamorphic Rocks - Any rock derived from pre-existing rocks by mineralogical, chemical and structural changes essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress and chemical environment at depth in the earth's crust.

Miocene - An epoch of the Upper Tertiary period, after the Oligocene and before the Pliocene.

Miogeosynclinal - A geosyncline in which volcanism is not associated with sedimentation.

Mississippian - A period of the Paleozoic era after the Devonian and prior to the Pennsylvanian. Thought to have covered a time span of 345-320 million years ago.

Nevadan Orogeny - A time of deformation, metamorphism and plutonism during Jurassic and Early Cretaceous time in the western part of the North American Cordillera.

Oblique Slip - Movement or slip of a fault that is intermediate in orientation between the dip slip and strike slip.

Oliogocene - An epoch of the lower Tertiary, after Eocene and before Miocene.

Orogenic - The process of formation of mountains. Is the process by which structure within mountain areas were formed, including thrusting, folding, and faulting in the outer and higher layers and the plastic folding, metamorphism and plutonism in the inner or deeper layers.

Paleomagnetic - The natural remanent magnetization used to determine the intensity and direction of the Earth's Magnetic field in the geologic past.

Paleozoic - An era in geologic time, from end of Pre Cambrian to the beginning of the Mesozoic.

Pleistocene - An epoch of the Quaternary period, after Pliocene of the Tertiary period and before the Holocene. Generally referred to as Ice Age.

Pliocene - An epoch in Tertiary period, after Miocene and before Pleistocene.

Plutonic - Pertaining to igneous rocks formed at great depths.

Pre Cambrian - All geologic time, and its corresponding rocks before the beginning of the Paleozoic. It is about equivalent to 90% of all geologic time.

Quaternary - The second period of the Cenozoic era following the Tertiary. Considered to cover the last two to three million years.

Right Slip - A right lateral fault, in plan view the side opposite the observer appears to have moved to the right.

Seismicity - Seismic activity, characterized generally by frequency of occurrence vs magnitude of earthquakes observed in a given region. The phenomenon of Earth movements.

Sevier Orogeny - A series of deformations occurring along the eastern edge of the Great Basin in Utah (eastern edge of the Cordilleran miogeosyncline) during time intermediate between the Nevadan Orogeny to the west and the Laramide Orogeny to the east, culminating early in the late Cretaceous. During the orogeny the folding and eastward thrusting of the miogeosynclinal rocks over their foreland was largely completed.

<u>Sial-Sialic</u> - A petrologic name for the upper layer of the Earth's crust composed of rocks rich in silica and alumina. (ie: granitic rocks).

<u>Silicic Volcanics</u> - Silica-rich igneous rocks or magma, in which 2/3 of the rock is composed of silica. Generally free silica in the form of quartz is present. Rhyolitic flows are typical example of silicic rocks.

<u>Sima</u> - A petrologic name for the lower layer of the Earth's crust, composed of rocks that are rich in silica and magnesia. It is the source of basaltic magma.

<u>Stress Drop</u> - The decrease in stress level along a fault that occurs during an earthquake; this is thought to be more or less proportional to the tectonic stress acting along the fault, and appears to be an important determinant of maximum near-fault earthquake accelerations.

<u>Subduction</u> - The process of one crustal block descending beneath another by folding or faulting or both.

<u>Subduction Zones</u> - An elongate region along which a crustal block descends relative to another crustal block. ie: The descent of the Pacific plate beneath the Andean plate along the Andean trench.

<u>Swarm (of earthquakes)</u> - A number of earthquakes clustered in time and space, having nearly equal magnitudes.

<u>Tectonics</u> - A branch of geology dealing with the broad architecture of the upper part of the part of the Earth's crust. It is the regional assembling of structural or deformational features, considering their mutual relation, origin and historical evolution.

<u>Tectonic Plate</u> - An extensive area of the lithosphere (crust and upper mantle, extending to depths of from 60 to 150 km) which has moved as a unit relative to adjoining plates and is distinguished by a particular style of tectonic deformation (or lack of it).

Wisconsin: Fourth and probably last glacial stage of the Pleistocene epoch in North America. Began about 85,000 ± 15,000 years ago and ended about 7,000 years ago. Five sub-stages have been described.

Geologic Time Scale

Glacial Epochs

Period	Epoch	Age Glacial Stage Continental	Time Scale B.P.	Glacial Sub-Stage Continental	Time Scale B.P.	Glacial Sub-Stage Northwest	Depositional Stage	
Quaternary	Holocene	Recent			1×10^3	Temple		
					4×10^3	Lake		
						(Alpine)		
	Pleistocene	Early	7×10^3	Cochrane	7×10^3	Pinedale II		Late Glaciation
		Wisconsin		Valders	25×10^3	Pinedale I		
				Mankato			4th	
		Early		Cary	32×10^3	Bull Lake II		
		Wisconsin	85×10^3	Iowan	80×10^3	Bull Lake I		
		Sangamon Interglacial Stage						
		Illimoian	115×10^3			Buffalo & Earlier	3rd	Early Glaciation
		Yarmouth Interglacial Stage						
		Kansan	400×10^3				2nd	
		Aftonian Interglacial Stage						
		Nebraskan	1×10^6				1st	

B.P. - Before Present

Geologic Time Scale

Era	Periods	Epochs	Time Scale Years Since
Cenozoic Era	Quaternary	Historical	
		Holocene	$50x10^3$
		Pleistocene	$1x10^6$
	Tertiary	Pliocene	$12x10^6$
		Miocene	$30x10^6$
		Oligocene	$40x10^6$
		Eocene	
		Paleocene	$60x10^6$
Mesozoic	Cretaceous		$120x10^6$
	Jurassic		$155x10^6$
	Triassic		$190x10^6$
Paleozoic	Permain		$215x10^6$
	Carboniferous		$300x10^6$
	Devonian		$350x10^6$
	Silurian		$390x10^6$
	Ordovician		$480x10^6$
	Cambrian		$570x10^6$
Pre-Cambrian	Z		Z $570x10^6$ $800x10^6$
	Y		Y $800x10^6$ $1,700x10^6$
	X		X $1,700x10^6$ $2,600x10^6$
	W		W $2,600x10^6$

NOTICE

THIS MAP IS PRELIMINARY AND SUBJECT TO REVISION AS NEW INFORMATION BECOMES AVAILABLE. IT IS NOT INTENDED FOR DIRECT ENGINEERING USE WITHOUT CONSIDERATION OF FOUNDATION CONDITIONS AND TYPE OF STRUCTURE OR WITHOUT APPROPRIATE REFERENCE TO THE ACCOMPANYING REPORT. A COPY OF THE REPORT MAY BE OBTAINED BY CALLING (208)384-3600.

PLATE 3. MAXIMUM PROBABLE EARTHQUAKE ACCELERATIONS ON BEDROCK IN IDAHO

PROBABILITY OF OCCURENCE OF ACCELERATION GREATER THAN OR EQUAL TO MAPPED VALUE = 10^{-4} PER YEAR

EXPLANATION

- ACTIVE FAULT (WISCONSIN OR YOUNGER) OR PROBABLY ACTIVE FAULT (MAJOR DISPLACEMENT OF PROBABLE LATE QUATERNARY AGE).
- 4 — MAXIMUM PROBABLE ACCELERATION CONTOUR, IN GRAVITY UNITS; POSITION CONTROLLED BY MAPPED FAULTS; ACCELERATION MAY REACH 1.0 G WITHIN 2 KM OF FAULTS.
- MPA ≤ 0.16 — MAXIMUM PROBABLE ACCELERATION FOR EARTHQUAKES OCCURRING RANDOMLY WITHIN GIVEN TECTONIC PROVINCE (G-UNITS)
- - - - - BOUNDARY OF TECTONIC PROVINCE.
- .75 — MAXIMUM PROBABLE ACCELERATION FOR RANDOMLY LOCATED EARTHQUAKES, LACKING KNOWN-FAULT CONTROL IN REGION OF YOUNG FAULTING (G-UNITS)

PREDOMINANT PERIOD

0.35 ± .05 SECONDS IN CONTOURED AREAS; UNKNOWN BUT SHORTER OTHERWISE.

DURATION

18 TO 24 SECONDS IN CONTOURED AREAS; UNKNOWN BUT SHORTER OTHERWISE.

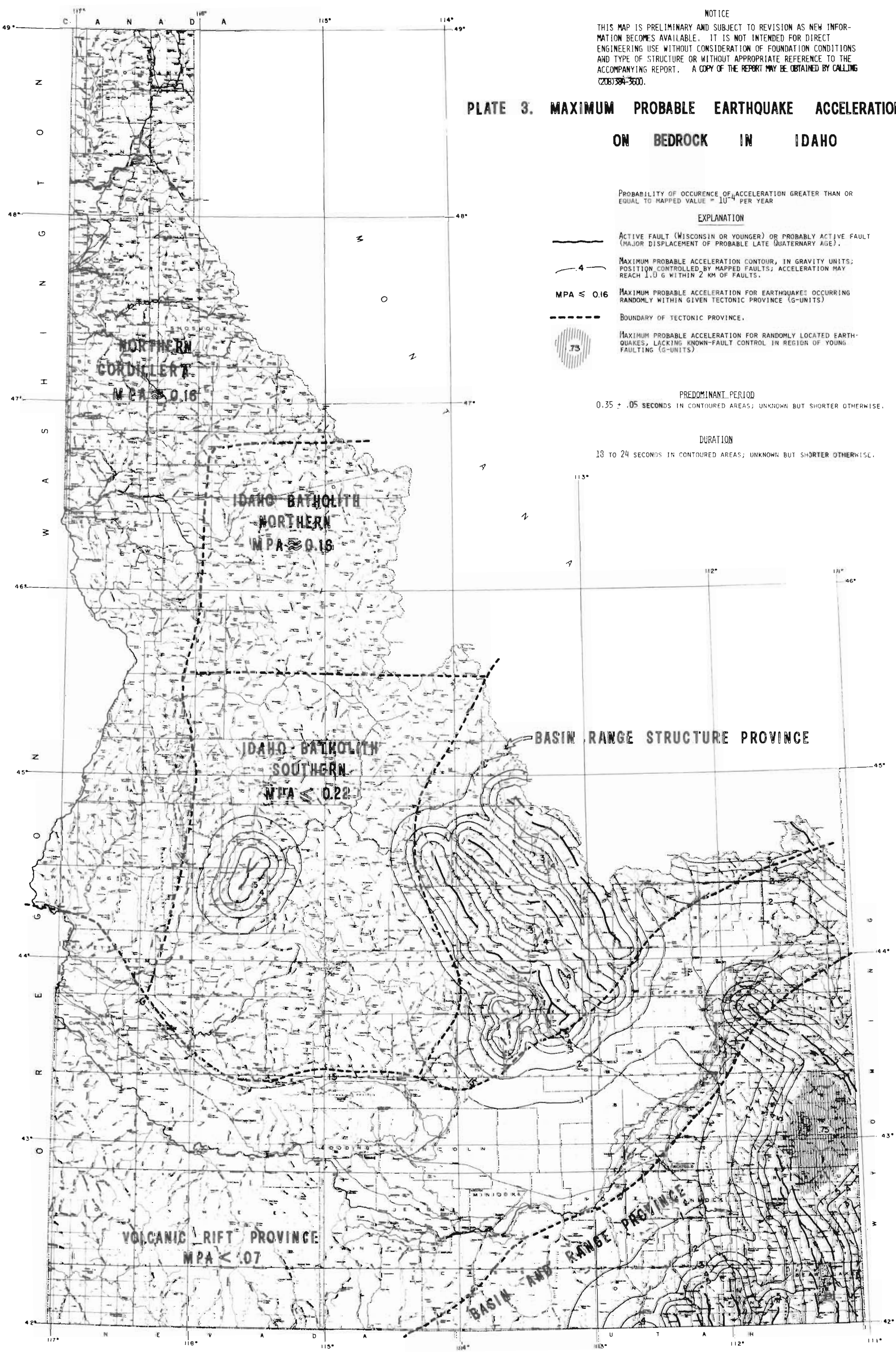

PLATE 2. HISTORIC SEISMICITY OF IDAHO AND SURROUNDING REGIONS, 1869 - 1976

Data Source: National Oceanic and Atmospheric Administration; Computer plot supplied by Woodward-Clyde Consultants.

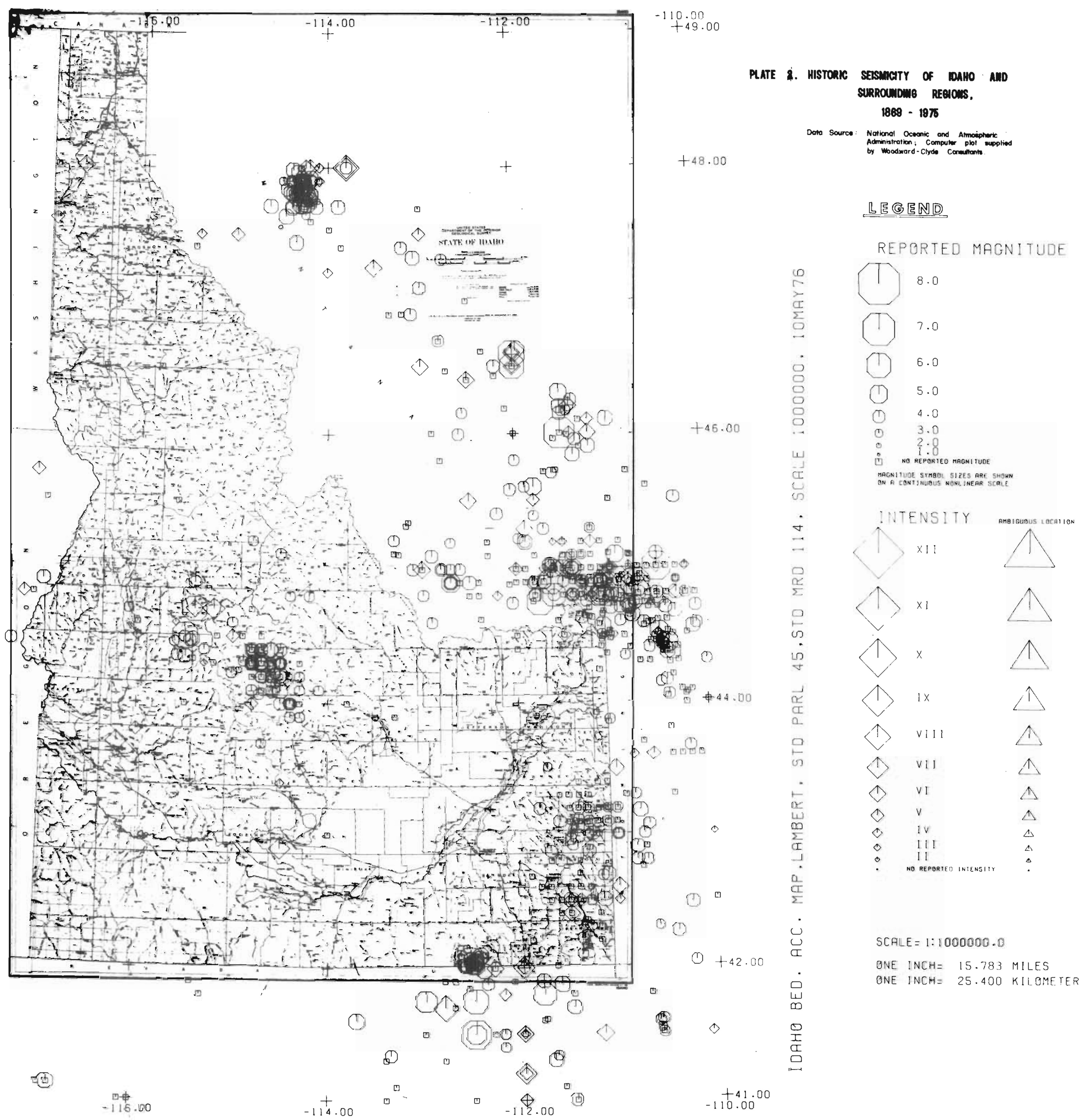

PLATE 1. QUATERNARY FAULTS OF IDAHO AND ADJACENT AREAS