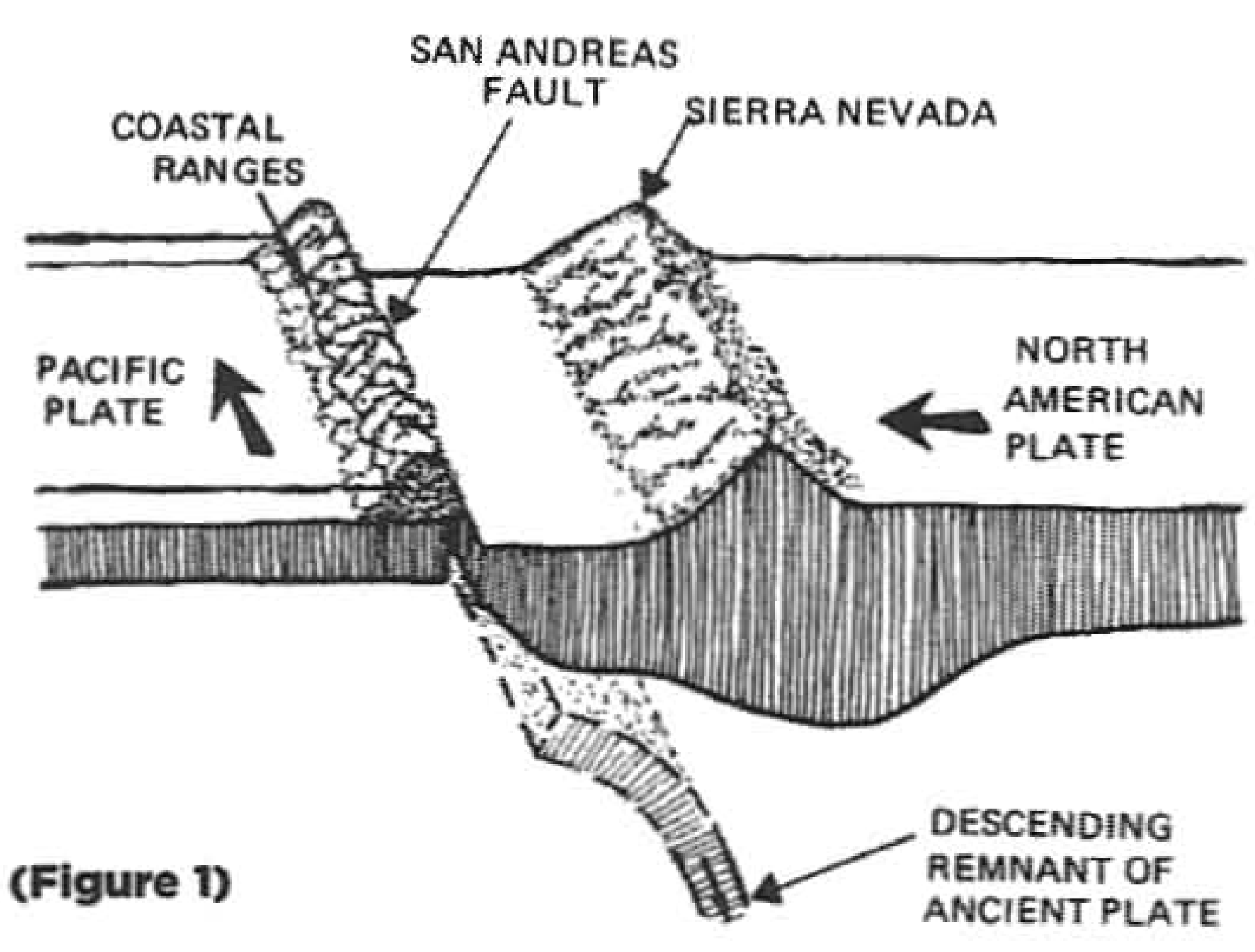
The Source of Earthquakes—The Theory of Continental Drift and Plate Tectonics

Even today, the causes of earthquakes are not completely understood. But there is now sufficient scientific evidence to conclude that the tremors are the effect of a rebalancing of forces arising from the collision of continuously moving plates on the earth's surface. This idea is based on the theory of plate tectonics, developed in the 1960s, which incorporates older theories of continental drift and the concept of seafloor spreading.

(Figure 1) California's San Andreas fault is one segment of the line of intersection between the North Pacific and the North American tectonic plates. Both plates are moving slowly north and west at different rates, producing the frictions and temporary locks along the fault that are released in the sudden shifts of earthquakes, the surface distortions of the broad fault zone, and the gradual growth of the coastal ranges. The Sierra Nevada ranges were formed when the two plates collided directly, and the thinner Pacific plate was forced downward, buckling the continental plate, lifting the mountain range and forming the westernmost portion of California with an accretion of materials from the oceanic plates. The descending remnant of the ancient plate is representative of a blind thrust fault like the ones that caused the 1994 Northridge, Los Angeles, quake.

(Figure 2) The same geological changes that cause earthquakes to occur are also a source of much natural beauty. This is illustrated at 1000 Island Lake on the John Muir Trail in the California Sierras.

(Figure 3) The dark areas on this map indicate the distribution and relative density of earthquakes recorded throughout the world. These belts of seismic activity mark with dramatic clarity the turbulent boundaries of the drifting, colliding tectonic plates that form the earth's crust. The mid-oceanic lines of activity represent the towering mountain ranges and deep rift valleys where the younger tectonic plates are renewed and pushed outward, altering the sea floors a few inches every year. About 80 percent of the planet's earthquakes occur along the Circum-Pacific seismic belt, which loops completely around the Pacific Basin. The Alpide belt, which extends from Java through the Himalayas and into the Mediterranean is responsible for about 17 percent of the world's seismic activity. The remaining 3 percent of all earthquakes strike along the Mid-Atlantic Ridge and in scattered pockets of seismic activity throughout the world.

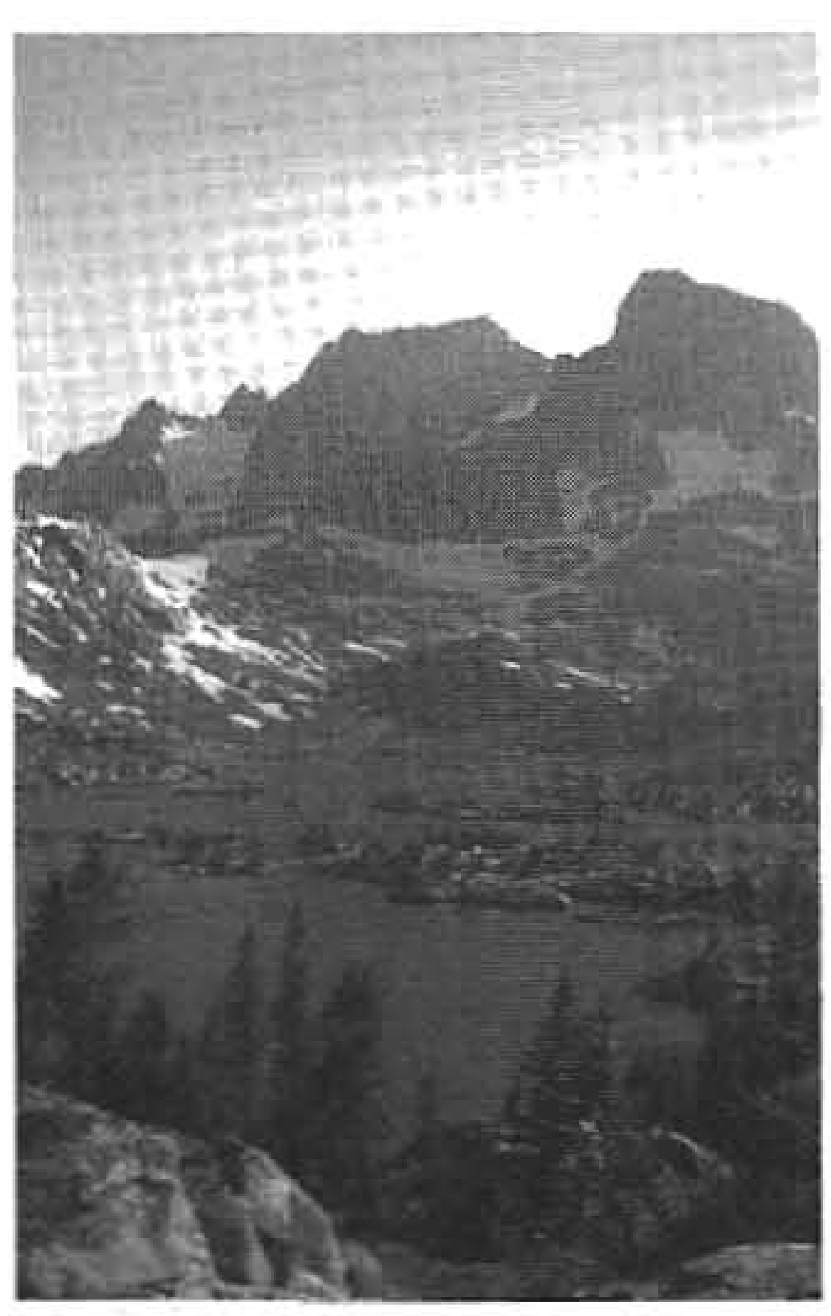


(Figure 1)

The theory of plate tectonics states that the outermost part of the earth is made up of two layers: the lithosphere and asthenosphere. The lithosphere "flows" atop the relatively fluid (geologically speaking, that is; it is actually pretty solid stuff) asthenosphere, and is broken up into several major, and many minor, tectonic plates, which are up to approximately sixty miles thick. As these plates collide and move against one another, mountains form, volcanoes erupt, and earthquakes relieve the built-up frictional forces that resist their movement. The plates move laterally at typical speeds of a few inches per year, the usual rate at which fingernails grow.

The newest and thinnest of these tectonic plates are the ocean floors, which are still being formed from molten materials flowing from the earth's interior. This flow emerges in deep rift valleys that form the inner boundaries of the suboceanic tectonic plates and divide vast, continuous mountain ranges that traverse the length of all the ocean basins. Molten materials from the earth's interior well up through the rift valleys and solidify to build the edges of the oceanic plates. These young oceanic plates are then pushed slowly but steadily away from the rift valleys, pressing their outer edges against the established and heavier plates that make up the continental land masses. It has been demonstrated, for example, that the Atlantic Ocean is spreading from the Mid-Atlantic Ridge at about one inch a year, so that within an average person's lifetime, the continents of Europe and North America move about six feet farther apart.

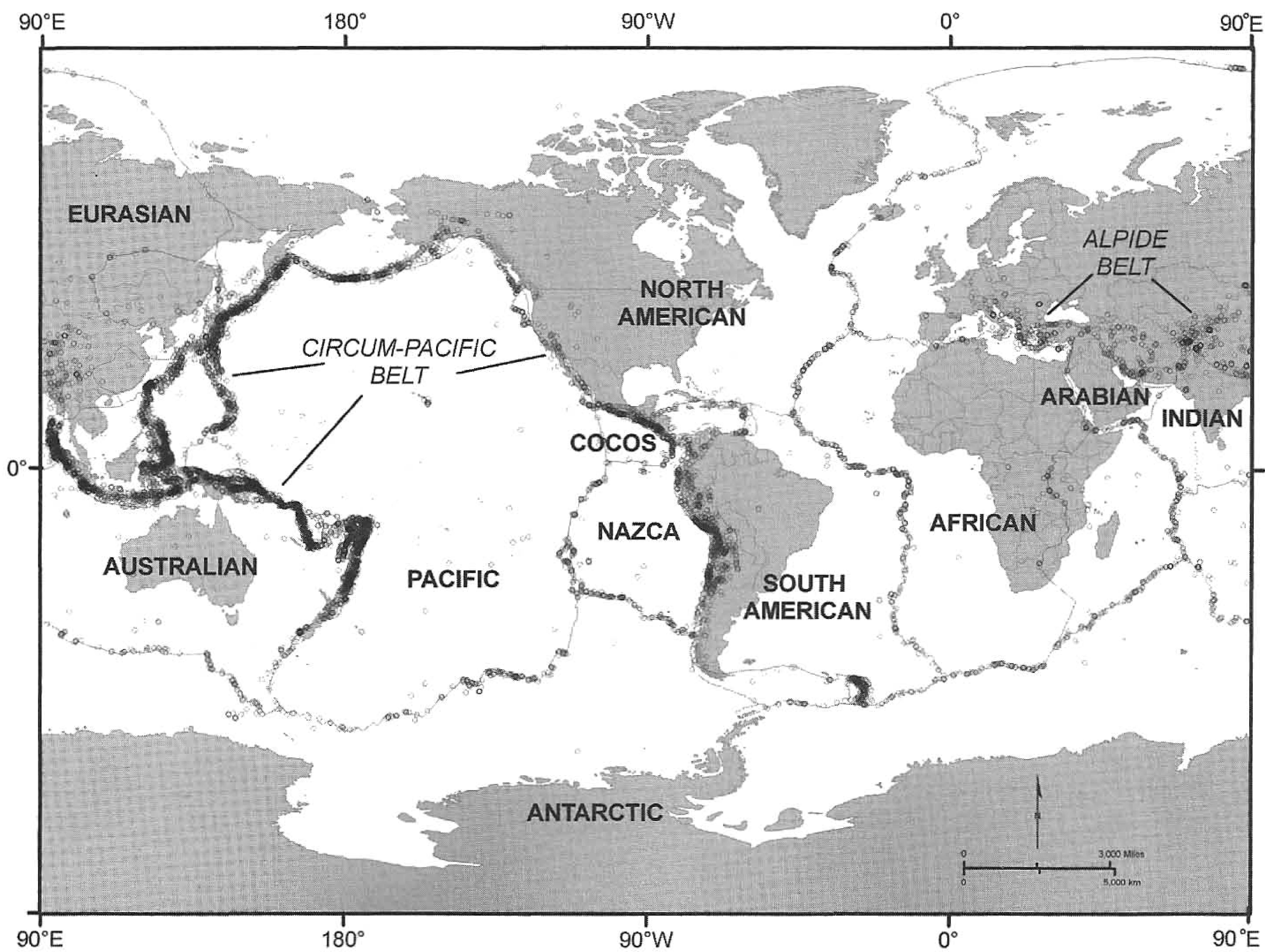
As the oceanic plates meet the continental plates, tremendous pressures buckle the earth's surface (creating mountain ranges); plunge the thinner, weaker oceanic plates into deep-sea



(Figure 2)

trenches beyond the continental shelves; and trigger volcanoes and earthquakes. Along the western coast of South America, for example, the thinner oceanic plate is forced downward by the thicker and heavier continent. As it is propelled below the continental plate and melts into the earth's core, the Andes mountains are pushed continually upward. At the same time, friction causes a temporary lock between the two plates. The inevitable and frequent failures of this fragile bond cause the deep, powerful earthquakes typical of Chile and Peru. A similar type of collision can occur between two thick continental plates as well. For example, the subcontinent of India is a separate plate that is moving northward against the Asian mass. The soaring Himalayas, as well as such destructive tremors as the 2001 Bhuj (India), 2005 Pakistan, and 2008 Wenchuan (China) earthquakes, are the result.

Some of the largest faults—breaks in the rock of the earth's upper crust—are formed in the region of the line of collision between tectonic plates. The San Andreas fault system of California is the result of the ancient and continuing collision of the North Pacific plate and the North American continent. Many millions of years ago, the more massive westward-moving continental plate overrode the opposing Pacific plate, driving the latter downward into the earth's crust, pushing up the Sierras, and causing the violent blowouts of such volcanoes as St. Helens, Shasta, Lassen, Rainier, and Hood. At the same time, some of the plunging Pacific plate was scraped off against the continent at the San Andreas fault zone, so that the coastal surface of western North America grew outward by about one hundred miles in a very gradual accretion of new materials, forming much of California and its coastal ranges. Thus, the southwestern third of the state west of the San Andreas fault is made up of relatively new geologic materials riding the Pacific tectonic plate, while the remainder of the state forms the western edge of the North American plate.



(Figure 3)

Today, these two plates have changed directions, so that they are essentially sliding past each other along the San Andreas fault. The great Pacific plate carries the ocean floor, a part of California, and all of the Baja peninsula northwestward in relation to North America, while the North American plate, pushed by the seafloor spreading at the Mid-Atlantic Ridge, moves west at a slower rate. The two plates finally collide directly in the far north, along the Aleutian archipelago, where the Pacific plate is driven downward. It is estimated that at the present rate of movement, the Los Angeles area, riding the Pacific plate, will draw abreast of the San Francisco Bay Area in about ten million years (no doubt to each other's dismay).

The Mechanism of Earthquakes—The Theory of Elastic Rebound

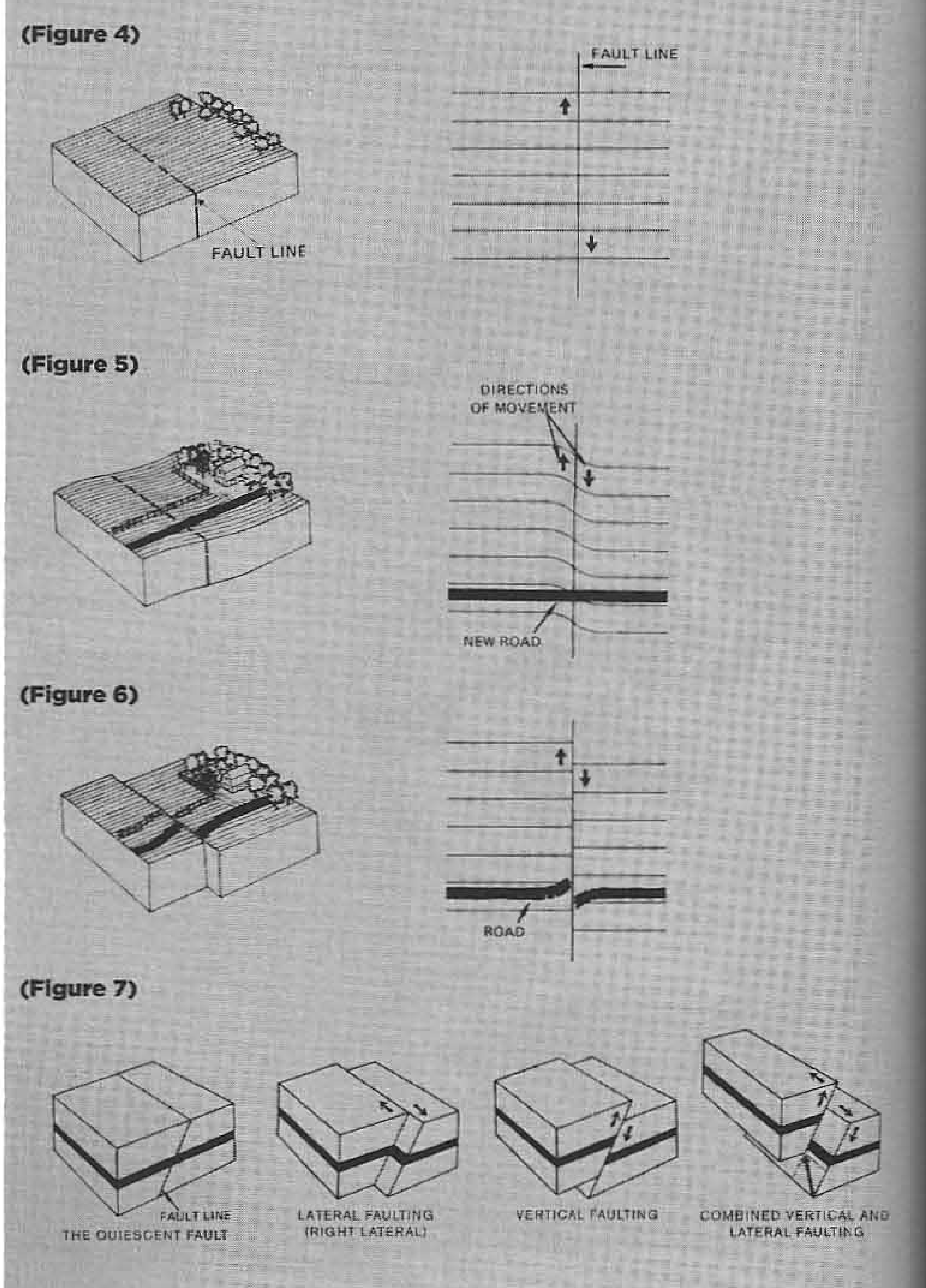
The edges of the plates have a certain amount of elasticity and tend to hold their positions along the fault. Portions of the fault frequently remain locked in this way, under tremendous stress, for several years or even centuries. Finally, when the accumulated sliding force exceeds the frictional force that binds portions of the plates and prevents their natural movement, the distorted rock along the two sides of the fault suddenly slip past each other in an explosion of movement that allows a new position of equilibrium.

This slippage, termed elastic rebound, produces powerful vibrations, sometimes ruptures the earth's surface and may shift the positions of the two sides of the fault by several feet both horizontally and vertically. Earthquakes are the result of these violent adjustments of a temporarily locked fault.

Two types of earthquakes are associated with different types of plate collisions. Shallow-focus earthquakes, with an average depth of three to ten miles below the earth's surface, result from the slippage of primarily laterally moving plates and are typical of California and most of the seismic regions of the American West. Both the 1989 Loma Prieta and 1994 Northridge foci were approximately eleven miles deep. Deep-focus earthquakes usually occur where plates collide directly and one is forced below the other. For example, the great Chile quake of 1960 and the 2001 Nisqually, Seattle, earthquake both occurred at a depth of about thirty miles. The 2004 Indonesia earthquake (which caused the devastating Indian Ocean tsunamis) originated at a depth of about twenty miles. Many other earthquakes in subduction areas occur at depths greater than seventy-five miles.

An earthquake's destructiveness is closely related to its depth: The shock waves of deeper earthquakes generally dissipate as they rise to the surface and are therefore less damaging. On the other hand, deep-focus tremors usually affect a much wider area. Shallow-focus earthquakes are felt over a smaller area but are sharper and usually more destructive. For example, earthquakes in the Puget Sound area of Washington have depths typically three to five times greater than those of equally large earthquakes along the San Andreas fault, and historically, these shocks have been, so far, considerably less destructive than those in California.

TYPES OF FAULTS AND FAULTING



(Figure 4)

The quiescent fault

A few faults may move relatively freely and very slowly along the plane of the drifting tectonic plates. This movement is termed fault creep.

The Calaveras fault and a portion of the San Andreas fault near Hollister in Northern California have moved in this way. Other faults become locked with the friction of the colliding plates and move only when the rocky layers of the plates become strained beyond endurance, then slip apart with the violence of an earthquake.

(Figure 5)

The strained fault before an earthquake

The gradual movement of the tectonic plates has created strain (or stored energy) in the rock of the fault where the two plates meet. The frictional force of the collision locks the two sides of the fault and prevents any movement. The limited elasticity of the rock allows the strains of this locked fault to accumulate for decades. Finally, the rocks give way, allowing the two sides of the fault to realign and causing the upheaval of an earthquake and surface and below-surface displacements.

(Figure 6)

The adjusted fault after an earthquake

The fault has moved into a new, unstrained position, causing surface displacements that have destroyed the continuity of the highway and fence and producing intense shock waves during the quake that have demolished poorly engineered buildings near the fault zone.

(Figure 7)

The direction of faulting

Faults typically move either laterally, vertically (thrust and/or graben faulting), or in a combination of vertical and lateral shifts. The San Fernando and White Wolf faults in Southern California fit this latter category of movement, which is quite common. The faults of the San Andreas fault system move primarily laterally. The Wasatch fault in Utah and the Kern River and Pleito faults in Southern California are vertically-moving faults.

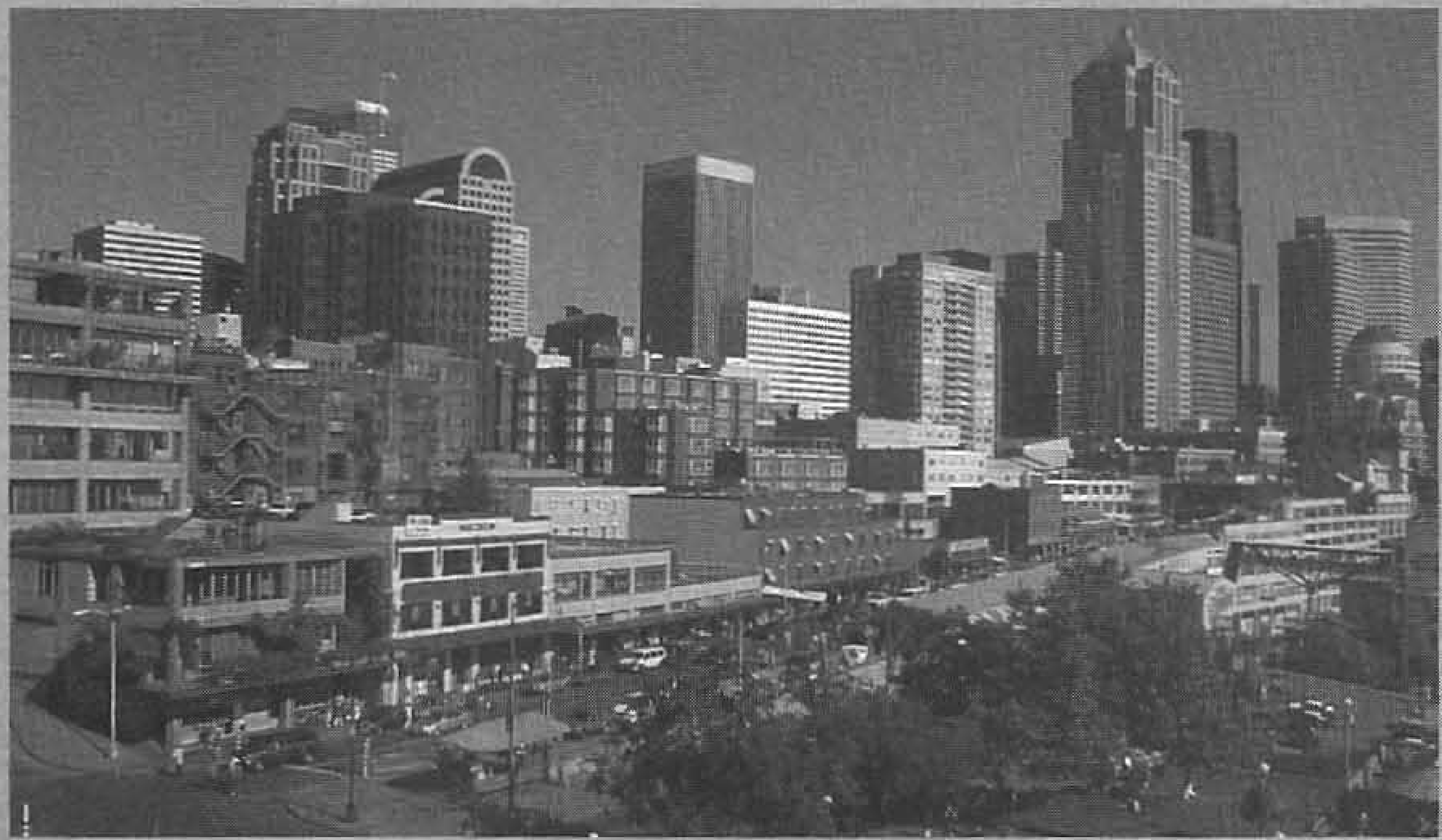
DON'T BE FOOLED BY THE 2001 NISQUALLY EARTHQUAKE

Was the magnitude 6.8 Nisqually earthquake of 2001 the largest that the Puget Sound area can expect? No, not even close. Earthquakes of magnitude 9 or greater are possible here, and buildings in the region, even the newest ones, simply were not (and are not) designed for this level of earthquake.

The Nisqually earthquake was a deep interplate earthquake, originating a full thirty miles beneath the surface. By the time the earthquake waves reached the surface, their damaging effects had been greatly diminished. These types of deep earthquakes occur in the region approximately every thirty to fifty years, most recently in 1949, 1965, and 2001. There is an 85 percent chance of another earthquake of this caliber striking the Puget Sound region in the next fifty years.

Earthquakes resulting from shallower faults in the region, like the Seattle fault, would have a much greater impact than the Nisqually one did. A recent study of possible effects of a Seattle fault zone rupture predicted sixteen hundred deaths and $33 billion in damage, and much higher numbers are possible. There is a 15 percent chance that an earthquake of this type could occur in the next fifty years.

Potentially causing even greater damage would be a rupture along the Cascadia subduction zone, a fault spanning from Vancouver Island to Northern California. Caused by the North American plate colliding with and sliding over the Juan de Fuca plate, this fault could produce earthquakes of magnitude 9 and greater. Again, there is as much as a 15 percent chance of such an earthquake occurring over the next fifty years. The Pacific Northwest and British Columbia have not experienced this type of an earthquake, or disaster, in modern history. Such a disaster could be as destructive to the economy of the area as the 2005 Hurricane Katrina was to the economy of New Orleans.



Seattle, Washington