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GEOLOGIC BACKGROUND FOR EVALUATING SURFACE-FAULTING HAZARDS

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Geologic observations have indicated that moderate- to large-scale faults have moved repeatedly in the recent geologic past. This allows us to evaluate the future behavior of a fault based on geologic information. In this paper, the essential characteristics of active faults are reviewed, and problems in evaluating surface faulting by using geologic information are discussed.

Key Words : *active faults, surface faulting, tectonics, paleoseismology, slip rate, secondary faults, blind faults*

1. INTRODUCTION

Surface-faulting hazards associated with large earthquakes are, in general, not so widespread as those directly due to seismic waves. Damages to constructions due to surface faulting are restricted to zones along pre-existing faults as narrow as several ten meters or less. However, we can predict the exact locations of, and hence can evaluate the hazards due to, surface faulting by using geologic information, whereas the source locations of strong seismic waves are difficult to predict precisely.

An earthquake is generated by sudden slip on a geologic fault. In the upper half of the earth's crust are geologic faults, most of which have been *consolidated* or inactive, but some of which are still capable of generating earthquakes under the present stress fields in the crust and hence are called *active*. Although the term *active fault* is usually used only for the surface manifestation of such a seismogenic fault, in this paper we apply this term to a fault whether or not it cuts through the crust up to the surface.

Active faults in the world develop mainly at or adjacent to plate boundaries, although some of active faults are located far from plate boundaries. The Japanese Islands, for example, are an island arc associated with the westward subduction of the Pacific plate at the Japan trench and the northwestward subduction of the Philippine Sea plate at the Nankai-Ryukyu trench. Active faults developing along these deep-sea trenches are surface manifestation of sources of subduction-type large earthquakes and disastrous tsunamis. Within the Japan arc, there is significantly strong intraplate crustal deformation, which is caused principally by westward push of the Pacific plate against the island arc. Densely distributed active faults on the continental side of the Japan arc are a spectacular surface expression of this intraplate deformation (**Fig.1**). Earthquakes generated by these faults are not so large as those at subduction zones and rarely exceed seven and a half in magnitude. However, these intraplate faults are more important from the viewpoint of disaster prevention; some of them pass through or close to densely populated areas, so that they would be quite disastrous when activated. This has been evidenced by a number of historic surface-faulting events, including the Hyogo-ken Nanbu (Kobe), western Japan, earthquake of January 17, 1995.

In this paper, I review the essential characteristics of active faults with special reference to Japanese examples, and discuss some problems in evaluating surface-faulting hazards in the future by using geologic information.

2. BEHAVIOR OF FAULTS IN THE GEOLOGIC PAST

Geologic observations of surface ruptures associated with historical earthquakes in the world have indicated that surface ruptures occurred, without any definite exceptions, on pre-existing faults. Moreover, there are lines of evidence indicating that moderate to large-scale (i.e., map scale) faults have moved repeatedly in the geologic past. This is because a fault coalesces other faults and fractures near its edge every time it slips, and grows larger and larger with time.

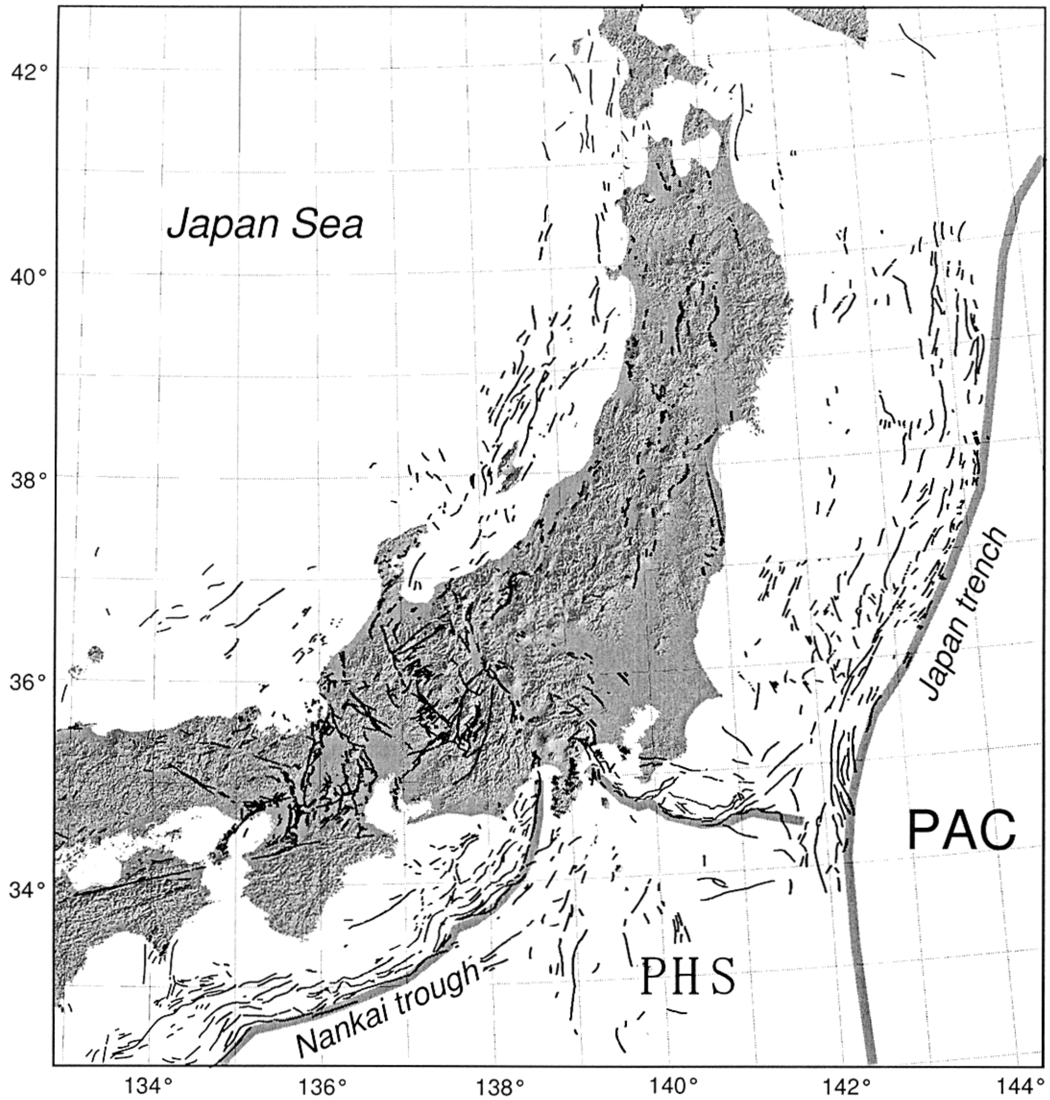

Fig.1 Active faults in northern and central Honshu, Japan (data from Research Group for Active Faults[1),2)]). PHS and PAC denote the Philippine Sea and the Pacific plates respectively. Note that the distribution of active faults in northeast Honshu is underrated because many active folds resulting from blind thrust faults are not mapped here.

Conversely, a map-scale fault cannot be formed in a single event. The repetitive nature of faulting gives us an important basis for predicting future activity of faults by using geologic information.

(1) Recurrence intervals

The timing of individual faulting events on an active fault in the recent geologic past is a key to evaluating its future activity. In the late 1970's, Kerry Sieh[3)] excavated small trenches in young alluvial sediments across the San Andreas Fault in central California, in order to reveal the timing of individual great earthquakes produced by slip on the fault to a precision of several ten years. Such a high temporal-resolution study of faulting in the recent geologic past is called *paleoseismology*.

Kerry Sieh's excellent work on the San Andreas inspired world's researchers including Japanese geomorphologists and geologists. During the last one and a half decades, exploratory trenches have been excavated at more than a hundred sites. These excavations have revealed that the average recurrence interval ranges from one thousand to several ten thousand years for earthquakes produced from an individual intraplate active fault in Japan. However, the quantity, as well as the quality, of paleoseismological data is far from sufficient. After the Hyogo-Ken Nanbu earthquake of January 17, 1995, Japan's paleoseismological research has been accelerated. The Geological Survey of Japan started a 10-year program of paleoseismological studies of about 100 major faults over the Japanese islands; the Ministry of Science and Technology also started a 5-year program, in which research projects proposed by local prefecture governments are conducted. These two programs have similar objectives and targets, and are complementary to each other, although the latter places more emphasis on active faults in or close to urban areas.

Paleoseismological data allows us to make *long-term prediction* of earthquakes. If the recurrence interval and the date of the last faulting event are known, the timing of the next earthquake would be predicted. Since the earthquake recurrence intervals of intraplate faults in Japan are at least one order of magnitude longer than that of the San Andreas Fault and other plate boundary faults, such a prediction involves a considerably broad range of uncertainty. The range of uncertainty would be broad, not only because of errors included in paleoseismological estimation but also because of the stochastic nature of faulting processes. Such information might seem useless, because the duration of human life is much shorter than the earthquake recurrence intervals of intraplate faults. However, paleoseismological data are still useful in evaluating the earthquake risk potential of each fault.

It should be noted that active faults mapped from surface or shallow subsurface geologic evidence include both primary (master) and secondary faults (see the next chapter). Therefore, the recurrence interval of faulting for an individual active fault does not necessarily mean the recurrence interval of strong seismic waves that are produced by slip on the master fault.

(2) Average slip rate

Almost all the active faults known in the world move episodically and suddenly with varying intervals of quiescence. One very rare exception is the central segment of the San Andreas Fault from San Juan Bautista to Parkfield in California[4], where the fault is moving progressively at a rate as high as about 30 mm/y. Although active faults move episodically, geologic evidence has suggested that slip rates averaged over long periods of time are fairly uniform in recent geologic time. The average rate of slip on a fault is proportional to the rate of seismic moment release from a unit area of the fault plane. Therefore, it is a good indicator of overall activity of the fault.

(3) Mapping active faults

Another important implication of the repetitive nature of faulting is for mapping active faults. Surface or near surface faulting produces deformation in sedimentary layers and geomorphic surfaces. Although deformation associated with an individual faulting event is small (normally several meters or less), it becomes progressively larger with time because of repetition of faulting. Thus, the deformation of sedimentary layers or geomorphic surfaces older than 10^3–10^4 years is "visible" enough to detect active faults by geologic and geomor-phological methods.

One of the most effective methods for mapping active faults is air-photo interpretation of tectonic landforms. The Research Group for Active Faults[1),2)] (1980 first edition, and 1991 second edition) mapped active faults over the Japanese Islands according to fixed standards, and compiled the results into a set of 1:200, 000 sheet maps with explanatory text (**Fig.1**). Since 1982, the Geological Survey of Japan has published *the Neotectonic Maps*, which also covers the entire Japanese Islands on a scale 1:500,000. Such medium to small scale fault maps are, however, not sufficient in accuracy for engineering purposes. Since 1993, the Geological Survey of Japan has published strip maps of selected fault zones on a scale 1 : 25,000 to 1 : 100,000 as part of *the Tectonic Map Series*. Since 1996, the Geographical Survey of Japan also started to publish *the Active Fault Maps of Urban Areas*, which covers densely populated areas on a scale 1 : 25,000.

3. PROBLEMS RELATED TO SURFACE FAULTING

(1) Earthquakes with or without surface ruptures

Most of historic surface faulting was associated with shallow (< 20 km deep) earthquakes of magnitude about 7 or greater; there were very few cases, in which smaller earthquakes have resulted in surface breaks (e.g., the Parkfield earthquake of 1966[5),6)]). It is because the fault plane that generates an earthquake of this magnitude is large enough to cut through the entire thickness of the seismogenic crustal layer. The size of an earthquake (more exactly, the seismic moment release) is proportional to the area of fault plane that breaks in a single faulting event. Because the thickness of seismogenic layer (upper crust) is typically 15 ± 5 km, faults whose dimension is larger than this value are more likely to produce surface ruptures when activated (**Fig.2**). Moreover, the uppermost several kilometers of the crustal rocks are not seismogenic and hence initial ruptures cannot nucleate here[7)], so that faults with typical size smaller than several km cannot produce surface ruptures.

Important exceptions that should be considered are low-angle faults whose leading edge is buried beneath thick sediments. Such faults are called *blind*. Even a very large-scale fault could be blind, and could produce big earthquakes. For example, several destructive earthquakes in western Taiwan in early 20th century with magnitude close to or larger than 7 did not

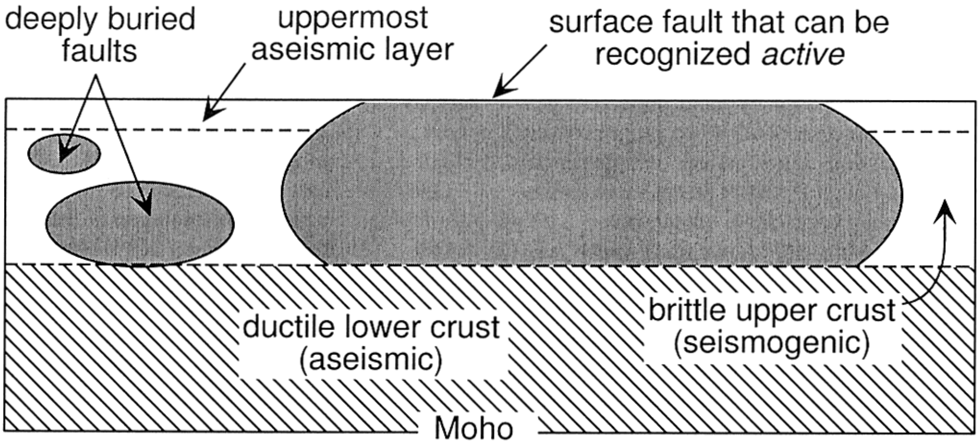

Fig.2 Schematic cross section of crustal layer, demonstrating that potentially seismogenic faults with large dimension generally produce surface ruptures whereas smaller ones do not necessarily produce surface ruptures.

produce significant surface breaks; these earthquakes are likely to have resulted from slip on flat-lying faults (detachment faults) beneath young sediments as thick as 4–6 kilometers. Such deeply buried faults may exist in the Tertiary-Quaternary fold belts in northeastern Honshu and Hokkaido, Japan, but the details are not fully understood. Further investigations, including high-resolution seismic reflection profiling, drilling, and careful mapping of surface deformation, are necessary.

(2) Secondary or master?

Careful mapping of active faults has shown that there are many fault strands shorter than a few kilometers[1),2)] (**Fig.1**). Some of them constitute a narrow, linear zone of subparallel strands, and hence are a direct surface manifestation of a large master fault that extends deep into the crust.

However, a considerably large number of short fault strands remain isolated from each other. Since the uppermost 2–4 kilometers of crustal rocks are generally aseismic and do not produces earthquakes (**Fig.2**), such faults with a short strand are likely to be secondary faults that are generated, not by regional stress field, but by secondary stress associated with slip on a master fault at depth. Stress concentration occurs near the leading edge of the master fault. Stress concentration (and surface deformation as well) occurs also where the master fault plane is geometrically irregular. The Tertiary-Quaternary fold belts in northeastern Honshu and Hokkaido, for example, are likely to be underlain by large-scale detachment faults with flat-ramp geometry[8)]. Sato & Ikeda[8)] interpreted that most of active folds and small-scale faults in these areas are controlled by ramps in flat-lying detachment faults at depth.

(3) Migration of deformation fronts

In planning measures against surface faulting hazards, we may generally assume that all the active faults are pre-existing; the distribution and geometry of faults do not significantly change on a time scale of hundreds to thousands of years. However, considerations for longer time-scale tectonic processes are necessary in some particular cases such as high-level radioactive waste disposal.

Ikeda[9)] systemized the phenomenology of and modeled the surface deformation associated with the migration of thrust fronts. Many ranges and intervening basins develop in Hokkaido, northern and central Honshu, Japan. These ranges are bordered on one side, or both sides, by thrust faults (referred to as *boundary faults*), along which rocks composing the ranges are thrust over syntectonic basin fills. The thickness of the basin fills generally increases toward the boundary fault to form a sedimentary wedge. In many cases, incipient active faults or flexures (referred to as *frontal faults/flexures*) develop several km in front of the boundary fault. On the upthrown side of a frontal fault/flexure, basin fills are strongly deformed and eroded to form foothills.

The Ina Valley fault zone (IVFZ) in central Japan is a typical example of thrust-front migration (**Fig.3**). The boundary fault of the IVFZ marks the physiographic boundary between the Kiso range on the west and the Ina Valley on the east. The frontal fault is located 1–5 km east of the boundary fault. Gravity measurements and seismic reflection profiling revealed that the sedimentary wedge beneath the Ina Valley is thrust under the basement rocks of the Kiso range for about 4 km, and that the frontal fault is likely to be a detachment fault developing along the wedge-basement interface.

Migration of thrust front has been observed for many thrust zones in Japan and in the world, and

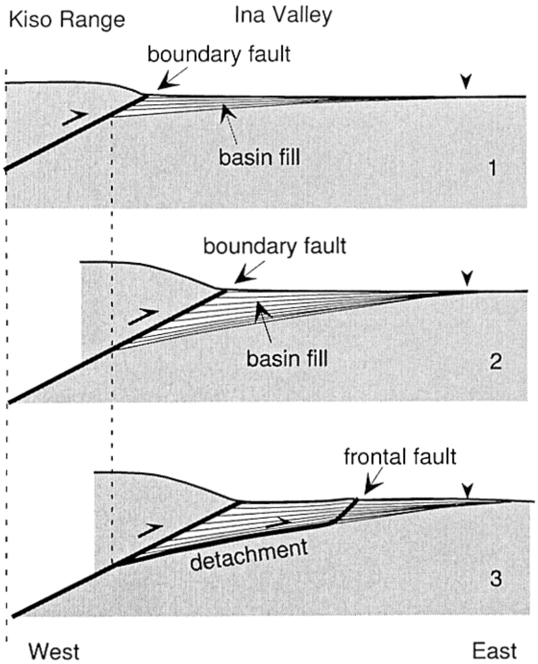

Fig.3 Thrust-front migration in the Ina Valley Fault Zone, central Japan (modified from Ikeda[9]).

seems a common phenomenon[9]. It is observed also in fold-and-thrust belts associated with collision-type plate boundaries, including the Himalayan front and the Western Foothills of Taiwan. Some selected examples suggest that thrust-front migration occurs on a 10^5 year time scale[9].

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