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Reconstruction of Relative Tectonic Movements Using Transgressive Ravinement Erosion Surfaces: A Case Study for the Shallow Subsurface Geology of the Osaka Plain, Japan

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Abstract

Ravinement surfaces are produced when the sea floor is eroded into a flat surface by the action of waves or tides during a marine transgression. They are preserved in the transgressive deposits as a sharp erosion surface. In a geological cross section across the ancient shoreline, primary ravinement surfaces appear as a subhorizontal line slightly dipping toward the sea. In a cross section, comparing successive ravinement surfaces deformed by tectonic movement allows for the reconstruction of relative tectonic movement. For example, when successive ravinement surfaces are parallel, the entire region has subsided or uplifted uniformly. However, when the lower ravinement surface dips more steeply than the upper ravinement surface, this indicates differential subsidence. We used the reconstruction of tectonic movement derived from ravinement surfaces to reconstruct the shallow subsurface geologic structures of the Osaka Plain, an intra-arc basin in the Japan island arc. For this study, we constructed cross sections from drill hole data extracted from a civil engineering drilling database. Our study revealed that, in different areas of the Osaka Plain, the land had been uplifted and differentially subsided toward the sea; a relatively large uplift occurred near a flexure zone, and the rate of the tilting of an anticline was constant.

Keywords: Ravinement surface, tectonic movement, intra-arc basin, Quaternary, drilling database

1 Introduction

A key feature for a reference plane or layer used in reconstructing regional tectonic movements needs to be distinguishable and continuous. Ravinement surfaces, produced

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by erosion of the sea floor by waves or tides during transgression [1] meet these conditions. These are easily distinguishable in the stratigraphic record because they are sharp erosion surfaces. Furthermore, ravinment surfaces are often preserved because they are covered by younger marine deposits. Many ravinement surfaces are preserved in Quaternary sediments of the Osaka Plain and these surfaces record hundreds of thousands of years of successive eustatic sea level changeswhich can be used for reconstructing tectonic movements.

The Japan island arc is located along an active plate margin, and several intra-arc basins have formed because of tectonic movements during the Quaternary. The Osaka Plain (the Osaka sedimentary basin) is an intra-arc basin, where Quaternary sediments have accumulated during basin subsidence. These sediments have reached a maximum thickness of around 2,000 m [2, 3]. Masuda (2007) [4] described a sharp ravinement surface at the base of a marine clay bed in the uppermost part of the Quaternary section in the Osaka Plain. This marine clay bed was deposited on the inner bay floor during a transgression around 6 ka ago. Similar marine clay beds are present in the upper parts of the subsurface strata in the Osaka Plain, and these marine clay beds were deposited during highstands, which were controlled by eustatic changes [5].

In this paper, we use the ravinement surfaces to evaluate the tectonic movements and present a case study that describe the tectonic movements of the Amagasaki, Suminoe, and Kaizuka districts in the Osaka Plain using geological cross sections constructed from drill hole data.

2 Methodology: Reconstruction of the Tectonic Movements Derived from the Ravinement Surfaces

As mentioned previously, a ravinement surface is a erosional surface formed by the action of waves or tides during transgression [1, 6]. More specifically, Swift et al. (2003) [7] named “transgressive ravinement” those ravinement surfaces created during transgression, whereas “oceanic ravinements” [4, 7] were created by storm waves at the shoreface in the open sea. In the inner-bay area, the sea floor also is flattened by wave erosion, and ravinement surfaces are created by tidal erosion and called either “tidal ravinements” [8] or “bay ravinements” [1].

The flattened ravinement surface is a useful reference plane for interpreting tectonic movements. The ravinement surfaces can be assumed to be pretty much the same feature if they were formed at close time intervals in the same region. If this hypothesis is accepted, the deformation history of a region can be revealed by comparing the successive ravinement surfaces in a particular stratigraphic sequence. In a geological cross section crossing the shoreline, the ravinement surface can be depicted as a straight line slightly dipping toward the sea. If the successive ravinement surfaces in the cross section are parallel, it suggests that the entire region has subsided or been uplifted. If they are not parallel it indicates progressive tilting or folding of the region.

If the upper and lower ravinement surfaces have been created during the comparable transgression, the amount of the subsidence or uplift in the region can be estimated by comparing the elevations of the landward ends of the surfaces in the cross section. For example, if the landward end elevation of the lower ravinement surface is 10 m lower than that of the upper ravinement surface, it shows that the land has subsided 10 m during the age interval between the generation of the lower and upper ravinement surfaces. Similarly, if the landward end elevation of the lower ravinement surface is 10 m higher than that of the upper ravinement surface, it suggests that the region has been uplifted 10 m.

Further, the three-dimensional tectonic movements in a region can be reconstructed by analyzing extensively distributed data. Furthermore, the tectonic movement rate can be estimated by determining the age of the upper and lower ravinement surfaces.

3 Case Study

For this case study, we investigated the tectonic movements of the Amagasaki, the Suminoe, and the Kaizuka district in the Osaka Plain, Japan (Figure 1). In these studies, we used ravinement surfaces identified from cross sections constructed from drill hole data.

3.1 Geological Setting of the Osaka Plain and the Drilling Database

The Osaka Plain is surrounded by 300–1,100 m high mountains that consist of basement rocks. In the central part of the plain, there is an elongate topographic high called the Uemachi Plateau trending north from the southern mountains (Figure 1). A delta plain with an elevation of 5 m or less is developed to the west of the Uemachi Plateau, and a flat plain dominates the area to the east. In contrast, north and south of the Osaka Plain terraces and hills ranging in elevation between 30 and 150 m occur near the mountains. There are active faults at the foot of the mountains and along the western side of the Uemachi Plateau.

The subsurface of the Osaka Plain consists of Quaternary sediments ranging from 1,500 to 2,000 m in thickness [2, 3]. The upper part of the section consists of sand and gravel interbedded with marine clays that represent inner bay floor sediments deposited when the sea level is higher, the highstand being controlled by eustatic changes [5]. The strata near the active faults exhibit drag deformation caused by fault movement [3, 11, 12, 13]. The Osaka sedimentary basin began to form about 3.3–3.5 Ma ago [14], and formation of the basin is associated with mountain uplift and basin subsidence because west-east compression in the southwestern Japan [15].

A database containing information from drill holes in the Osaka Plain has been

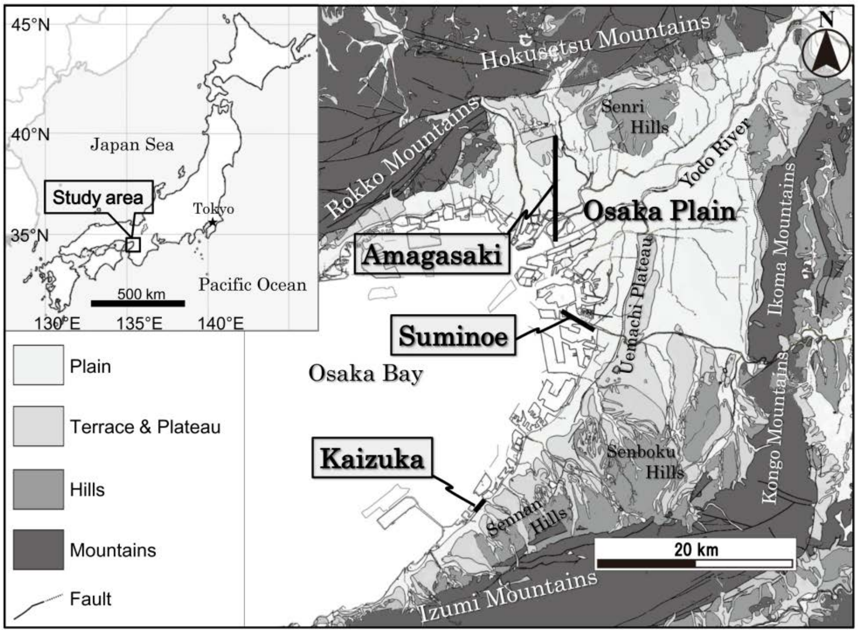

Figure 1: Location of the study area and the lines of cross section (map compiled from the Geological map of Japan 1:200,000 “Kyoto–Osaka” [9] and “Wakayama” [10]).

compiled and is maintained by the Kansai Geo-informatics Network. The database includes information from approximately 56,000 holes drilled for civil engineering projects. The database includes general information on lithofacies (such as gravel, sand, silt, and clay), N-value (Standard Penetration Test results), and other geotechnical engineering data. Its usefulness lies in the large number of subsurface geological data that it contains.

3.2 Results

3.2.1 The Amagasaki District

The Amagasaki district is located in the northwest part of the Osaka Plain (Figure 1). The cross section (Figure 2) is oriented north–south, parallel to dip in this part of the Plain. In this section, we compared the ravinement surface of the most recent transgression, age around 6 ka, with the ravinement surface of the previous transgression, age around 125 ka. This comparison shows that the landward part of this district has apparently been uplifted around 14 m, an average rate of uplift of around 0.12 mm/year between around 125 and 6 ka (Figure 2). The amount of uplift was measured from the elevation of landward ends of the ravinement surfaces. These two transgressions correspond to Marine Isotope Stage (MIS) 1 and MIS 5e, and the eustatic sea level rise of both these Stages was approximately the same [16]. Note that the lower ravinement surface in this section dips seaward more than the upper ravinement surface. This shows that the seaward part of this district has dipped seaward (southward).

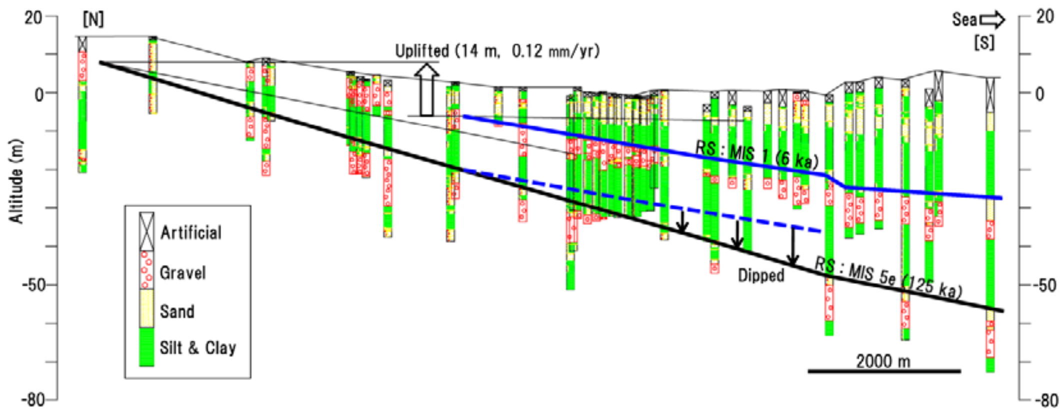

Figure 2: Geological cross section of the Amagasaki district (location shown in Figure 1). RS; Ravinement Surface.

3.2.2 The Suminoe District

The Suminoe district is located in the western part of the Osaka Plain (Figure 1). In this district, we oriented the geological cross section orthogonal to the axis of the Suminoe flexure [17] and compared the ravinement surface of the last transgression (6 ka) with the ravinement surface of the same 125 ka transgression identified in the Amagasaki section. In this section, we estimate that the Suminoe flexure has been displaced around 31 m, an average movement of 0.26 mm/year between around 125 and 6 ka (Figure 3). In contrast to the Amagasaki section, the ravinement surfaces in this part of this district are parallel, suggesting that viewed in this orientation, the opposite sides of the flexure apparently subsided together.

Nanayama et al. (2001) [18] also used ravinement surfaces to estimate the rate of the Suminoe flexure displacement. In their study, they used cross sections constructed from six drill cores and results from a seismic reflection survey and noted the sharpness and continuity of the ravinement surfaces in the seismic profile.

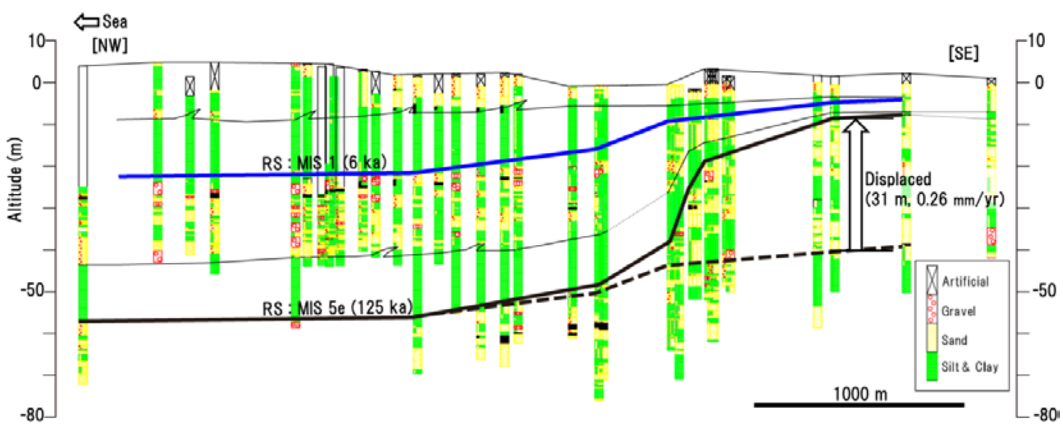

Figure 3: Geological cross section of the Suminoe district (location shown in Figure 1). RS; Ravinement Surface

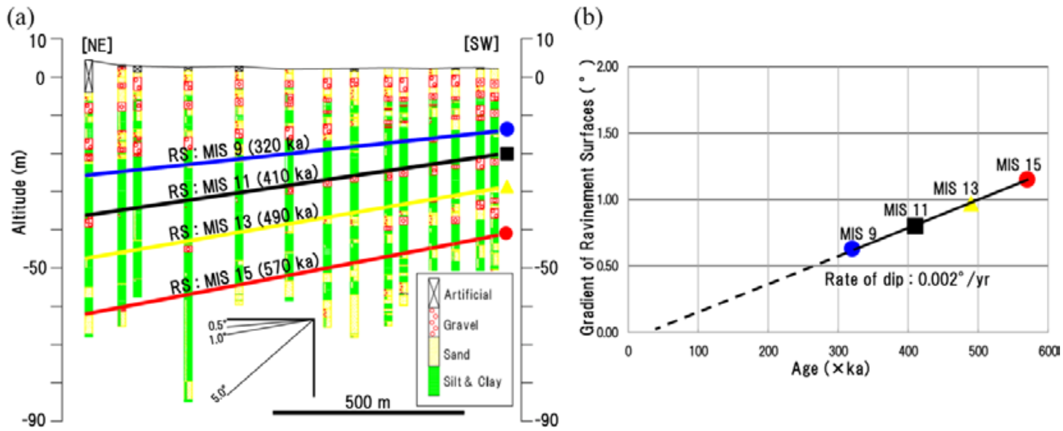

Figure 4: (a) Geological cross section of the Kaizuka district (location shown in Figure 1). RS; Ravinement Surface, (b) Rate of dip of the ravinement surfaces.

3.2.3 The Kaizuka District

The Kaizuka district is located in the southwest part of the Osaka Plain (Figure 1). In Kaizuka, we measured the gradient of four ravinement surfaces created by the MIS 9, 11, 13, and 15 [5] transgressions in a section crossing the north limb of an anticline(Figure 4). The age of these four transgressions correspond to around 320, 410, 490, and 570 ka [19]. The lower ravinement surfaces dip more steeply than the upper ravinement surfaces with the dip increasing with age from around 0.6° to 1.2°. Plotting the dip and the age of the individual ravinement surfaces show that the dip of the ravinement surfaces, and by inference the dip of the anticline's north limb, has been increasing at a constant rate of around 0.002°/year during the period from around 570 to 320 ka (Figure 4).

4 Conclusion

In this paper, we used the successive ravinement surfaces to evaluate the tectonic movements. Meanwhile, volcanic tephra has commonly been used as reference layers for the reconstruction of tectonic movement. In a geologic time frame, these deposits are formed instantaneously, are easily dated, and conform to the topography at the time of deposition. However, if tephra is deposited where erosional processes dominate, like on land, they may have been eroded or reworked. And if tephra is deposited as a thin layer on the sea floor, it may be difficult to distinguish later in outcrop or core because of bioturbation. Furthermore, distribution of widespread tephra is limited active plate margins such as the Japan island arc. In contrast, because the ravinement surfaces can be recognized in the transgressive deposits all over the world and are usually preserved because they are buried by later by marine deposits, they are a useful reference plane for the reconstruction of tectonic movements.

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