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GIS Analysis of the Erosional Process of Volcanic Deposits in Inukai Area, Japan

by

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Abstract

The Aso volcanic deposits in Inukai area mostly consist of the Aso-4 pyroclastic flow deposit, which is divided into A4 and A4W. A4 overlays A4W and mainly composed of tuffs, whereas A4W, of welded tuffs. Erosional process of volcanic deposits may cause slope failure hazards requiring continuous monitoring in order to manage probable risk over people, surface affairs and infrastructure. Erosional process is studied by utilizing 1:50,000 geological map and, digital elevation model processed in geographical information systems (GIS). The present topographic surface was obtained from all the elevation points, whereas the contact surface between the A4 and A4W rock units was generated by utilizing spline interpolation involving only elevation points along the A4-A4W geological boundary. The present topography and the A4-A4W geological contact surface were performed to calculate the total thickness of A4 unit. Generally, the A4 rock unit is characterized as poorly welded and lower resistance to abrasion than A4W, so the distribution would be constrained by regional erosion. GIS analysis has made it possible to evaluate the thickness distribution of the A4 rock unit and erosional process in this area. Comparison between these results and the distribution of slope failure risk zones (which were defined accordingly with the methodology to analyze high angle risk zones from the Japanese Ministry of Construction) would allow reclassifying slope failure risk zones.

Keywords: Geographical Information Systems, Aso pyroclastic deposits, Inukai

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1. Introduction

The study area of Inukai (414 km^2) is located in Oita Prefecture, Kyushu Island of Japan (30°0′-33° 10′ N; 131°30′-131°45′ E) situated in the east mountainside of the Aso Volcano (**Fig. 1**). Deposits from the Aso volcano have been widely spread at the east mountainsides during the Quaternary period (Late Pleistocene). These deposits consist mainly of pyroclastic and lava flows classified as Aso-1 to Aso-4 (Ono et al., 1977). The study area consisted mainly of Aso-4 with very small portion of Aso-3. Aso-4 consists of two units, the A4 and A4W. A4 overlays the A4W and mostly composed of tuffs, whereas A4W mainly composed of welded tuffs.

The relative fast erosional process that affects these volcanic deposits generates natural hazards such as slides and slope failure phenomena. Previous studies have identified different kinds of risks existing in some of the areas (Ministry of Land Infrastructure and Transport 1996). Thus, analysis of evolution of erosional process that causes the natural hazard becomes an important task specifically for the local society and official of the Oita Prefecture.

Since it has been assumed that A4 and A4W differ in their erosional process, the A4 unit is more likely to have faster and earlier denudational process, because A4 is more exposed than A4W (A4 overlies A4W) and A4 has lower strength and lower resistance to abrasion. The welded tuffs of A4W have vertically prominent joint systems that form regulated vertical columns and consequently their main outcrops in the valleys are in cliffs. Those cliffs cause the rock falling, slumping and toppling phenomena.

Inukai area in Oita, Japan, is analyzed with GIS, where geological characteristics and a digital elevation model (DEM) of the area has been processed to obtain present topography as well as the thickness distribution of the A4 rock.

The purposes of this study are as follows: (1) to understand more comprehensively the spatial evolution of the erosional process of the Aso volcanic deposits; (2) to model the geological boundary between the A4 and A4W rock units and the 3-D distribution of the A4 unit, through GIS process; (3) to estimate the thickness distribution and configuration of the present A4 unit, as well as elevation, and slope distribution of both A4 and A4W units; and (4) to compare slope failure risk map with slope and distribution of A4 and A4W, as well as with the A4 thickness map.

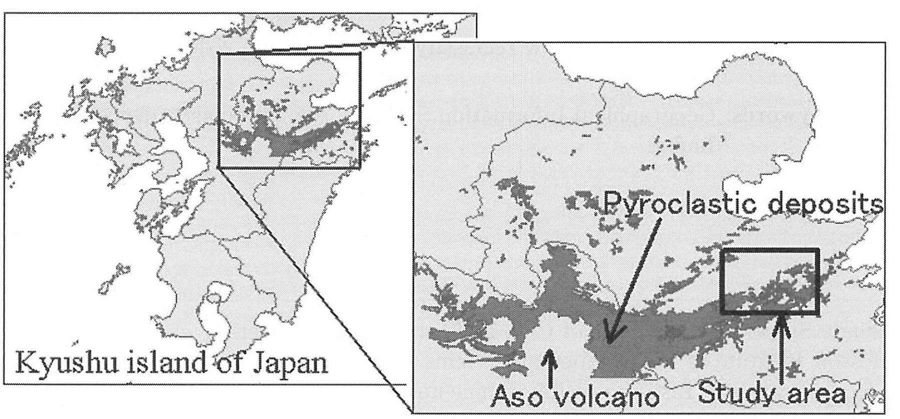


Fig. 1 Study area.

2. Formation of the A4 and A4W rock units

The Aso pyroclastic flows accompanied with air fall pyroclastic of its four cycles formed pyroclastic plateaus surrounding the caldera. The third and fourth cycles (Aso-3 and Aso-4) form bulk of the pyroclastic plateau, which was cut by valleys between each cycle and later pyroclastic flow filled up the valleys and covered plateau surface, thus resulted in densely welded valley-fill faces and non-welded plateau-top faces as typically seen in the Aso-4 pyroclastic flow (Ono et al, 1977).

After deposition of the pyroclastic deposits, the cooling process differentiates the tuffs and welded tuffs. At the base of the deposit, heat storage is at maximum, the material cools very slowly and becomes densely welded. The degree of welding decreases progressively at the higher portion of the deposit, closely until the top most part, thus making the material totally unwelded.

At the top of the profile is a zone of poorly welded material which is characterized by high porosity, low strength and the tendency to completely break down under wetting and drying and mechanical abrasion. This zone is prone to physical weathering and erodes very easily, often showing extensive gully development. With its low compressive strength and lack of joints the material comes to behave more like a soil than a hard rock (Selby et at, 1988).

A4 and A4W rock units are pyroclastic rocks from the Aso volcano, deposited in Late Pleistocene (>43,000 years ago; Ono et al., 1977). The Aso volcano eruption type is such as very voluminous material discharge and involves a relatively continuous collapsing pyroclastic fountain. Such eruptions are frequently associated with caldera development and therefore may not have a unique vent, but may form along a series of vents fissures marking the caldera ring faults (Hidreth and Mahood, 1986). This type of pyroclastic flows could poorly fluidized having relative slow moving. They are thus controlled by the topography and conserve heat during the solidification. Although these hot, poorly fluidized pyroclastic flows are largely restricted to the valleys, the quantity of material produced is such that they inundate the land surface, leaving a plateau which covers all but the highest peaks.

In the study area, initially the upper surface conformed by the A4 unit is rapidly denudated resulting from the tendency of the superficial material to erode faster than the underlying material of the A4W unit.

3. Methodology

3.1 Interpolation methods

During the GIS processing of this study, two interpolation methods are used. Inverse Distance Weighting (IDW) and spline. IDW is utilized for the interpolation of the 50 m elevation point mesh in the whole area of Inukai, while spline method is utilized to obtain the boundary surface between A4 and A4W units.

3.1.1 IDW interpolation

The IDW assumes that each input point has a local influence that diminishes with distance. Accordingly, ESRI (1996) reported that IDW weights the points closer to the processing cell greater than those farther away. A specific number of 8 points are used to determine the output value for each location. A barrier is used in order to improve the interpolation in the cliff zones. The barrier which is utilized is a polyline traced along the boundary of welded tuff in the geological map. The interpolation process involving a barrier enables calculations from the points near the barrier, while disregarding the points behind the barrier. Therefore, the elevation in the barrier (in the cliff) will not be smoothed out, on the contrary it will try to show the vertical slopes (Pupo et al., 2004). High slope angles, like those occurring in the cliffs, are difficult to model with a simple interpolation. The methodology of the interpolation with barrier, allows to model vertical or sub-vertical topographical profiles. The accuracy of the calculated slopes with this method depends on the density of the original elevation points utilized.

3.1.2 Spline interpolation

Spline estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points (ESRI, 1996).

It was found that spline interpolation performs better than IDW for calculating the A4-A4W boundary surface, because spline minimizes the total curvature of the surface and it is very suited for very gently varying surfaces. The IDW interpolation does not suit for A4-A4W boundary surface calculation because this method assumes that each point has a local influence that diminishes with distance. Abrupt changes in the A4-A4W boundary surface are not expected to occur because in known outcrops, the A4-A4W boundary is almost always very smooth.

Comparing with Kriging interpolation method, spline interpolation can get a better representation of the A4-A4W boundary surface, because like IDW interpolation, Kriging forms weights from surrounding measured values to predict values at unmeasured locations.

3.2 GIS processes

The available data utilized in this study consist of a 50 m elevation point mesh (Geographical Survey Institute, 2001) and 1:50,000 geological map of the Inukai area (Teraoka et al., 1991).

Figure 2 shows the detailed procedure in determining the preliminary A4 thickness map, as well as the A4 and A4W slope, elevation and distribution maps that were used in the analysis of the erosional process of the A4 and A4W rock units. Also the process includes comparisons between slope failure risk zones and slope, distribution and thickness maps. Using the 50 m elevation point mesh of the Inukai area, the inverse distance weighted (IDW) interpolation is performed to model the present topography. Slope map is generated from the surface topographical model. Slope and elevation maps are used to calculate the mean slope and mean elevation along the study area.

The 1:50,000 geological map is scanned and digitized to obtain separate polygon layers of A4 and A4W units. In the same way, the boundary between the units A4 and A4W is digitized to obtain a different polyline layer. The relative abundance of the A4 and A4W units is determined at the ground surface by calculating the area of the polygons for A4 and A4W units derived from the digitized geological map. In order to analyze the distribution of the A4 and A4W rock units, the area is divided into 27 bands (each having 1 km wide) perpendicular to the assumed depositional flow direction of the pyroclastic deposits (**Fig. 3**).

The selection of elevation points in A4-A4W boundary is obtained from the intersection between the elevation map and the A4-A4W polyline digitized in the geological map. The selection of elevation points in A4 polygons (Present topography) is generated through the intersection between elevation points in the elevation map and polygons of the digitized A4

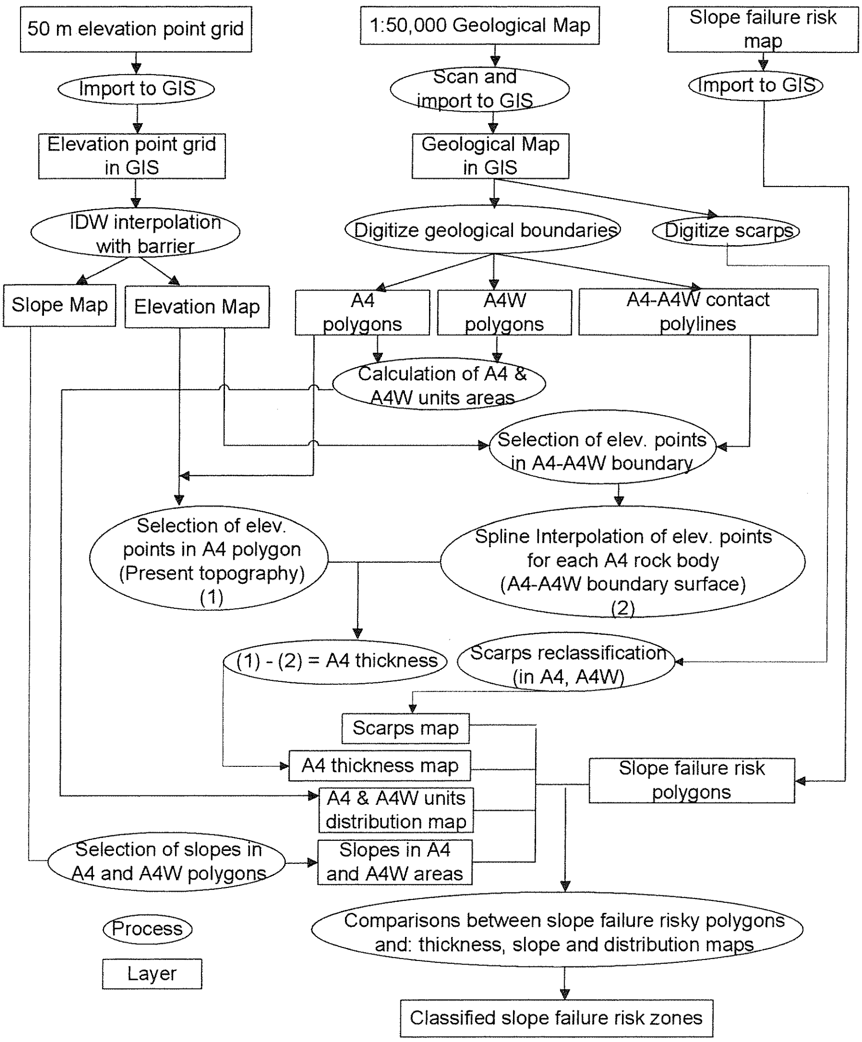


Fig. 2 GIS process to analyze elevation, slope and distribution of the A4 and A4W rock units. Also involves the A4 thickness calculation and comparisons with slope failure risk zones zones.

unit.

The boundary surface between A4 and A4W rock units is calculated by performing a spline interpolation process using only the outcrop elevation points of this boundary surface. For A4 thickness calculation, it is necessary to determine the upper and lower surfaces of this rock unit. The upper surface is represented by the present topography, whereas, the lower surface is the boundary surface between the A4 and A4W rock units (**Fig. 4**).

The A4 thickness is obtained by calculating the difference between elevation points of A4 present topography and A4-A4W boundary surface. The calculated A4 thickness also gives the thickness map. This study estimates that A4 thickness distribution, which can be used in future studies as an important parameter that influences the susceptibility of mass movement.

Scarps defined as lines of cliffs formed into a steep slope that are usually caused by erosional process. The scarps are digitized from the geological map previously input to GIS.

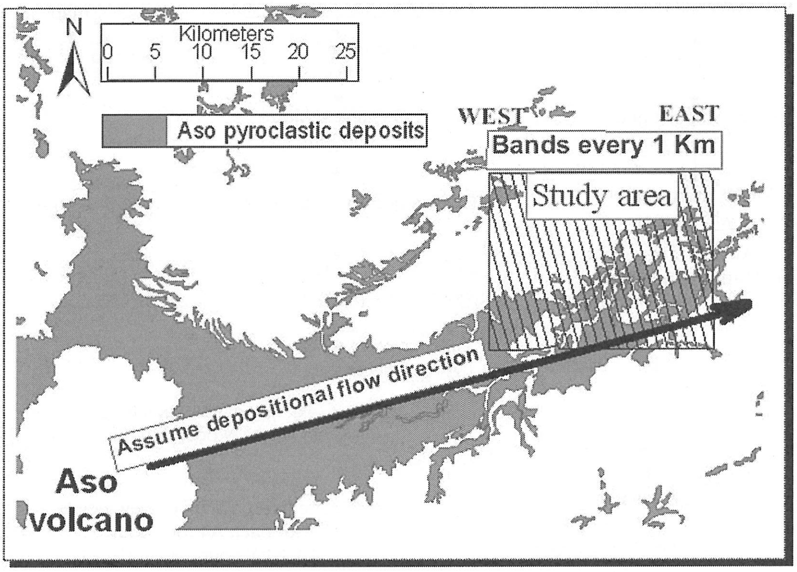


Fig. 3 Division of study area in bands (1 Km width) perpendicular to the assumed depositional flow direction.

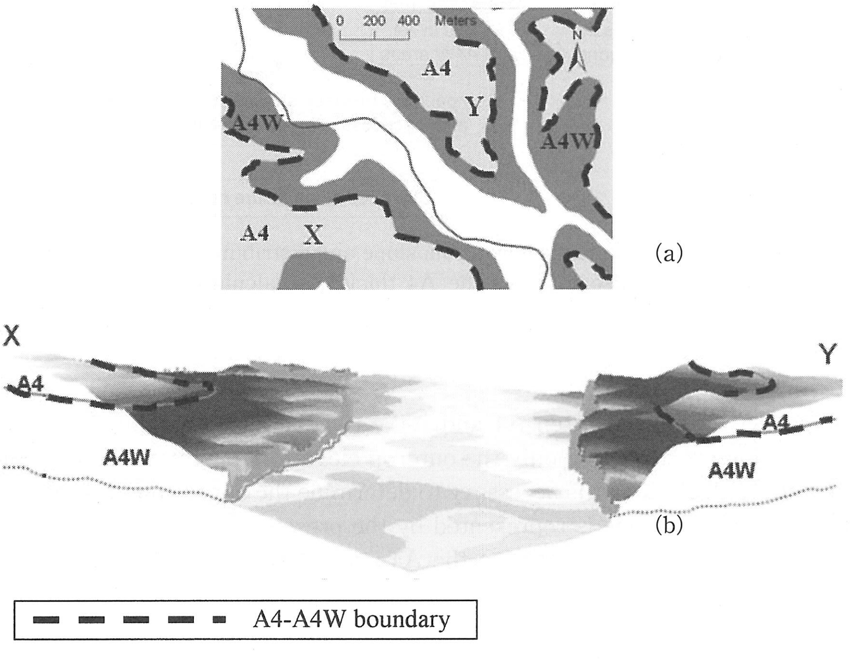


Fig. 4 (a) Geological map showing the rock units A4 and A4W. (b) 3-D view (from South) obtained from the geological map depicting the A4 and A4W rock units and the boundary surface between them.

Also, Geological contacts between A4, A4W, alluvial deposits and older rocks (older than Aso deposits: Middle Pleistocene gravels, sandstones, and Cretaceous sandstones and shales) are digitized to produce separate polyline layers. The digitized scarps are classified according to scarps that intersect in each of the geological contacts (A4-A4W; A4W-alluvium; A4-alluvium; A4-older rocks and A4W-older rocks) and also scarps in the A4 and A4W zones.

Slope failure risk zones are imported to the GIS in order to compare them with slope, distribution and scarp maps of A4 and A4W units as well as with the A4 thickness map. The slope failure risk areas are defined in accordance with the methodology used by the Ministry of Construction of Japan, which considers the dimensions of the slope and the area that can be affected by the occurrence of a mass movement event. Risky slopes are identified when infrastructure, buildings and facilities can be affected by a probable occurrence of a landslide event. The risky areas are selected when there are 5 m height slopes or above, when 5 or more families live in the area or when there are public facilities like hospitals, schools, hotels or government offices.

The distribution of slope failure risk zones was analyzed in bands (1 Km width) from West to East, perpendicular to the flow depositional direction.

4. Results and discussions

4.1 Distribution

The distribution of A4 and A4W units exposed in the Inukai area shows that 62% of the total Aso-4 pyroclastic deposits in the area, is dominated by the A4W unit and 38% by the A4 unit, respectively. In relation with the area of Inukai map (43,113 Ha), A4 covers 3,838 Ha and A4W, 6,108 Ha (**Fig. 5**).

Expected differential erosional rate between the A4 and A4W rock units could be attributed by the unique characteristics of the two rock units. The A4 unit is mainly characterized as having poorly welded, low strength and known for having low resistance

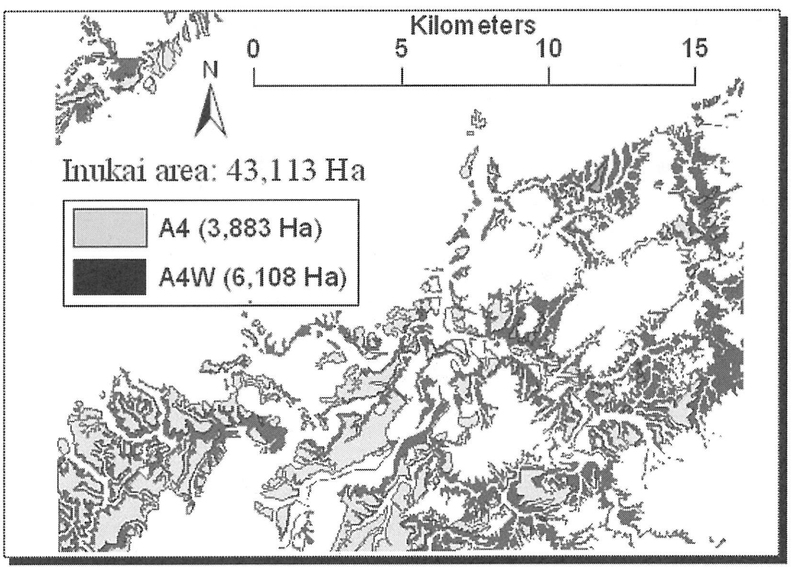


Fig. 5 A4 and A4W rock units distribution in Inukai area.

against abrasion thus are more likely prone to the occurrence of faster erosional process. Whereas, the A4W unit is characterized of being highly welded, medium strength and have high resistance against abrasion that makes it more resistant against erosion. Non-welded tuffs normally are subjected to rapid erosion and formation of steep gullies whereas, narrow gorges are developed in the welded tuffs as a result of stripping of non welded materials.

The differential erosional process of the pyroclastic flow rocks is explained by Selby et al (1988) in three stages. In the early stage there is a rapid erosion of steep gullies in the upper poorly welded zone; the middle stage stripping of poorly welded material exhumes the columnar welded tuffs and in the later stage the valleys widening leaves only the outcrops of the welded tuffs. Different erosional stages can be appreciated also in different parts of the Inukai area and gradually variations from one stage to another are carrying out from the whole A4 and A4W outcrops.

4.2 Slope

The slope frequency distribution of A4 and A4W is plotted in **Fig. 6** covering the study area. The slope interval is set at 5°. Initially, the slope frequency distributions of A4 and A4W units differ greatly particularly at slope range 0-5° with differential range of 32% favoring the A4 unit. The succeeding slope frequency distributions falls almost the same trends with an increase in slope range where higher frequencies were observed in A4W than A4 irrespective of slope range. The slope frequency distributions of both A4 and A4W are approximately more than 90% and 80% of which occurs within the slope range of 0-20°. The higher frequency of A4 in the slope range of 0-5° explains that A4 mostly present even topography.

The mean slope angle of A4 and A4W units versus elevation ranges is shown in **Fig. 7**. The elevation is set at an interval of 10 m. Slopes in A4W are greater than in A4 unit in all the elevation ranges. The two rock units almost follow the same increasing and decreasing trend. **Figure 7** shows greater tendency of an increase in mean slope angle at the elevation of 280 m specifically in the case of A4W unit. Comparison between the A4 and A4W units shows that A4W unit has higher mean slope values than A4 unit as manifested following the increasing trend in mean slope as elevation increases.

The slopes in A4W units are basically steeper than A4 with its continuous increases in

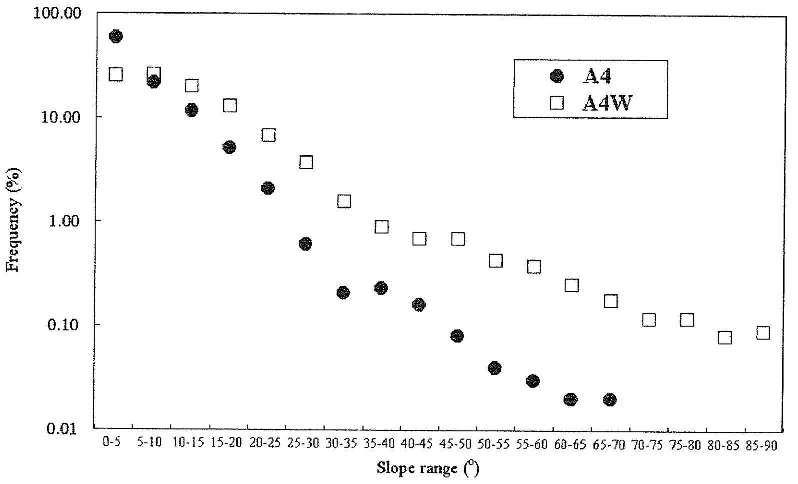


Fig. 6 Slope frequency distribution of A4 and A4W rock units.

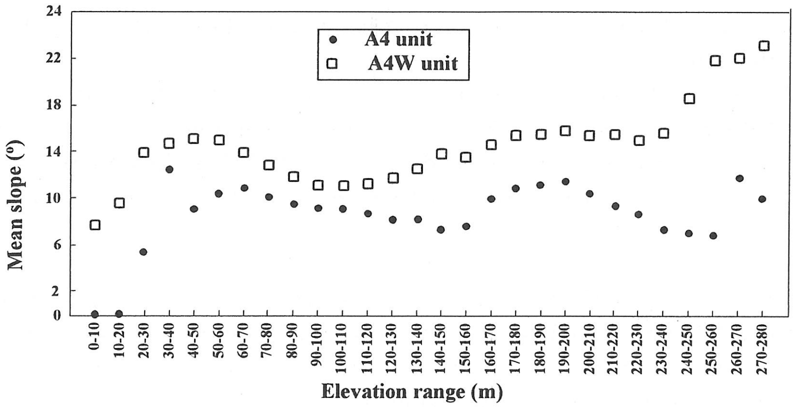


Fig. 7 Mean slope angle versus elevation ranges.

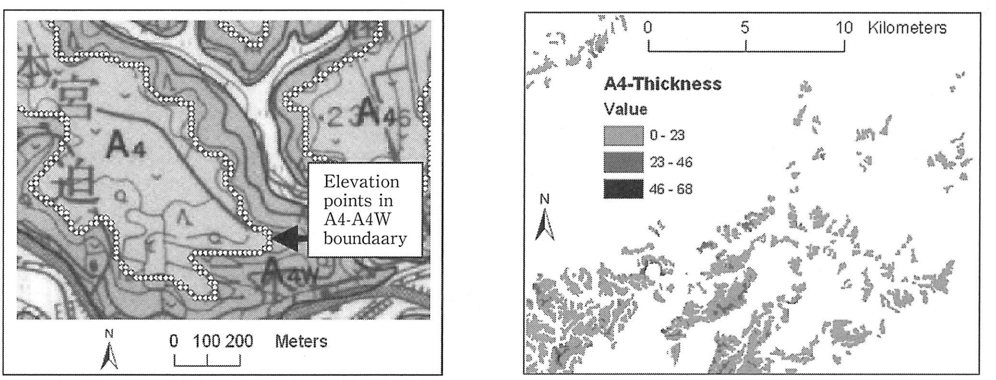
differential range at higher elevations. This result consists with the fact that at steeper places in Inukai Area, A4W only shows mostly the exposed faces of vertical outcrops.

Existing A4W at steeper slopes than in A4 unit suggests that A4W has more resistance to abrasion and form vertical and sub vertical cliffs. The lower angles of the A4 unit are explained by its lower resistance to abrasion and lower strength that facilitate faster action of water and gravity in the denudational process.

4.3 Thickness calculation

The thickness of A4 rock unit calculated with the GIS proposed method, varies from 0 to 68 m. Its distribution mostly confined at the south and west part of the study area (**Fig. 8**). Significantly highest percentage of 90% of all the A4 thickness falls within the thickness range of 0 to 23 m, with relatively little percentage of 10% falls within the range of 23 to 68 m in thickness.

With respect to the thickness distribution maps, it is necessary to take into consideration that the method do not intend to obtain the exact values of thickness in every given location, instead the method intends to obtain a preliminary relative thickness distribution particularly



(a) (a)

Fig. 8 (a) Elevation points along the outcrop of A4-A4W boundary surface used to perform the spline interpolation process. (b) A4 thickness calculated map. Values ranges from 0 to 68 meters.

of the A4 rock unit. Therefore, comparisons between thicknesses calculated in this study and thickness from boreholes or other method are necessary for the calibration of the GIS method employed in this study.

A4 thickness calculated near the outcrops is a useful parameter that contributes in the study of hazard mass movement prediction because as mentioned earlier, the A4 rock unit has a relatively fast erosional process and it is expected that thickest parts (near to the outcrops) of this rock unit must have higher susceptibility to cause mass movement events.

4.4 Scarps

Table 1 shows the classification and length of scarps. From the total length of the scarps (156,096 m) 57% fall within A4W areas, contrasting with only 15% of the scarps length in A4 zones. The remaining scarp's length, which occur in the intersection with geological boundaries, 12% and 9% correspond to A4W-alluvium contact and A4W-older rocks contact respectively; and only 5%, 1% and 1% correspond to A4-A4W, A4-alluvium and A4-older rocks, respectively.

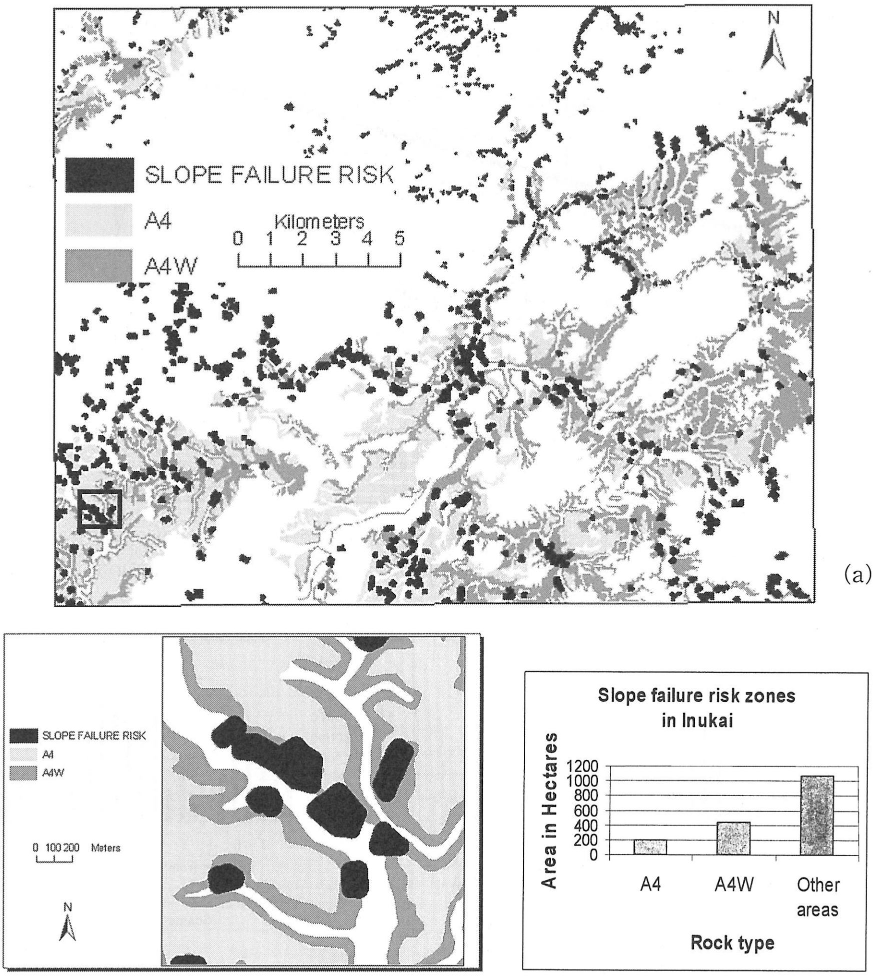
Scarps are mainly related with the A4W areas, as the highest percent of scarp's length (57%) falls within these areas. In relation with the intersections between scarps and geological contacts, it is remarkable that scarps intersecting the A4W-alluvium contact and A4W-older rock contacts (12% and 9% respectively) predominate over other geological contacts. Scarps are potential source of mass movements therefore their occurrence must be compared with the slope failure risk areas.

4.5 Comparisons with slope failure risk areas

In Inukai area the slope failure risk zones (**Fig. 9**), cover 1709 hectares which 197 ha and 434 Ha fall in A4 and A4W, respectively. The comparisons with slope failure risk zones are carried out along bands (1 Km width) perpendicular to the assumed depositional flow direction (**Fig. 10**). In the case of A4 unit the higher concentration of slope failure risk zones is distributed within the bands 10 to 13 and the lower concentration are at the east part, between bands 14 to 17. In bands from 18 to 27 there are not slope failure risk zones in A4 zones, because this rock unit is almost completed denudated at the East of the study area. (**Fig. 11**). In the case of A4W unit higher concentrations of slope failure risk zones are within 9 to 16 and 1 to 6, with a tendency for lower concentration at the East in the bands 20 to 27 (**Fig. 12**).

Table 1 Scarps classification within A4 and A4W zones, some of the geological contacts and slope failure risk areas.

	SCARPS IN A4 AREA	SCARPS IN A4W AREA	SCARPS INTERSECTING				
			A4-A4W BOUNDARY	A4W - ALLUVIUM CONTACT	A4W - OLDER ROCKS CONTACT	A4 ALLUVIUM CONTACT	A4- OLDER ROCK CONTACTS
LENGTH OF SCARPS (m)	24,290 (15%)	89,126 (57%)	7,537 (5%)	18,120 (12%)	14,229 (9%)	1,380 (1%)	1,414 (1%)
LENGTH OF SCARPS IN SLOPE FAILURE RISK ZONES (m)	951	4,830	234	174	1,080	0	211



(a)

(b) (c)

Fig. 9 (a) Slope failure risk zones in Inukai area. (b) Slope failure risk zones occur more frequently in A4W areas than in A4 areas. (c) Areal distribution of slope failure risk zones in A4, A4W and other areas.

More than 90% of the slope angles in A4 and A4W risky zones fall within 1° to 38° and 1° to 46°, respectively. The mean slope angles are 13° and 16° for A4 and A4W areas respectively. The relatively low mean slope values (13° and 16° for A4 and A4W respectively) in the slope failure risk zones show that topography is in general not very steep, except in the scarp areas where slope angles are near to vertical (90°). Although scarp areas (counted as number of cells in the GIS grid map) cover less than 1% of the total risky area, higher slope values in the A4W zones reflect that the welded tuffs tend to form cliffs, or sub-vertical profiles, which also explains that the concentration of slope failure risk zones in A4W areas is higher than in A4 areas.

The A4 thickness in the risky zones is between 1 to 50 m, having a mean value of 11 m.

The slope failure risk zones are estimated in the valleys and represent the critical advancing erosional places.

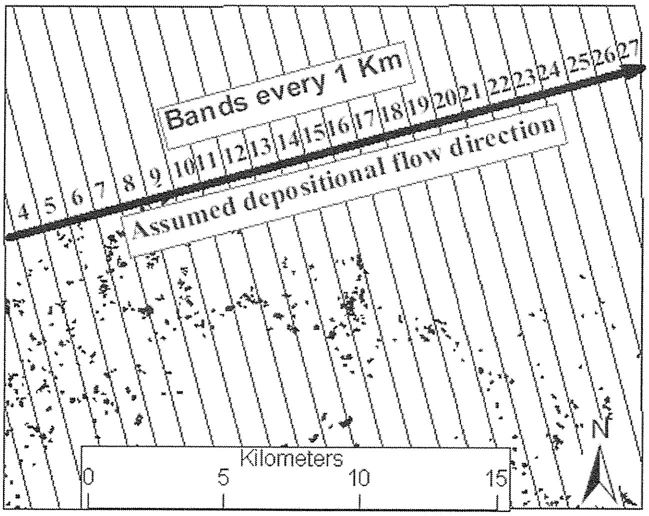


Fig. 10 Division of slope failure risk maps in bands (1 Km width) perpendicular to the assumed depositional flow direction.

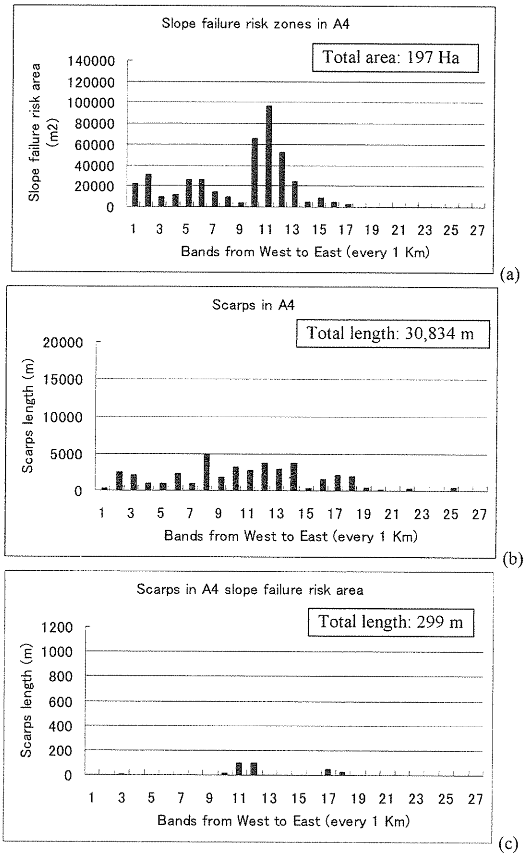


Fig. 11 (a) Slope failure risk zones in A4 areas distributed in the bands perpendicular to the assumed depositional flow direction. (b) Scarps in A4. (c) Scarps in A4 slope failure risk area.

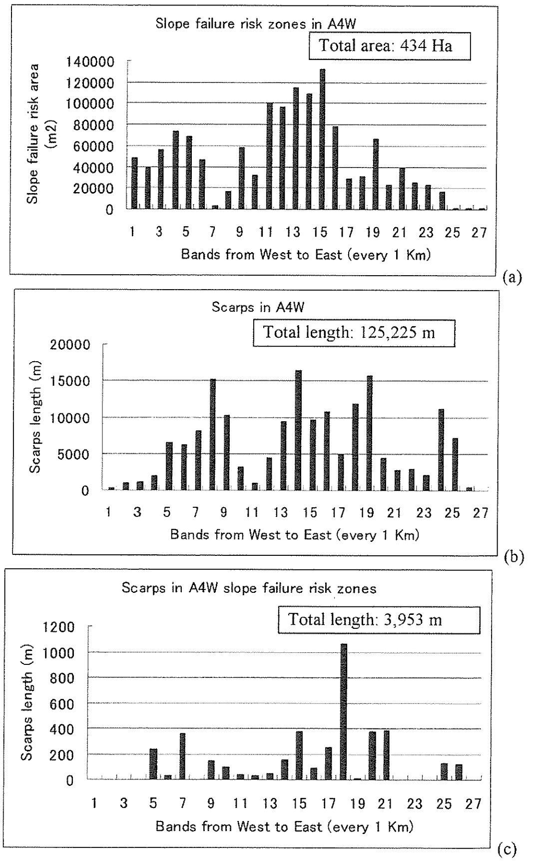


Fig. 12 (a) Slope failure risk zones in A4W areas distributed in the bands perpendicular to the assumed depositional flow direction. (b) Scarps in A4W. (c) Scarps in A4W slope failure risk area.

The scarp group in A4W zones show a widely distribution between bands 5 to 25. Highest concentration of scarps occurs between bands 14 to 19. From the comparisons between both scarp and slope failure risk maps, it is inferred that there are zones with highest susceptibility of mass movement risk, which are found between the bands 10 to 12 for the A4 risky zones and between bands 13 to 15 for the A4W risky zones.

4.6 Applicability of the method to Inukai area

The method used in this study is considered as valuable and applicable specifically with respect to the study of erosional process of the volcanic deposits of these zones because the manipulation of a DEM and geological information in a GIS allows determining easily the present distribution and area of the rocks affected by the erosional process. Moreover, the simple structure of the A4 and A4W deposits (almost horizontal layers) permit to model the ancient and future scenarios of the evolution of landforms.

The advantages of the method are: 1. It allows a fast calculation over wide areas even with limited information such as DEM and geological maps processed in GIS; 2. It allows approximate calculations of boundary rock surfaces, where more or less there are expected regular boundaries between layers (as the case of A4-A4W boundary); 3. It provides acceptable approximation of thickness calculations of the rock layers which are limited by the present topography and regular contact boundaries; 4. It can be applicable for both early and advanced steps with respect to the study of erosional process, particularly if more information is added to improve the results obtained.

5. Conclusions

The IDW interpolation with barrier in GIS process could produce elevation maps that represent very closely the real topography in the cliff zones. The spline interpolation process applied can be acceptable for the calculation of the A4-A4W boundary surface because it is appropriate for smoothed surfaces. Moreover abrupt changes in the A4-A4W boundary surface are not expected to occur because in known outcrops, the A4-A4W boundary is almost always very smooth.

The A4 thickness map represents not exact values of thickness in every given location, but intends to show relative thickness distribution. Highest values of A4 thickness map in the slopes can be source of mass movement events.

Generally, the A4 rock unit is characterized as poorly welded and lower resistance to abrasion than A4W, so the distribution would be constrained by regional erosion. Thus, higher susceptibility to erosion of the A4 unit will continue to occur in the near future, while A4W will remain more resistant to erosion and could remain immovable for longer period of time. Given this result, the thicker and wider portions of the A4 units particularly at the west part are predicted to be the source of potentially future mass movement events.

A4W presents higher mean slope values than A4 unit, along the Inukai area. A4 presents higher slope frequency than A4W at slope range 0° to 5°. Increasing slope range from 5°, A4W presents higher slope frequency than A4, which explain the tendency of A4 to form even topography and the tendency of A4W to form steeper slopes and cliffs in the outcrops at the valleys.

Scarps are closely related with A4W zones because greater percent of the scarps (57%) fall within those areas, contrasting with only 15% in A4 zones. Also there is greater percent of scarps intersecting A4W-alluvium and A4W-older rock contacts (12 % and 9 % respectively), than scarps intersecting A4-alluvium and A4-older rock contacts (1% and 1%).

Slope failure areas are widely distributed in A4W zones along Inukai area (with higher concentration in the bands 9 to 16 and 1 to 6); on the other hand, slope failure areas in A4 zones are mostly concentrated in bands 10 to 13.

Highest concentration of both, slope failure zones and scarps occur in the group bands: 10 to 12 for A4 and 13 to 15 for A4W. This zones can be considered as having the highest slope failure risk.

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