https://doi.org/10.20965/jdr.2021.p0646

Paper:

Geometry and the Mechanism of Landslide Occurrence in a Limestone Area – Case Examples of Landslides in Vietnam and from Europe, China, and Japan –

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[Received November 29, 2020; accepted April 12, 2021]

Landslide damage has been reported in many limestone areas in Europe, where the population lives close to limestone areas, and in Guilin in southern China and Ha Long in Vietnam, which are known for their unique limestone landscapes. There are few studies on the mechanism and type of landslide motion in and around such limestone areas. The lack of basic data is a problem for risk assessment and countermeasures in limestone areas. In this study, we summarized the causes and mechanisms of landslide occurrence, including geology and groundwater, focusing on six landslides that occurred in limestone areas in northern Vietnam, and classified them into six types of landslide movement. In the case of Japan, the occurrence of landslides in limestone areas is rare despite the wide distribution of limestone, and it is difficult to classify the type of movement. Differences in the landslide mechanisms are caused by the difference between limestones generated in the pelagic environment of Japan and limestones developed along the Tethys Sea coast, which are mixed with pelitic rocks as shallow-water sediments in Europe, China, and Vietnam. It is necessary to elucidate the relationship between landslides and the formation environment and sedimentary characteristics of limestone as an accretionary prism based on comparisons of a wide range of cases in future studies.

Keywords: limestone, landslide, karst, landslide movement type, groundwater

1. Introduction

Limestone is a carbonite rock, composed of carbonate minerals such as dolomite. It is a biogenic sedimentary rock that contains more than 50% calcium $CaCO_3$ and has a calcareous shell, composed largely of corals and foraminifera. The distribution of limestones is widespread in the Northern Hemisphere, especially in North America, Europe, and Asia (**Fig. 1**). Limestone is easily dissolved in rainwater containing carbon dioxide, and is known to have features, such as karst topography, due to weathering and erosion, and a large quantity of groundwater flowing through its cavities. Landslide hazards in limestone areas occur frequently in the vicinity of mountain ranges in Europe and North America, and in a wide limestone area from southern China to the Indochina Peninsula [2]. In recent years, the areas where slope disasters have occurred frequently in the Asian monsoon region have overlapped with these limestone areas, and the relationship between these disasters and meteorological conditions, such as heavy rainfall, has attracted attention [3]. However, there is a lack of comprehensive discussions on the geomorphological and geological mechanisms and movement types of landslides in these limestone areas, therefore, there is a lack of basic data on landslide initiation mechanisms necessary for risk assessment (e.g., [4]) and planning landslide countermeasures.

The purpose of this study is to clarify the kinematic types of landslides that occur in such limestone areas, the depositional environment of limestone that forms the background of such landslides, the relationship in terms of deposition between limestone and pelitic rock, and the involvement of groundwater in the limestone area as a factor in their occurrence.

The landslides we studied were mainly those in northern Vietnam [5], which we have studied in the past, as well as those in limestone areas in Europe and southwest-

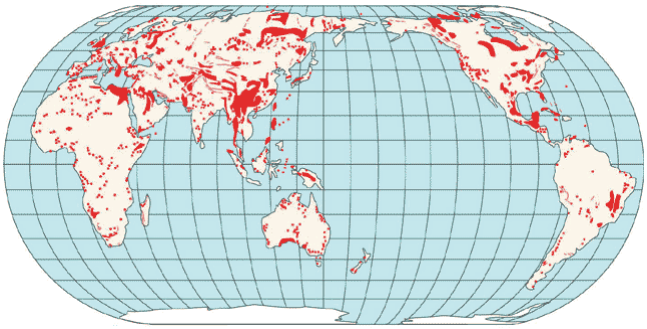

Fig. 1. Distribution of carbonate rocks. From Kano [1]. The gray area indicates the distribution of carbonite rock.

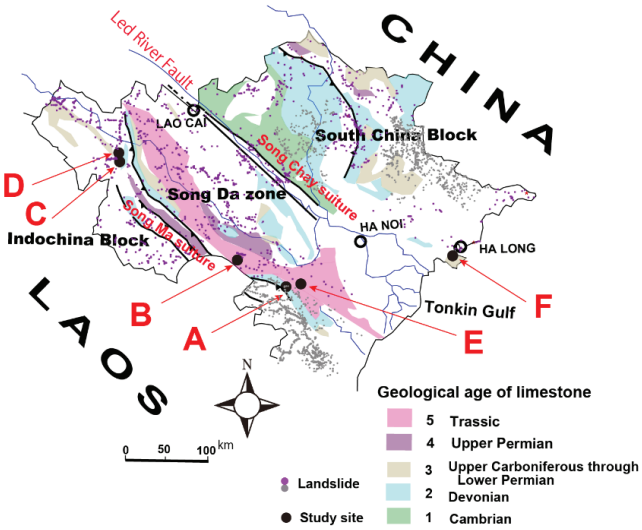

Fig. 2. Limestone distribution area and study area in northern Vietnam. The distribution of limestone and the geological structure were developed based on Khang [8]. The landslide distribution map was obtained from the Department of Geology and Minerals of Vietnam [9]. The gray points of landslides are not classified in terms of scale and may include small-scale landslides such as boulders. Other points indicate landslides with a landslide volume of 1,000 m^3 or larger.

ern China, which were deposited on the continental margin of the Paleo-Tethys Sea [6] during the late Paleozoic and Mesozoic eras. We compared those areas with limestone areas in Japan, where there are few landslides despite the large distribution of limestones.

2. Definitions of Method and Terms

2.1. Method

Discussions on landslides in this study are based on case studies of landslides in northern Vietnam, the Mt. Reschberg and Rindberg landslides in Austria, and the literature, which was surveyed in the field from 2010 to 2019. In this study, landslides in the limestone area caused by earthquakes with different generation mechanisms were excluded. Since there is no data on limestone alone, the limestone distribution maps used are all based on carbonite rock or karst area distribution maps instead. The age of the geological features in the landslide area in Vietnam is based on a 1:200,000 geological map [7].

In order to understand the relationship between groundwater in the limestone area and surface or groundwater in the pelitic rock zone bordered by faults in Vietnam, groundwater analysis was conducted in the landslide area (B in **Fig. 2**) in the Mac Chau region, one of the study sites. Water temperature, pH, and electrical conductivity were measured at the site. The samples were filtered through a 0.45 μm membrane filter and brought back in polyethylene containers for an analysis of the major ions and dissolved silicic acid. Major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were analyzed by atomic absorption spectrophotometry, anions (Cl^-, NO^{3-}, and SO_4^{2-}) by ion chromatography, alkalinity (equivalent to HCO^{3-} concentration) by acid titration using the Gran method as the endpoint determination method [10], and dissolved silicic acid (silica SiO_2) by molybdenum yellow absorption spectrophotometry. The analytical results were organized in stiff diagrams and tri-linear diagrams, and PHREEQC (an earth science code developed by the USGS) was used to calculate the equilibrium partial pressure of carbon dioxide (P_{CO_2}) in groundwater and the saturation index (*SIc*) for calcite.

2.2. Terms

Landslides occurring in and around the limestone area are hereafter referred to as "limestone area landslides." The term "pelitic rock" used in this study is a generic term for mudstone, marl, shale, or muddy schist intercalated in or faulted with limestone.

3. Case Examples of Landslides

3.1. Case Examples of Landslides in Vietnam

The northern part of Vietnam has many mountainous slopes, and landslide disasters caused by typhoons and heavy rainfall during the rainy season are common annually. Most landslides occur in the weathered areas of pelitic rock and granitic rocks, and few of them occur in limestone areas. In recent years, however, landslides have occurred frequently along the national roads parallel to the Laotian border in northern Vietnam, along the Song Ma suture zone and the Red River fault, which was the collision site of the South China and Indochina cratons in the late Paleozoic and early Mesozoic (**Fig. 2**).

These landslides are classified into two types: those occurring in the pelitic rock distribution area, which meets the limestone with a fault (A, B, C, and D in **Fig. 2**), and those occurring in the limestone layer where the stratigraphic dip is more than 70° (E and F in **Fig. 2**).

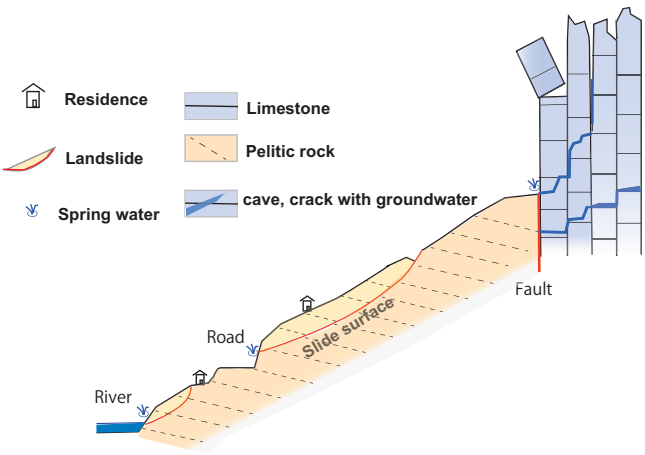

Fig. 3. Geomorphological and geological characteristics of landslides (A, B, C, and D in **Fig. 2**) along the Song Ma suture zone in northern Vietnam. Landslides occur in the pelitic rock zone, which is in contact with limestone at a fault.

Fig. 4. Site A: Don Ban region – Landslide toe area –.

3.1.1. Landslides Occurring in a Pelitic Rock Distribution Area That Is in Contact with Limestone at a Fault

As shown in **Fig. 3**, all these landslides occurred in the Mesozoic pelitic rock distribution area, which is in contact at a fault with the Late Paleozoic to Early Mesozoic limestone.

In the Don Ban region (A in **Fig. 2**), a 40 m wide area collapsed in 2012 (**Fig. 4**), killing two people on the national road. About 200 m north of this point, cracks and deformation were observed on the slope of the road that was being improved in 2007. About 100 m to the north, another landform above the slope in a village shows traces of past landslide occurrence. Shale and crystalline schist are distributed on the road slope, and at the top of the slope Triassic limestone, which is in contact with these strata at a fault, forms a north-south ridge. Limestone masses with stalactites are scattered under the steep limestone cliffs. During heavy rainfall, a large quantity of surface water flows down from the limestone area to the road slope, which is a major cause of landslide occurrence.

Fig. 5. Main scarp of landslide at site B (Moc Chau region). The arrow indicates landslide movement direction.

In the Moc Chau region (B in **Fig. 2**), houses in the village were deformed and roads were cracked during the heavy rains in 2017. The Triassic limestone in the uppermost part of the slope is in contact, at a fault, with the mudstone and siltstone in the middle and lower part of the slope, and the limestone area is bordered by groundwater springs from cavities. The slope is covered with rainwater gullies, and some of them are deeply scoured to form streams. The slump type slides (**Fig. 5**) of 10–20 m width, occurring from the road slope to the village area, are all moving toward the stream formed by such scouring.

In 2010 and 2012, landslides occurred at site C in the Muong Lay region (C and D in **Fig. 2**), with a width of about 300 m and a length of about 100 m, due to road widening. A part of the landslide's moving soil mass hit the wall of a hospital located at the bottom of the slope and stopped. The Devonian limestone at the top of the slope is connected to the pelitic rock (siltstone, shale, and crystalline schist) from the middle to the bottom of the slope by a fault. The slope is dotted with springs, and some basalt boulders are observed. The landslide occurs in muddy rock, and a main scarp can be seen at the head and a slip surface at the toe (**Fig. 6**).

In addition, a landslide with a width and length of about 300 m occurred at site D, about 10 km south of site C, during heavy rains in 2011, burying a road and part of a river. The geology of the landslide slope consists of shale and siltstone as in site C, and limestone is distributed at the top of the slope (**Fig. 7**). The landslide's moving soil mass is mixed with shale, siltstone, and limestone gravel containing stalactites.

3.1.2. Landslides That Occur in the Limestone Layer with a Steep Geological Slope

The landslide that occurred in the early morning of October 12, 2017 at site E (Khanh Village region) in **Fig. 2**, was about 120 m high, buried 4 houses, and killed

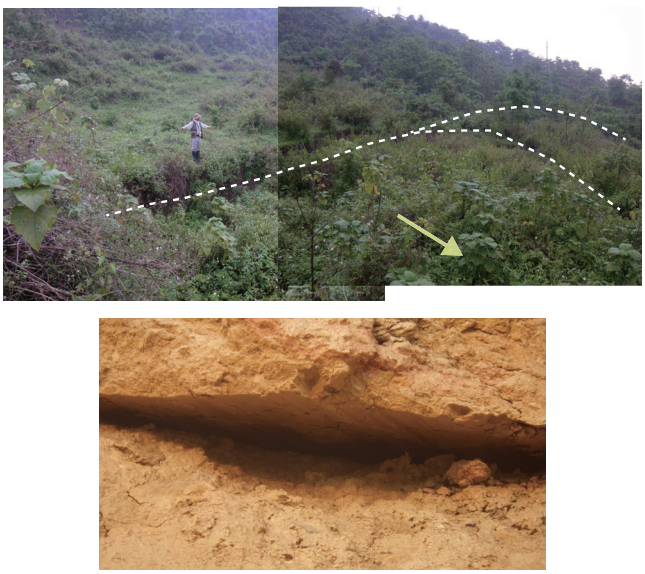

Fig. 6. Site C: Muong Lay region. Upper: Landslide main scarp. The arrow indicates the direction of the slide. Lower: Slip surface appearing at the toe of the landslide.

Fig. 7. Main scarp at site D. The arrow indicates the direction of landslide movement.

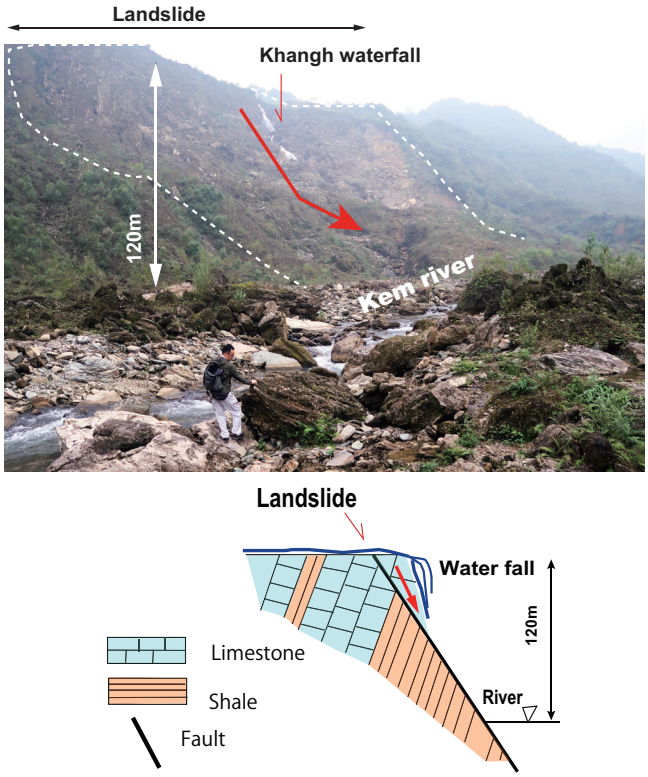

Fig. 8. Landslide and geological schematic cross section at site E (Khanh waterfall). Upper: Panoramic view. The slide's width was about 200 m. Lower: Geological schematic cross section. The bold arrow indicates the direction of landslide movement.

18 people. The collapsed soil of the area, including the Khanh waterfall which is also known as a tourist attraction, crossed the river flowing down the lower slope and overcame the hill on the other side (left bank), with a height of about 30 m, to reach the paddy field (**Fig. 8**). As a result, the Khanh waterfall has now receded by 40–50 m. The geology of the area consists of Mesozoic Triassic limestone and shale. The strike of the stratum is N10°–40°W with a dip of 70°–80°E, which is close to vertical (**Fig. 8**).

The Ha Long region (F in **Fig. 2**), which is well known as a limestone tower karst landscape, has experienced many landslides in recent years. The geology of the area consists of shales with coal, gray massive limestones, siltstones, and conglomerates of Carboniferous to Triassic. This site is on the extension line of the Red River fault (**Fig. 2**). The landslide, which occurred in 2017 on a slope under road construction, with a width of about 70 m and a length of about 120 m, is located on the synclinal axis of the folding structure, and pelitic rock (coal, shale, and siltstone) in a wedge shape, sandwiched by limestone layers on both sides, was moved to the front. In the middle and lower areas of the landslide, several springs can be observed from the cavity in the limestone layer. The main reasons for the occurrence of landslides are the existence of pelitic rock layers that are fractured into wedges due to the folding structure, and the large quantity of spring water from the cavity of the limestone area during heavy rainfall (**Fig. 9**).

3.1.3. Relationship Between Groundwater in Limestone and Landslides

All the aforementioned landslides in northern Vietnam seem to be influenced by limestone groundwater. In particular, the groundwater in the limestone behind the slopes at A–D may play an important role in causing the landslide of pelitic rock on the lower part of the slope. Therefore, we analyzed the groundwater quality of limestone and pelitic rock (**Fig. 10**) in the Moc Chau region (B in **Fig. 2**) [5].

All the springs are rich in Ca^{2+} ion and HCO_3^- ion and are classified as "alkaline-earth metals, bicarbonate type" (**Fig. 11**). Of the six locations, G015 and G016 are spring water from cracks in the limestone or spring water

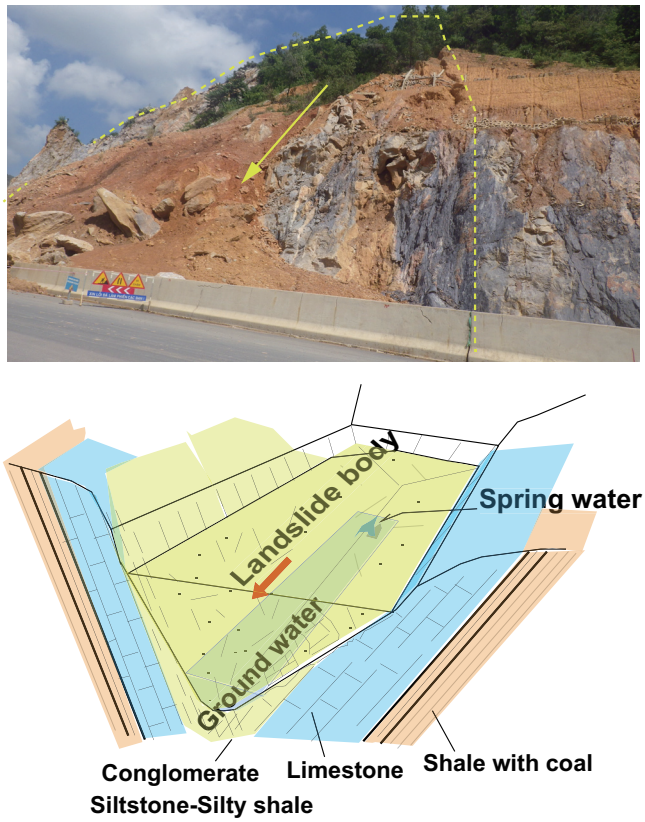

Fig. 9. Panoramic view and modeled geological cross-sections of site F (Ha Long region). The dashed line in the photo indicates the landslide area and the arrow indicates the direction of landslide movement.

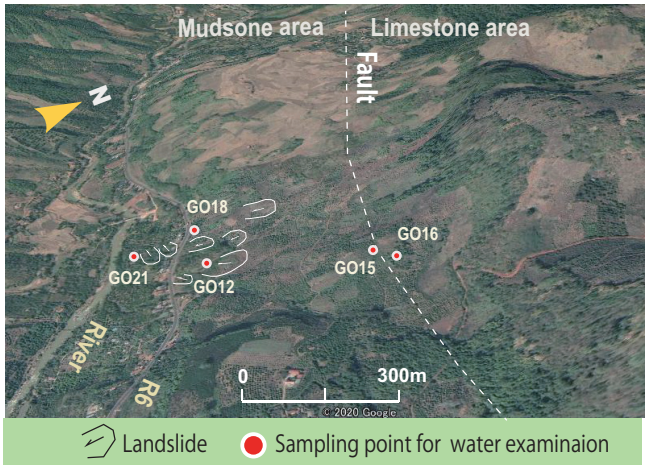

Fig. 10. Groundwater test sample collection point in the Moc Chau region (site B).

from the area behind the limestone. The other locations, G012, G018, and G021, are all springs collected from the slope of pelitic rock, and G010 is water from a small river flowing down the slope of pelitic rock. The groundwater from the limestone area has higher electrical conductivity than the groundwater in the mudstone zone (i.e., more dis-

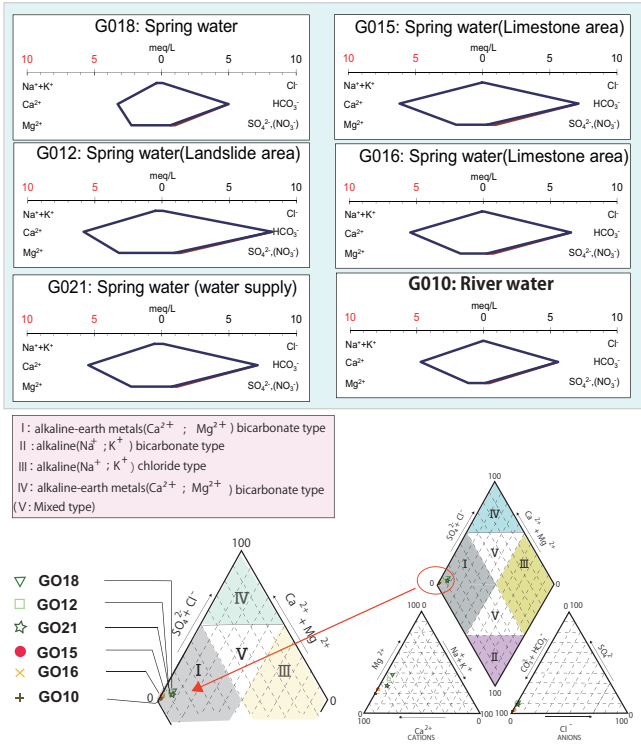

Fig. 11. Stiff diagrams (upper) and tri-linear diagram (lower). Modified from Tung et al. [5].

solved ions), but has low SiO_2 content (**Fig. 12**). **Fig. 13** shows the relationship between the HCO_3^- ion concentration and the concentrations of the major cations (Ca^{2+} ion and Mg^{2+} ion). The fact that both are plotted on a straight line passing through the origin suggests that dissolution of minerals by dissolved CO_2 (chemical weathering) is involved in the formation of the water quality of these springs.

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad \ldots (1)$$

(Calcite)

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O$$

(Ca-feldspar)

$$\rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^- \quad \ldots (2)$$

(Kaolinite)

The lower SiO_2 content in the limestone area, compared to that in the pelitic rock slope, can be explained by the smaller contribution of chemical weathering of feldspars, as shown in Eq. (2).

Table 1 shows the equilibrium partial pressure of carbon dioxide (*SIc*) in groundwater, calculated using PHREEQC (USGS). The carbon dioxide concentration is higher (0.04–2.2%) in soil than in air (0.04%) [11]. In some places, such as near faults, the carbon dioxide concentration is even higher due to the carbon dioxide supply from deeper layers. The spring from a crack of limestone (G015) is characterized by a high P_{CO_2} of 6.3%. The equilibrium partial pressure of carbon dioxide in the

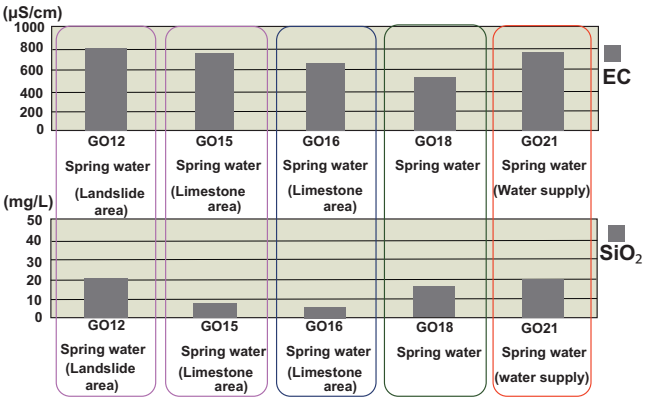

Fig. 12. EC and silica concentration.

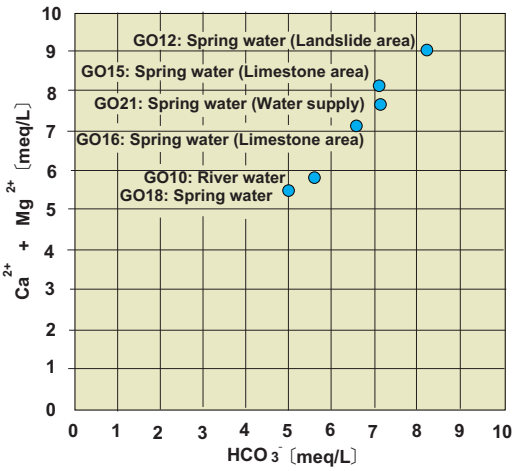

Fig. 13. Relationship between alkalinity and divalent cation concentration.

spring water is low because the water is in the process of degassing and is close to the atmospheric partial pressure of carbon dioxide (0.04%). Since the solubility of calcite is proportional to the cube root of CO_2 concentration, the *SIc* increases with degassing, and both slope springs are supersaturated with calcite ($SIc > 0$). **Table 2** shows the results of the calculation of P_{CO_2} where $SIc = 0$. This is an estimation of the state before the inflow (before degassing). Among the spring waters from the slope of silt and mudstone, the P_{CO_2} of the landslide edge spring water (G012) was found to be close to that of the spring water from limestone (G015). G018, on the other hand, showed a value (2%) normally considered as that of groundwater in soil.

Among the three springs from the pelitic rock, the springs with a high equilibrium partial pressure of carbon dioxide (G012 and G021) are plotted between G018 and the limestone groundwater group in the Tri-linear diagram of **Fig. 6**. This indicates that the mixing of these two groups is a possible explanation. In addition, these two springs are also used as a water supply source, and the flow rate is relatively stable. Therefore, the groundwater on the slope of the pelitic rock is likely to be mixed

Table 1. Carbon dioxide equilibrium partial pressure of spring water.

Site	pH	P_{CO_2} [%]	*SIc*
G015: Spring water (Limestone area)	6.80	6.3	−0.01
G012: Spring water (Landslide area)	7.20	3.0	0.43
G018: Spring water	7.80	0.5	0.63

Table 2. CO_2 equilibrium partial pressure calculated under the calcite dissolution equilibrium condition ($SIc = 0$) (Simulation result from PHREEQC).

Site	pH	P_{CO_2} [%]	*SIc*
G012: Spring water (Landslide area)	6.77	7.9	0.00
G018: Spring water	7.16	2.0	0.00

with the groundwater recharged by rainfall on the pelitic rock slope, and undergoing shallow flow (G018), and the groundwater with a relatively high carbon dioxide concentration, recharged by the limestone distribution area behind it.

3.2. Landslides in Places Other than Vietnam

3.2.1. Examples in Europe

Landslides in the limestone zone in Europe are mostly found in the Alps, the Italian Peninsula, and the Pyrenees of the Iberian Peninsula to the Mediterranean coast. These landslides mostly tend to occur on the margins of the limestone area rather than on the limestone (**Fig. 14**).

The most characteristic landslides in the European limestone area are lateral spread type landslides, such as the Mt. Reschberg landslide in Austria [14] (**Figs. 15** and **16**) and the Moute Verna landslide in Italy [16]. These lateral landslides were caused by the sinking of soft pelitic rock in the lower layer due to loading by limestone in the upper layer. In addition to the occurrence of lateral spread, landslides of the debris flow type, in which the limestone itself overturns and the pelitic rock mixes with the rock masses caused by falling rocks, have occurred. Such landslides have also been reported in the suburban Algiers landslide in North Africa [17] and at Turtle Mountain in Canada [18].

In the case of pelitic rocks, such as marl, shale, and muddy schist intercalated in limestone layers, or in the case of their intercalation, translational rock slides have occurred, such as the Vaiont dam landslide in Italy [19] which claimed more than 2,000 victims in 1963, or the Rindberg landslide in Austria [14], where Cretaceous limestone and pelitic rock moved on a scale of 2,400 m in length, 700 m in width, and a maximum slip surface

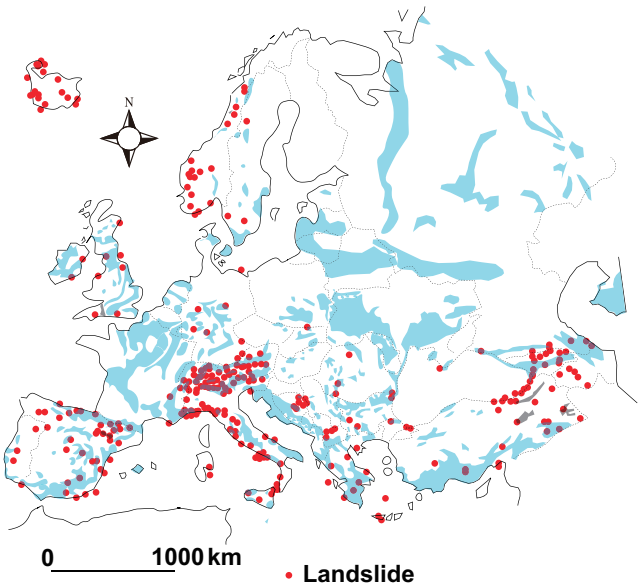

Fig. 14. Distribution of carbonite rock (blue) and landslides (red dots) in Europe. Most damaging landslide cases from 1995–2014 and 2016. Adapted from Haque et al. [12], carbonite rock distribution from Goldscheider [13].

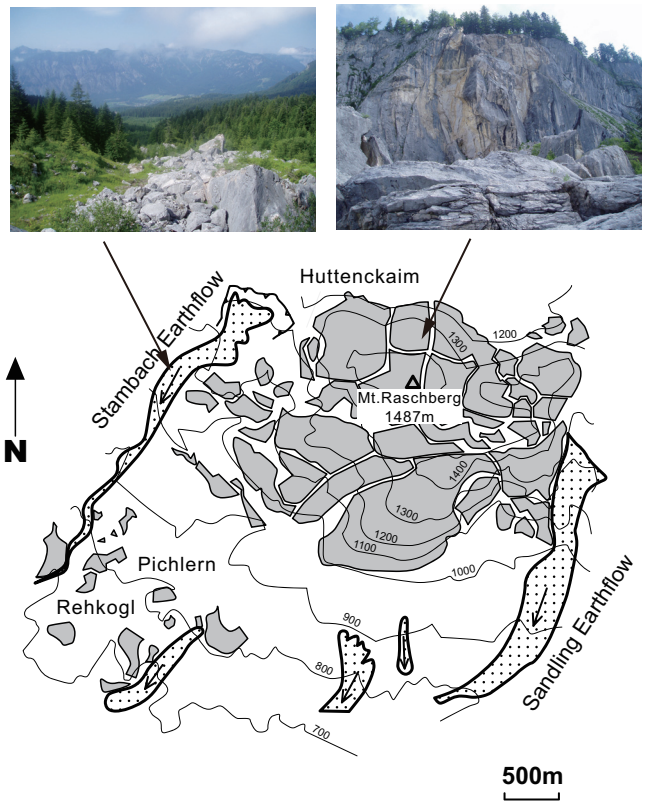

Fig. 15. Stambach and Sandling landslides on Mt. Raschberg (the plane diagram is based on the Upper Austrian Sabo Bureau [15] with some modifications and additions).

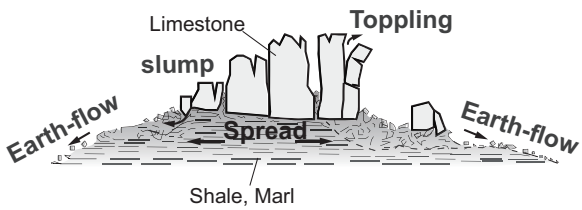

Fig. 16. Lateral spread and debris flow type landslides in the Stambach and Sandling landslides. Created from Upper Austrian Sabo Bureau [15].

Fig. 17. Panoramic view of the Rindberg landslide. From the Upper Austrian Sabo Bureau [15].

Fig. 18. Moving rock body exposed on the mid-slope of the Rindberg landslide.

depth of more than 80 m (estimated at 120 m) (**Figs. 17** and **18**).

3.2.2. Examples in China

In the southern part of China, there are extensive limestone belts, including in scenic areas such as Guilin. The landslides in the limestone belt are distributed around the limestone distribution areas in Sichuan, Yunnan, and Guizhou provinces (**Fig. 19**). However, the occurrence of limestone-related landslides is not as common as those in other formations in China [22, 23]. These landslides have slightly different moving types due to the location of the coal and shale formations intercalated in the limestone; however, limestone rock slides of more than 100 m have occurred, as in the case of the landslide represented by the Wangxia rock slump [24] (**Fig. 20**). In addition, several cases of limestone landslides, such as the Xintan landslide [23, 26] and Guang'an Village landslide [25], have been reported to flow as debris flows over long distances

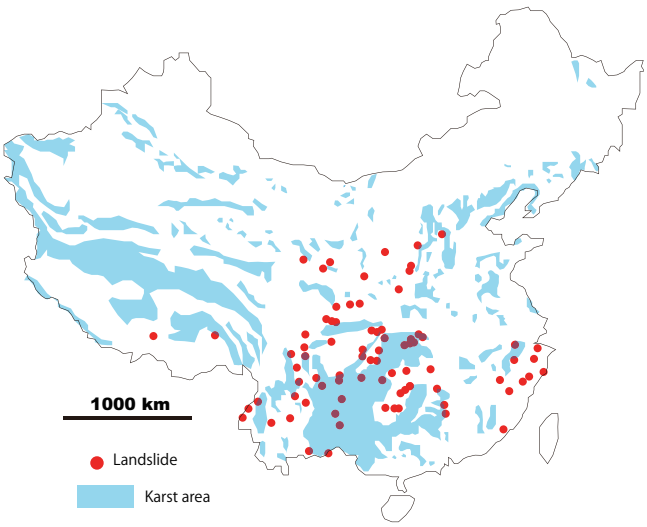

Fig. 19. Distribution of karsts and landslides in China. Karst data is taken from Liu and Zhao [20]. Landslides are catastrophic ones since the 20th century by Huang and Li [21] (earthquake landslides are not included).

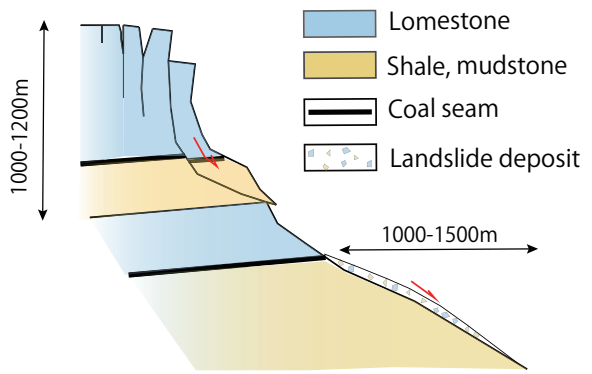

Fig. 20. Conceptual diagram based on landslide cases in limestone area in southeast China. Created by reference to Feng et al. [24], Wang et al. [25], Luo [26], and Wen et al. [23].

(1.5 km or more) on the lower slopes composed of shale and sandstone (**Fig. 20**).

3.2.3. Examples in Japan

Limestones as an accretionary prism of seamount origin [27] are widely distributed across the Japanese Islands (**Fig. 21**). The number of landslides in the limestone area in Japan is very small, although there were 6,785 designated landslides in 1998 [28] (**Fig. 21**). Only a few cases have been reported, such as the late Paleozoic to mid-Mesozoic limestone area landslide in the Shikoku region (**Fig. 22**) [30], which is similar to the landslide shape along the Song Ma suture zone in northern Vietnam (**Fig. 3**). Others include the colluvial landslide with slip surface on the weathered part of the Paleozoic limestone in the Hokuriku region [31], and the erosion landslide with Pliocene to Pleistocene mixed mudstones and

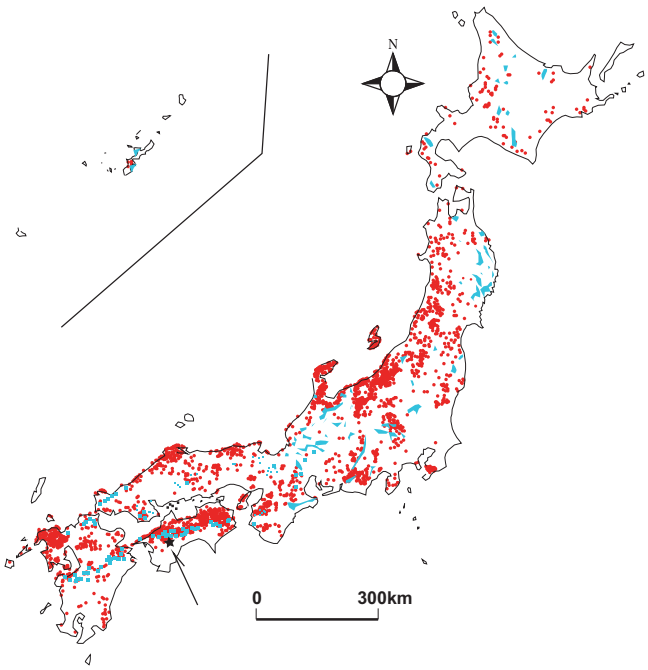

Fig. 21. Designated landslide areas in Japan (red dots) and limestone distribution (blue). The arrow indicates the point of **Fig. 22**. Araiba et al. [28], Urushibara-Yoshino [29].

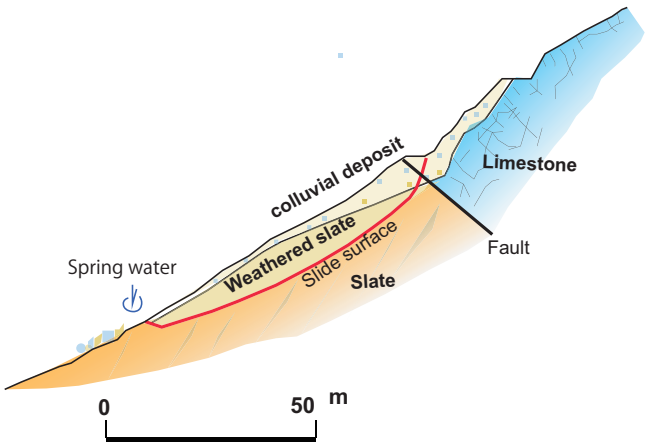

Fig. 22. Example of limestone area landslide in Shikoku, Japan. Arrow point in **Fig. 21** (modified from Utsunomiya et al. [30]).

mixed limestone in Okinawa, Japan [32]. There are no case reports for a slip surface of pelitic rock sandwiched between limestones, as seen in the aforementioned cases in Europe, China, and Vietnam.

4. Discussion

In the case of limestone, which is massive and poorly stratified, there are few cases of movement with a slip surface in the limestone except for rock falls and rock col-

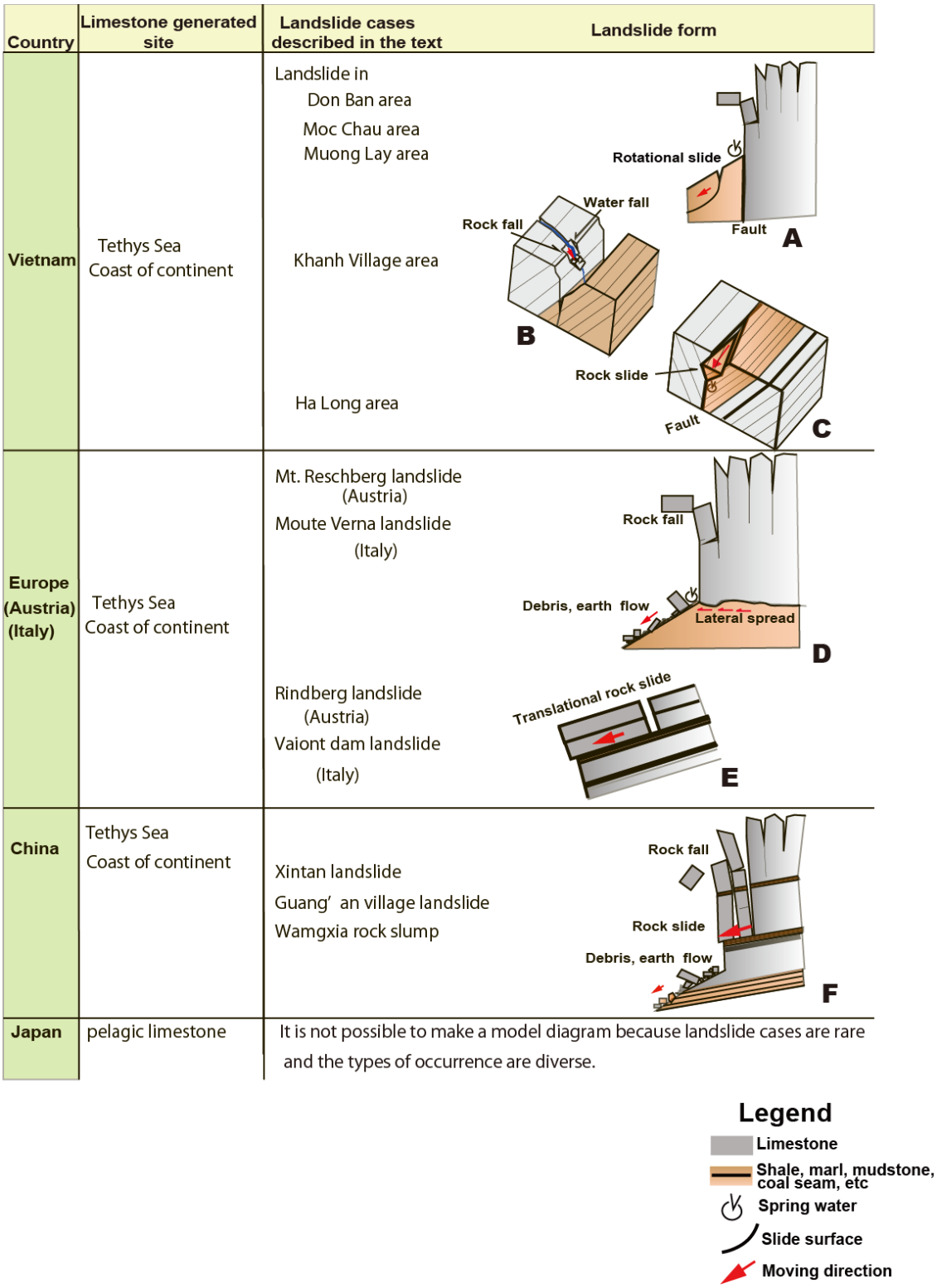

Fig. 23. Limestone area landslide types in Europe, China, Vietnam, and Japan.

lapses. Most of the landslides in the limestone areas occur as landslides with slip surfaces in mudstone or coal beds intercalated or interlayered with the limestone, or as landslides of pelitic rock in the pelitic rock zone near the limestone. If we summarize the shapes and movements of landslides in the limestone areas of various regions, we find that in Vietnam, most landslides occur as slump type landslides (**Fig. 23**, A) in the pelitic rock distribution area, where the limestone is faulted. In Vietnam, other unique types of landslides include a large-scale collapse of a waterfall formed during the development of a river which erodes the boundary between limestone and pelitic

rock (B in **Fig. 23**), and a wedge-type slide of the pelitic rock portion where limestone and pelitic rock meet at a high angle due to faulting and folding (C in **Fig. 23**). The common causes for the landslides in these limestone areas include erosion and the softening of muddy ground by spring water and surface water originating from groundwater flowing through limestone cavities, and groundwater supply into the landslide area.

In Europe, the pelitic rock is deformed by the load of limestone covering it in the form of cap rock, causing lateral spreading and then a transition to a flow type landslide (D in **Fig. 23**) or to a rockslide on a sliding surface of the pelitic rock sandwiched between limestones (E in **Fig. 23**).

In China, toppling and rockslide along the pelitic rock layer, intercalated in the thick limestone layer, as well as the debris flow of a mixture of limestone masses collapsed down the cliff and pelitic rocks in the lower part of the cliff (F of **Fig. 23**), are commonly observed.

The contact between limestone and pelitic rock, which influences the landslide shape, is formed by the depositional environment and geological structure of the geological age.

The limestones in the European Alps are frequently interrupted by pelitic rocks of Paleo-Tethys and continental origin. The stratum is significantly folding but relatively continuous, which provides a geological predisposition for the occurrence of large-scale rockslides along the bedding plane and lateral spread type landslides.

The limestone area in south China, several kilometers in thickness, is also mixed with continental clastic debris and pelitic rock from the Paleo-Tethys Sea. Currently however, there are more reports of limestone collapses bounded by pelitic rocks, and debris flows caused by collapsed limestones and pelitic rocks, than of rockslides such as those in the European Alps. Most of the landslides in and around the limestones in northern Vietnam are located in the areas where faults and folding structures are developed on the tectonic line (suture zone and Red River fault) where the South China and Indochina blocks collided across the Tethys Sea [33]. Such geological structures are geologically predisposed to landslides in the pelitic rock zone bordered at faults by limestones, and to wedge-like movement of the pelitic rock between limestones in folding structures.

In this study, we mainly focus on limestone area landslides at the collision site of continental massifs across the Tethys Sea, but we also attempt to compare them with landslides in Japan, where pelagic limestones are widely distributed. As a result, we found that Japanese limestones, deposited in the pelagic environment with little sediment supply from the continent, are characterized by a high purity of calcium carbonate, are lumpy and poorly stratified. This is why the number of slip cases in limestone areas in Japan is smaller than those in Europe and Asia.

5. Conclusions

The landslide shapes and movement types in the limestone areas discussed in this paper can be roughly classified as follows:

- Landslides of the limestone itself, such as a rock fall, toppling, or cavity collapse along a crack in the limestone.
- Rockslide, in which the slip surface is a muddy stratum that alternates with limestone or forms a thin layer.
- Landslides that occur as a lateral spread caused by the deformation of pelitic rock at the base due to the load of limestone, as well as landslides that occur as earth flow or debris flow of limestone and pelitic rock.
- Slump type landslides that occur in pelitic rock when groundwater is supplied from limestone with which the pelitic rock is in contact at a fault.
- Wedge type slides of pelitic rock in contact with limestone due to folding or fault structure.

Landslides occurring in limestone areas often occur at the margins of the limestone rather than the limestone itself. A common cause is the influence of abundant surface water and groundwater flowing down the limestone.

The landslides described above occur with different types of landslide movement, based on the geology and geological structure formed under various conditions, including: where corals developed along the continental margin during the mid-Paleozoic and early Mesozoic, with continentally detritus flowing into the Tethys Sea and pelitic rock of shallow-water sediments are sheared, fractured, and deposited as accretionary prisms by the movement and collision of land masses, or where they are folded and ridden up.

The limestones distributed across Japan are highly pure calcium carbonate limestones which were formed in a pelagic environment with little sediment supply from the continent, and are characterized by massive and poorly stratified accretionary prisms, which is the reason for the low occurrence of landslides.

In the future, when assessing the risk of slopes in limestone areas, attention should be paid to the pelitic rock in contact with the limestone from the viewpoint of geology and geological structure, and to the edge of the limestone from the viewpoint of topography. In addition, it is necessary to pay attention to the surface water and groundwater supplied to the slope from the limestone as a cause of landslides when considering countermeasure construction.

Limestone zones are widely distributed in other continents, in addition to the areas targeted in this study, and many of them are located outside human population areas. It is assumed that landslides with various types of motion, other than those mentioned above, probably occur in these areas. In the future, it is necessary to clarify the relationship between the limestone formation process, the deposit shape of the accretionary prism, and the mech-

anism of landslide occurrence based on a wide range of cases, including pelagic cases common in Japan.

Acknowledgements

This study was discussed in the "Vietnam Landslide Practical Technology Group" of Japanese and Vietnamese researchers in Hanoi. We would like to express our sincere gratitude to Prof. Kazuhisa Yoshimura, Professor Emeritus of Kyushu University, for his many insights on groundwater in limestone areas.

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