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Toward the Mechanism of Deadly Landslide and Debris Avalanche in Abikar Village, Farsan City, Chaharmahal and Bakhtiari Province, Iran

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ABSTRACT

Aims: On the evening of April 1, 1998, in Farsan city, Chaharmahal and Bakhtiari Province, western Iran, the southern edge of the valley of Mt. Kino, along the Labad river, slid down into the river valley, where the moved material sloshed up over hill on the opposite river bank to bury Abikar village. This event followed an exceptional rainfall exceeding 190 mm during a week. In this research, the unexpected behavior of the landslide, the possible causes of the long-runout of debris, and the probable mechanism of such movement are discussed.

Materials & Methods: This disaster was investigated, and we attempted to offer a schematic model for its occurrence using various field data such as structural geology, surface soil layers, local geomorphology, meteorological data, hydrology, and field evidence. The disaster claimed the life of 54 people, and 1300 livestock, and the destruction of 40 hectares of farmlands and orchids.

Findings: The remain of the disaster contains some extraordinary features such as the lack of debris or barrier across the river, high debris flow velocity, the transformation of some debris material by jumping into the far end of debris flow, and a severe air storm in front of the debris flow mass.

Conclusion: We suggest that, when a giant slab of rocks fell from the opposite flank, the generation of debris avalanche and the formation of an air cushion underneath the debris could be one of the reasons that facilitate the long runout of detrital flows.

Keywords: Air cushion; Block fall; Jumping debris; Rock Avalanch.

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Introduction

In a landslide study, identifying the type of landslide is one of the main tasks of the research team. This issue has long been considered by researchers. The first coherent classification was proposed by Varnes in 1978, which is based on the type of moving mass material and the mechanism of the primary failure initiation. In recent years, different types of classification have been presented by researchers, and each of them has examined this issue from a certain perspective [1, 2, 3, 4, 5]. Most of these classifications emphasize the initial conditions of motion and slope instability procedure. However, the majority of them did not address the kinetic behavior of the material or its displacement after the main slip. Unlike most previous classifications, the latest classification presented by Hunger, [10, 11] discusses both the formation of instability and the movement of materials, especially in debris flow materials.

Moreover, in landslide risk assessment and landslide-induced damage estimation, especially in large-scale landslides, estimating the debris flow velocities and runouts is one of the main findings contributing to the management of this natural disaster. Rapid landslides, debris flows, debris avalanches, rockslide avalanches, and large-scale liquefaction-induced landslides entail higher risk and usually lead to more severe injuries [12].

For many years, researchers have investigated possible explanations for the long runout of avalanches. A variety of reasons for unusually long runouts have been suggested. One of the hypotheses is having the material floating on a cushion or gliding over a friction-reducing layer of water or ice.

The original morphology of landslide areas such as slope angle, mass volume, and debris flow path controlling the landslide and its consequent behaviors. The type of mass material, as well as the shape of the landslide surface, are also effective in the post-failure behavior of moving masses and debris. For instance, in a clayey landslide, a creep-type movement at a low speed of about a few centimeters per year can continue for decades up to reach an equilibrium state [13,14]. For a certain size of the landslide that is classified as small landslides, typically the detached masses, flow about twice the distance of fallen downslope before they run out of energy [15]. But large landslides such as Seimareh (Western Iran) [16], Frank (Alberta-Canada), Ontake landslide (Japan), and Huascaran landslide (Peru) and their debris flow with millions of cubic meters of moving can sometimes travel more than 20 times farther than they fall points and sometimes even, like a fluid, move up over hills [18, 19].

According to a review of some works [20, 21] when the volume of a landslide exceeds about 1 million m^3, rock particles and boulders bouncing and colliding with one other create significant changes in the detrital material. Thus, in some of these landslides, the pressure inside the stream increases, therefore, the debris flow is transferred to a greater distance than expected. Despite numerous research efforts and models, a reliable method for accurate forecasting of the area covered by detrital materials to manage the crisis in susceptible areas has not been presented yet [22]. In some of these researches, the hypothesis of debris formation above a water-saturated layer or on a cushion of high-pressure air has been proposed [23, 24, 25]. They investigated how the fastest types of landslides and the subsequent debris flows occur, perhaps the role of the mixed air pressure in the body of the debris and the formation of air cushions beneath the masses is the only mechanism that can justify the mechanism of these events.

The Seimareh landslide (Figure 1A) was one of the largest in the world that occurred in western Iran, a large-scale debris avalanche with a volume of 32 million m^3 detached from the southern edge of Kabirkuh Mountain and flow

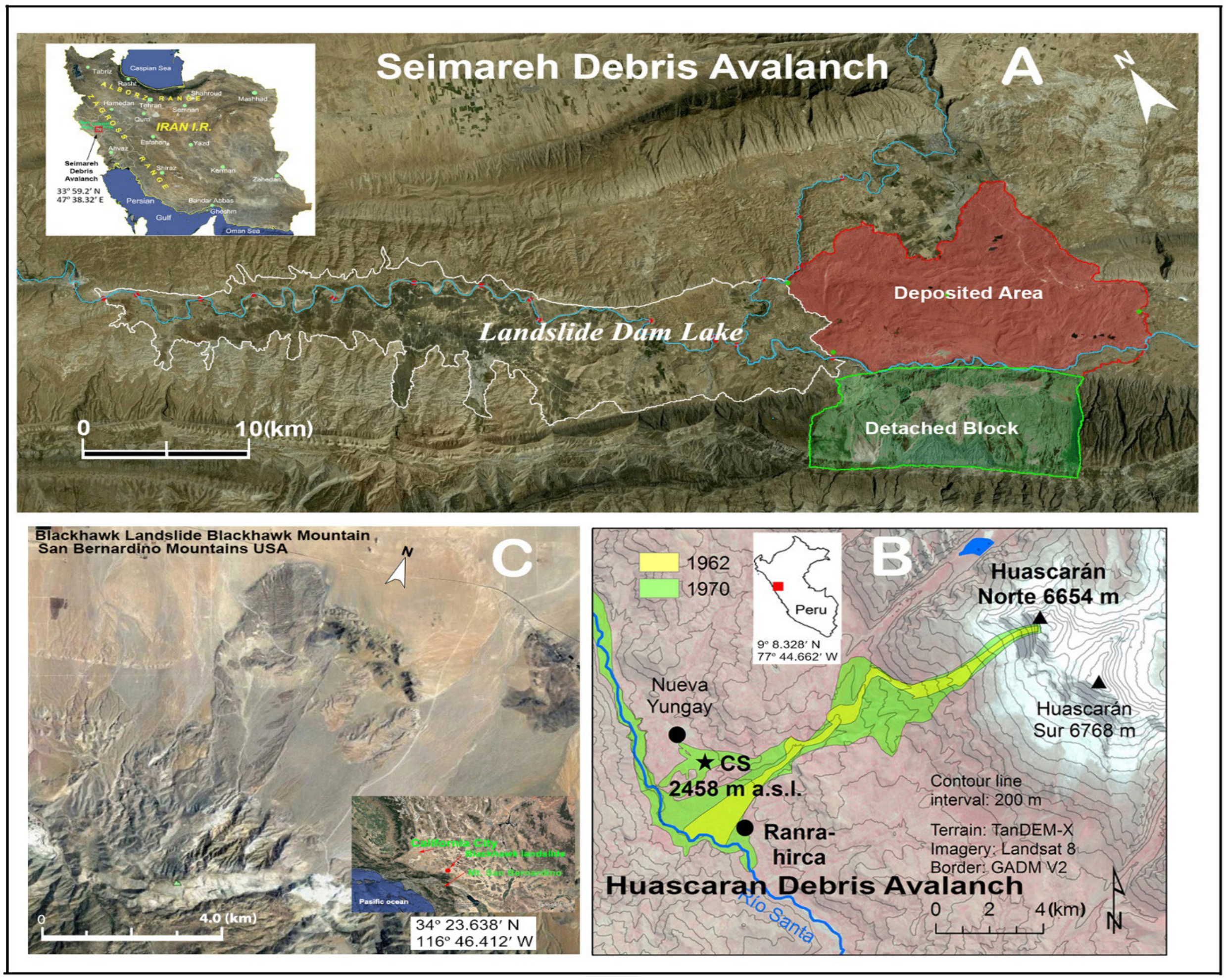

Figure 1) Some examples of giant landslides with long runouts; A: Seimareh landslide, B: Huascaran, C: Blackhawk, [18, 19, 25].

along Pol-e Dokhtar plain, with a slope of lower than 5 degrees, up to a distance of 24 km. In this event, the only possible hypothesis to justify this long-range displacement of dry debris is the formation mechanism of the cushion of air entrapped beneath the debris and the increased pressure of trapped air between the particles of debris. The Seimareh historical landslide has an alternating thick layer of limestone and marlstone of the Upper Cretaceous-Eocene. Some studies have considered heavy rains as the primary cause of landslides in Seimareh, however, in a newly designed model, given the landslide scale, the occurrence of this massive landslide without a severe earthquake has been reported as unlikely [26].

Another example of a long runout debris avalanche is the 1970 debris avalanche in (Figure 1B) Huascaran, Peru, in which 100 million m^3 of a mixture of rock, ice, snow, and mud entered the city in less than 3 minutes after passing a distance of 16 km. A densely populated area with an area of 8 km^2 was buried under the debris. The average thickness of the material left was about 5 meters.

A typhoon of compressed air took place at the forehead of the material with a thickness of about 80 meters [18] .The proposed theories of long and unexpected runout of Blackhawk landslides (Figure 1C) make the hypothesis of the generation of dense air mass under the detrital flow and the increase in fluid pressure more attractive and acceptable [19, 25, 27] .In such landslides, the debris mass will continue to travel

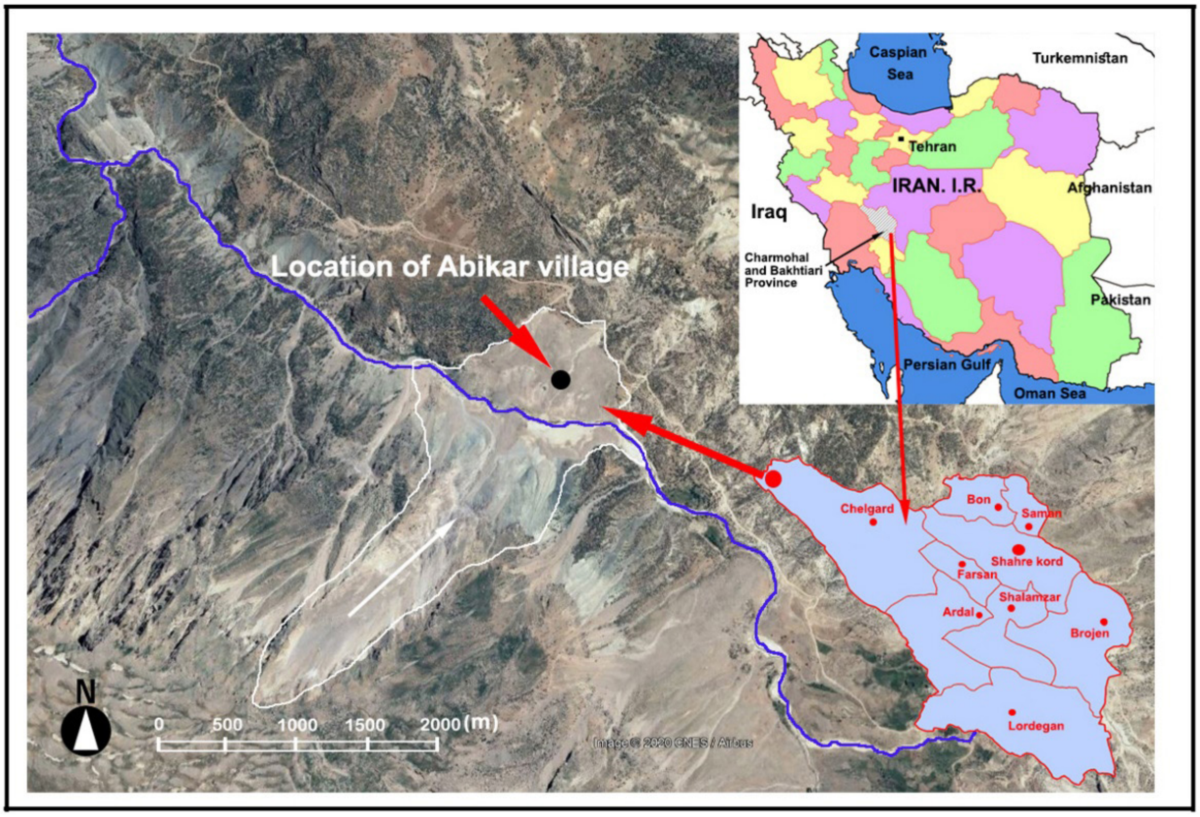

Figure 2) Location of the study area and the Abikar landslide.

long distances until the air cushion underneath the moving mass is drained. The question is if the pressurized air can remain beneath the debris mass for a long time and facilitate movement.

In the specific process in which a rock block hit the floor of the valley, before debris flow initiation, the rock blocks have become smaller pieces and due to high energy ascended into the air and finally as a throwing motion has been jumped to a distant point.

Little is known about jumping rock avalanches because their formation requires a special combination of slope topography and rock mass structure. For a jumping rock avalanche to occur, the slope of the rock mass near a rocky valley must be steep so that enough kinetic energy is generated to climb to higher altitudes and move longer distances [28].

Materials & Methods

Abikar landslide

Based on a phone call to the Landslide Research Group office of Soil Conservation and Watershed Management Research Institute (SCWMRI) of Iran, on the evening of April 1, 1998, part of Mt. Kino had fallen and moved up over the hill on the opposite river flank and buried Abikar village under several meters of debris (49:34’ East longitude, 32: 42’ North latitudes). The reporter said that there is no light or trace of Abikar village on the opposite bank of the Labad River in the dark of the night, and it seemed that the village had completely vanished. The next day (April 2), during an aerial field survey by a helicopter, it was observed that the northern ridge on which the village of Abikar was located was completely buried under the debris of the landslide separated from the southern ridge. This is while the river path was not blocked by landslide debris, and there was a little flow of water at the bottom of the river.

The first field survey team could access the landslide area two days after the incident

(April 4). It was confirmed from the first report of the dispatched team that the occurrence of the landslide at the southern edge of Mt. Kino is the main cause of this deadly debris avalanche. Due to its high velocity, the debris crossed the valley and moved to the opposite bank of Abikar village (Figure 2).

Abikar village is located in Chaharmahal and Bakhtiari Province. This province is a highland area located in the west of the Iranian plateau, in the foothills of the Middle Zagros Range which is known as the main source of water in western Iran. Based on the *climate classification*, this province has a typical Mediterranean climate of humid/very humid, cold/very cold alpine winters. Winter has the highest precipitation, and autumn and spring have moderate amounts of precipitation. The type of precipitation in this area varies according to geographical location and altitude. In the highlands, half of the annual precipitation is snow. Late melting of the snow cover in spring and the early onset of cold autumn are the characteristics of the region. Prolonged rainfall resulted in advanced weathering, increased weight of the rock block, increased driving force, and reduced shear strength of interbedded shale and marlstone in mountainous regions. In some exceptional years, long, heavy rains in the region and exceptional day and night temperature differences result in interlayer ice freezing and thawing, triggering landslide occurrence.

According to Iran Meteorological Organization, before the Abikar landslide, heavy rains and exceptional showers occurred in the region for three consecutive days (March 29 to 31, 1998). The total of 10 hours of rain amounted to 190 mm, of which 146 mm was on the last day. The intensity of this rainfall has been unprecedented over the past 50 years. The Abikar landslide occurred two days after the rainfall (April 2).

The casualty of the landslide was 20 males, 30 females, and 4 infants (54 persons) out of 65 total population of the village. Eleven survivors were working in surrounding villages and cities. Loss of 1,300 livestock and the destruction of 40 hectares of orchards and farmlands must be added to the damage induced by this landslide. The topographic map of the landslide area is illustrated in Figure 3.

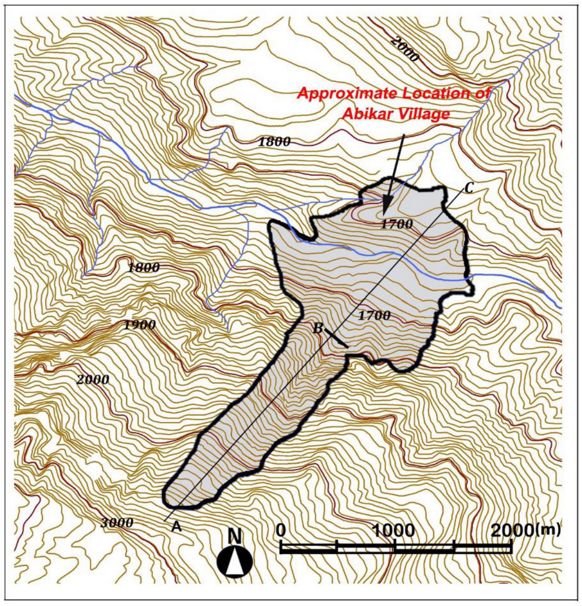

Figure 3) Topographic map of the landslide area. *AB* is the length of the source rock slab. *AC* is the direction of the section shown in Figures 5 and 6.

In the Abikar landslide, the detached block of the opposite outcrop has a slope of 75 degrees. The ridge of the highest point of the sliding block is 2750 m in altitude. The elevation of the bottom of the valley is 1600 m a.s.l. Thus, the height of the fall was about 1200 meters (Figure 4).

The height of the center of gravity of the falling block was approximately 600 m from the bottom of the block. The falling block on the southern ridge has a remarkable slope difference from the ridge on the opposite side where Abikar village is located (Figure 4). In this landslide, the volume of the separate mass was equal to 9 million m^3 covering an area of 120 ha. The thickness of the debris left in the village and the surrounding areas was about 15 meters. The runout distance of the moving material was estimated to be 200 to 300 m.

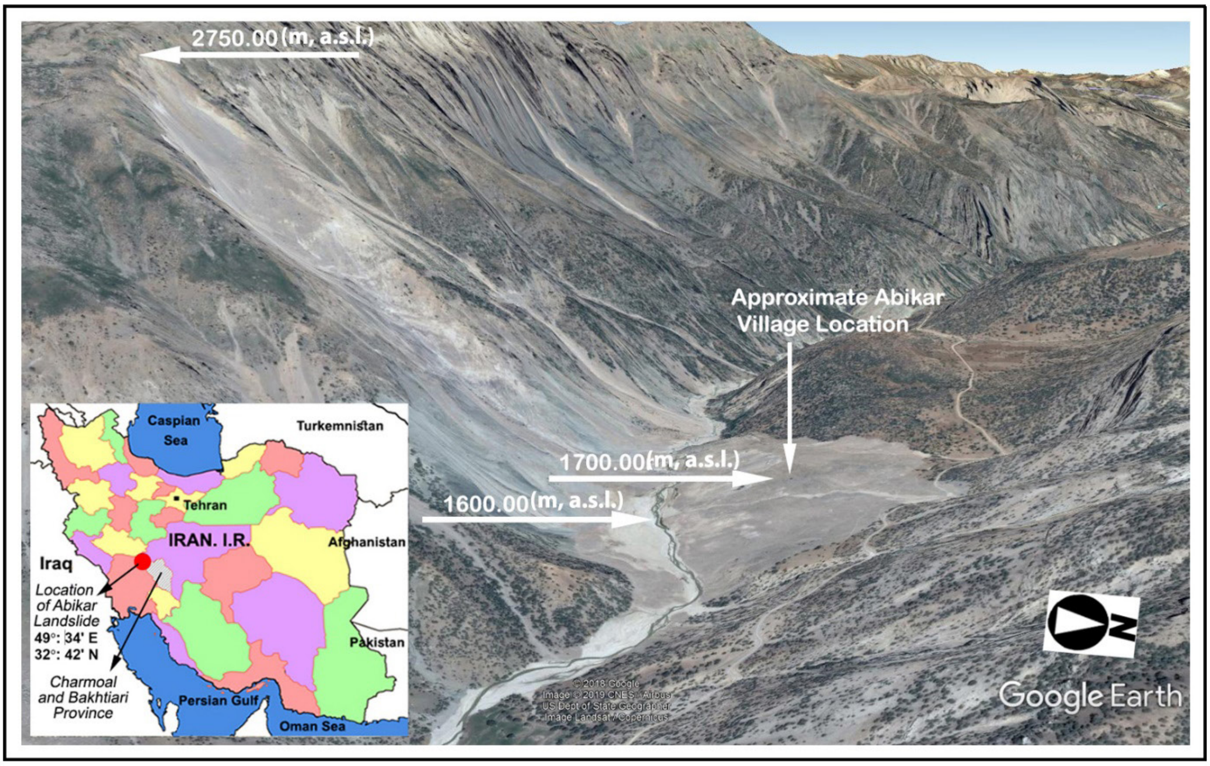

Figure 4) Location and altitude of the head scarp, toe, and Abikar Village.

The moving material crossed the river and ascended at an astonishing speed to a maximum height of 1700 meters over the opposite flank. Based on interviews with residents of villages upstream of Abikar, the estimated time length of the occurrence was about 4-5 seconds (After hearing the loud sound of falling rock blocks and the lights of Abikar village went out), and then, the debris flow velocity was estimated to be 50 to 60 m/s. These landslides and consequent debris flow should be categorized as extremely high-speed landslides [29].

An interesting observation by the rescue team from a helicopter is that the day after the event, there was no debris remained in the river, and no landslide dam or barrier was formed. In valleys of the Labad River, several landslides have been reported after heavy rains in the area. For example, research in 1980 reported that several landslides occurred in Hayes and Atok valleys near MT. Kino, after long, heavy rains and damaged parts of the electric power transmission line in the region [30].

Geology of the region

A vast portion of western Iran is covered by the Zagros Mountain range. Labad valley and region are located in the High Zagros in the southwest of the Zagros Range which is highly tectonically active (Figure 5). Alternation of hard calcareous layers and soft and erodible shale and marl layers (with northwest-southeast extension and gentle to steep slopes) as well as active tectonic, the passage of several main faults in this region, are among inherent factors contributing to the occurrence of many landslides [31].

Figure 6 shows that the oldest geological formations in this section are thick limestones with *Orbitolina* (K) with locally evaporite interlayers in the lower part. In this formation, the K8 series with shale and marl with marly limestone interlayers containing *Ammonite* and *Inoceramus* fossils can be seen. Over this formation, *radiolarite* deposits, calcareous layers, and conglomerate (KP) are deposited. This formation has less outcrop on the surface

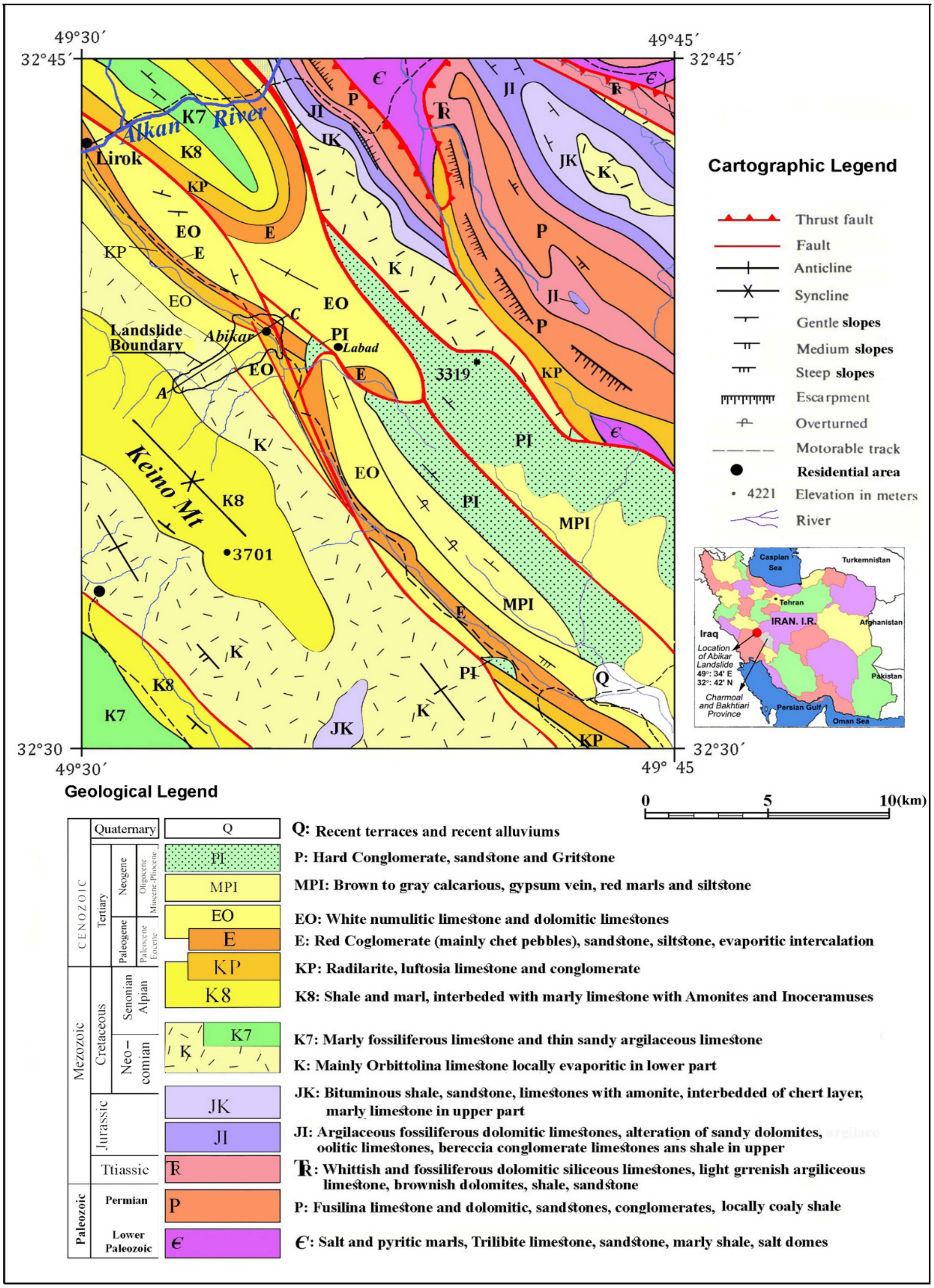

Figure 5) Geological map of the study area.

due to an unconformity resulting from a fault in the northern part of the valley. The green and gray colors of the Paleogene formation are composed of Paleogene-Neogene limestones and dolomitic limestones (EO) of Paleogene lime. This formation (E) consists of a red conglomerate, mainly composed of chert pebbles, sandstone, and siltstone, and evaporates interlayers. In the northern part of the Labad Valley, the EO formation of the lower Paleogene-Neogene is repeated with white *nummulitic* limestone and dolomitic limestone units. The K8 and K formations in this area are normally deposited, with no unconformities or faults. Moreover, in the southern part of the valley, the E and EO formations are in contact without any unconformities.

Conversely, due to the numerous faults that follow the fault trend of northwest-southeast, the K-series formation is located on EO, KP, and E with an unconformity. At the foot of Mt. Kino and under the hard limestone (K), the thin layer of shale and marl units of EO and KP belonging to the Pabdeh and Gurpi formations (Upper Cretaceous-Paleocene), can be observed. The erosion of these soft layers can play the main role in the occurrence of various types of instabilities in the region. Furthermore, heavy rain and saturation of these soft formations can result in sliding surfaces between the hard and soft formations. In addition to the effect of heavy rainfall, the alternation of freezing and thawing of water inside the joint and other rock mass discontinuities at daily and seasonal intervals, the presence of karstic limestone, high weathering capacities of limestone shale and marlstone, and different erosion severities in hard and soft layers predispose this region to the occurrence of this type of landslide.

A characteristic of this region is the abundance of minor faults due to the activation of some main compression faults during several tectonic phases. One of the most famous faults in the landslide zone is the Bazoft fault, which passes through 5 km of the area. As mentioned, the Zagros region is known for its large number of low-intensity earthquakes. Naturally, the occurrence of numerous mild earthquakes during the rainy season can generally be considered an influential factor stimulating landslides [32]. However, seismic information studies showed that no significant earthquakes had occurred in the region in the week leading up to the landslide [33].

Findings

Landslides are one of the most common natural disasters throughout the Zagros Range. A review of the literature on landslides in the Zagros region indicates that the leading cause of relatively large landslides in this region is alternating eroded soft layers and hard thick layers and sliding surfaces occur along soft interlayered shale and marl (Figures 5, 6).

These soft layers have low shear strength in the saturated and partially saturated states. Therefore, rainfall can be considered the most effective triggering factor .Obviously, due to the seismicity of the Zagros region, in addition to rainfall, earthquakes can also be a factor that can trigger some landslides. The combination of rainfall and earthquake as landslide-triggering factors in landslides in Chaharmahal and Bakhtiari Province has also been reported

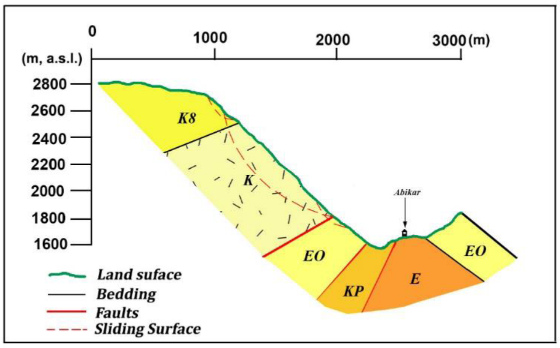

Figure 6) Geological cross-section along the axis of the landslide, direction of section (*AC*) is shown in Figures 3 and 5. For geological formations see the geological legend in Figure 5.

A study of the morphology of the Labad valley demonstrates that toe erosion provided suitable conditions for the fall of steep rock blocks due to its shale and marl bedrock. Due to the extension of the river to erodible sediments EO and KP, erosion will likely intensify in flooding seasons. Surveys at the same elevation adjacent to the landslide area show ample evidence that toe erosion is a dominant morphology in the region. The toe erosion is more severe, especially in areas where the river is twisted. However, due to the altitude of the toe of the detached block in the Abikar area, toe erosion can not be considered the effective factor contributing to the landslide. Saturation of marls and shales and a severe reduction in their shear strength can lead to the occurrence of block falls. The same type of landslide in the basins adjacent to the Abikar landslide has been reported. A deadly landslide also occurred in Chelo village located in the same region following the persistent rainfall in the spring of 1993. This landslide occurred in a broad area, 2000 meters long and 1500 meters wide. Other landslide events include dozens of landslides along the road under construction from Shahrekord city to Masjed Soleiman city, which reduces the resistivity of geological sandy and marl formations [33].

Several investigations were conducted to interpret the mechanism of the Abikar landslide, the most likely process proposed in this work is the occurrence of high-pressure air and water inside the debris that facilitates the movement of sub-saturated materials [33]. Another case that can describe the mechanism of initiation of high-velocity of debris flow is the formation of an air mattress beneath the falling debris. The compressed air mattress formed under the debris material prevents the material from colliding with the floor and the debris material mounted on the compressed air mattress travels long distances. However, some fragment of the fallen rocks transported in the form of jumping is angular particles that were found with fresh surfaces on the surface of the displaced debris. Based on the field observations and evidence analysis, a schematic presentation of the Abikar landslide processes and its consequent debris flow is shown in Figure 7.

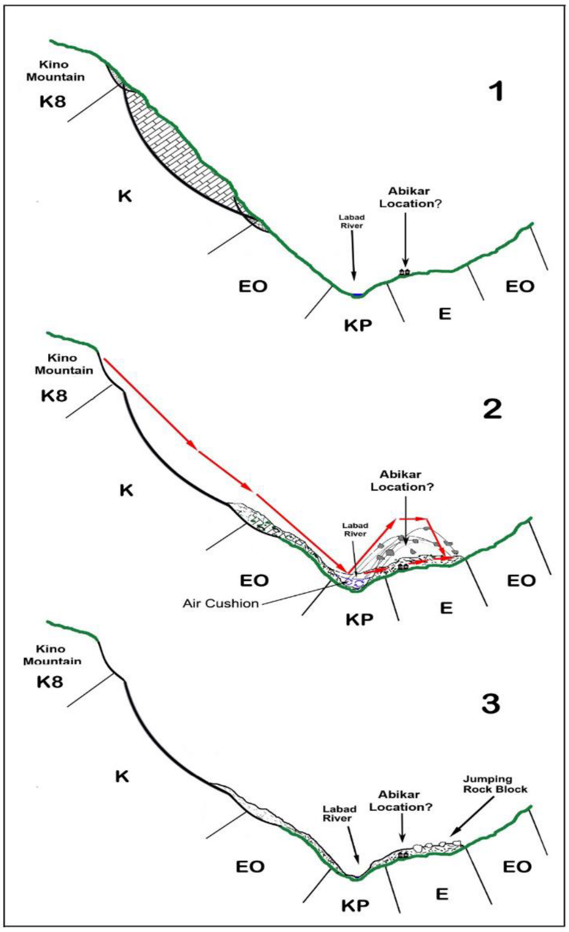

Figure 7) Schematic model of Abikar landslide.

Field evidence in the Abikar valley well demonstrates the accuracy of this schematic model. Due to the considerable base flow in the Labad River and the intense rainfall before the landslide, the accumulated bed sediments of the river should likely be fully saturated at the time of the landslide.

Discussion

As mentioned in the previous section, the absence of rock debris in the river after the occurrence of a landslide, indicate the formation of compact air mattress under the moving debris of a landslide. The sudden fall of the rock block and the lack of sufficient time to drain the air trapped beneath the debris, as well as the increased fluid pressure inside the debris, can explain the long runout of debris flow and burial of Abikar village under several meters of debris (Figure 7-2). Examining the debris flow texture and composition shows that most of the flow (high-velocity and low shear strength) is made of soft layers of EO and KP layers left in the Abikar village location. In field surveys, a 50-year-old walnut tree with all parts of trunk and roots was found at the end part of the debris material (location is shown in Figure 8), indicating the ground surface has been shaved by the debris to a depth of about 6 meters. A close-up view of the landslide satellite image is shown in Figure 8.

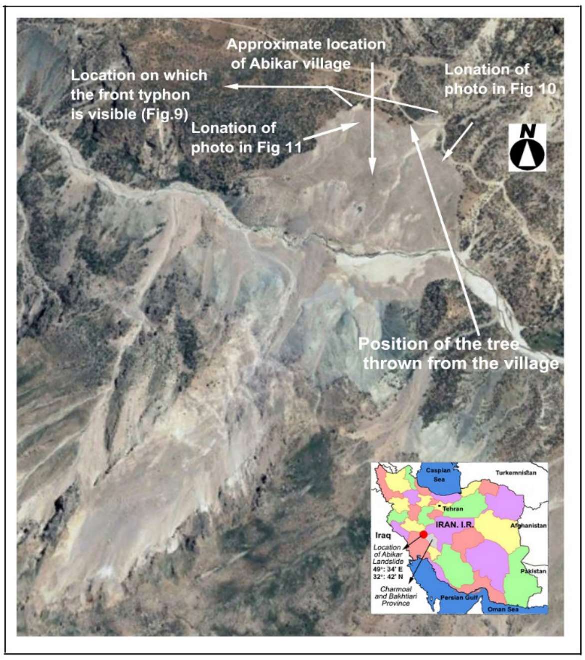

Figure 8) A close-up view of the whole area affected by the landslide.

Another interesting evidence for high-pressure air mattress formation is a storm surge caused by typhoons at the forehead of the moving debris, especially at the end of the displacement pathway, which has been cited in some studies (Yue Ping and Aiguo, 2012). Figure 9 shows that the storm has exerted an impact due to the sudden discharge of air trapped under the debris up to several hundred meters above the moving debris, while no trace of debris flows has been observed in this area (Figure 9). The intensity of this storm is such that the total vegetation cover in the affected area was completely clear-cut to the extent of a few hundred meters from the end debris zone without any traces of debris movement.

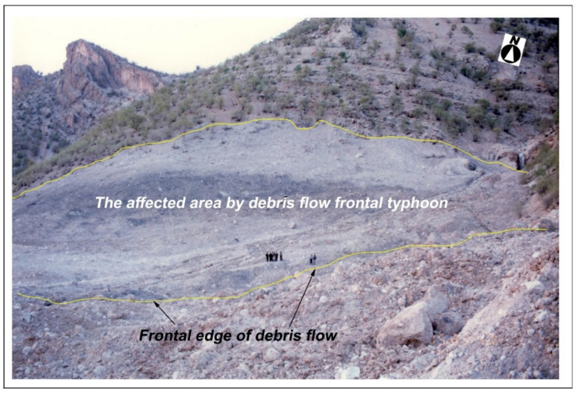

Figure 9) The affected area by debris flow frontal typhoon, where all vegetation cover was clear-cut (The location of this photo is shown in Figure 8.).

An examination of field information indicates that a significant part of the debris material has been transferred by jumping from the point of formation to the end of the debris flow zone. As mentioned in the previous section, the mechanism of debris avalanche transport is based on the energetic impact of the falling block to the bottom of the valley and the subsequent ascent with high altitude and displacement in the form of a jump. Evidence that confirms the occurrence of this mechanism is the presence of relatively large boulders at the end of the debris flow material on which there is no contamination of the muddy matrix of the debris flow on their surfaces. The images in Figure 10 illustrate two examples of these boulders. The positions of these images are depicted in Figure 8. Some of these boulders have fallen after the debris flow has stopped completely (Figure 10-A), and others have fallen on it in the last seconds of the debris flow, implying the accumulation of the debris material behind these boulders (Figure 10-B).

Figure 10) A boulder of rock jumped to the end portion of the debris, without contaminating the muddy matrix (A), and a boulder of rock to the end zone of the debris with debris accumulation on the back of the boulder (B).

Conclusion

Based on field studies and collected evidence, it can be concluded that the mechanism of landslide occurrence and the subsequent massive debris flow was an integration of mechanisms of several events. First, due to heavy rainfall, the weight of the mass increased and perhaps the instability of the underlying marl layers caused a huge block to fall into the valley. The weight of the mass, the velocity of the fall, and the collision with the hard bottom of the river facilitated an extremely high-velocity movement. This is why the compressed air under the mass did not have a chance to drain, and the air cushion facilitated the movement of materials to Abikar village. In the initial stages, before the aforementioned flow formed, the crown part of the block collided with the river floor at a different height of about 200 to 300 meters. Due to intense kinetic energy, part of the material jumped on the Abikar area and the village and buried the village under a layer with a thickness of about 8 to 15 meters .The landslide event could not be named based on conventional classification methods. In this paper, the Abikar landslide and its subsequent event were considered as a special case and suggested to be named the "*Rock Block Fall-Debris Flow-Debris Jumping Complex (Composite) Landslide*."

Based on the lessons learned from the Abikar landslides, it can be concluded that a similar event is expected to occur in areas with the alternation of soft and hard layers and large differences in height and slope angle of both flanks of the valleys. Any development plan should be avoided in such areas. Installation of any lifelines and any passage should be planned with special caution. A regional plan for relocating the villages in similar conditions of geology and topography to safer places. For surviving the residents during rainy seasons, the installation of sensitive devices or application of the various indirect method for early warning of landslides occurrence is recommended for highly sensitive slopes [37, 38]

Authors' Contributions: Zieaoddin Shoaei (First author), Main Researcher (80%) Jafar Ghayoumain (passed away) Field work (20%).

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Conflict of Interest: Not declared by authors.

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