

## REVIEW

# Next-Generation 3D Mapping Techniques for Geological Hazard Monitoring

*Shuai Fu*

*Lanzhou Petrochemical University of Vocational Technology, Lanzhou 730060, China*

## ABSTRACT

The increasing frequency and intensity of geological hazards such as earthquakes, landslides, volcanic eruptions, and floods underscore the need for advanced monitoring techniques. Light Detection and Ranging (LiDAR), satellite-based technologies, and Unmanned Aerial Vehicles (UAVs) are next-generation 3D mapping technologies that have transformed geological hazards monitoring due to their high-resolution, real-time data that could improve hazard detection, risk evaluation, and disaster management. Through these technologies, detailed and three-dimensional models of geological features can be produced, and this helps in the detection of hazards like fault lines, unstable slopes, and volcanic activities with more accuracy than before. The combination of several sources of data and the development of machine learning and predictive modeling has further increased the abilities of 3D mapping systems, which have allowed them to monitor hazards in real-time and provide early warning systems. The challenges associated with data quality, computational requirements, environmental issues, and data integration still persist despite the great advancement. The future development of sensor technology, autonomous systems, and predictive modeling has the potential to enhance hazard prediction and early warning and risk mitigation approaches. Due to the use of 3D mapping technologies, disaster preparedness can be enhanced, negative consequences of natural calamities can be decreased, and the overall resilience to geological threats can be improved. In this review, the development, present status, use, challenges, and future trends of 3D mapping in monitoring geological hazards have been discussed.

**Keywords:** 3D Mapping; Geological Hazards; Light Detection and Ranging; Unmanned Aerial Vehicles; Early Warning Systems

### \*CORRESPONDING AUTHOR:

Shuai Fu, Lanzhou Petrochemical University of Vocational Technology, Lanzhou 730060, China; Email: 1028146367@qq.com

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## 1. Introduction

Natural hazards include geological (earthquakes, landslides, volcanic eruptions, and floods), and can cause devastating loss of life, destruction of the infrastructure, and a huge disruption of economic activities<sup>[1,2]</sup>. These risks are always a menace to the communities, especially in a country that experiences frequent geological activity or when the population is very large. As an example, regions that are found along the boundary of tectonic plates are usually exposed to frequent landslides caused by soil erosion and volcanic eruptions, whereas mountainous areas are susceptible to landslides caused by tectonic plate movements and seismic activities. Likewise, coastal erosion can also affect coastal zones because of heavy rainfall, storm surges, and sea-level rise.

To reduce the risk posed by these hazards, the main priority is the early detection, monitoring, and proper prediction of hazards<sup>[3]</sup>. One of the greatest problems is how, where, and when these events will take place and the effects they will have on the environment and human settlements. In this respect, the capability to map and track geological hazards in 3D (3-dimensional) presents priceless information in risk evaluation, planning, and disaster control<sup>[4]</sup>. In comparison to the conventional 2D mapping methods, 3D mapping provides a more detailed view of the landscape and shows complex topographical details, movements on the surface, and changes in the environment, which are important in hazard monitoring.

Conventional practices of geological hazard monitoring are based mainly on field surveys, seismic, and 2D maps to determine risks<sup>[5]</sup>. Although the techniques work well in some applications, in other applications, they tend to fail to capture the full complexity of the terrain, particularly in regions that undergo frequent or rapid changes. An illustration is that 2D maps do not give a clear image of vertical movements, topographic changes, or underground formations, which are essential in revealing geological dangers like landslides, earthquakes, and volcanic activities.

The emergence of 3D mapping technologies nowadays has transformed the sphere of geological hazard monitoring<sup>[6]</sup>. The 3D mapping techniques have the advantage of providing a more detailed picture of the geological processes by including depth information and creating detailed spatial

representations of the terrain. Such technologies are able to record the elevation, surface movements, and topographical changes, which may provide more precise hazard evaluation and forecasting. In addition, 3D models are more useful in visualizing and interpreting complex geological information to enable researchers and decision-makers to make more informed choices regarding hazard preparedness, mitigation, and response<sup>[7]</sup>.

Beyond geometric representation, next-generation 3D mapping plays a critical role in advancing the understanding of environmental and geomorphic processes. High-resolution 3D datasets enable the quantification of surface deformation, erosion patterns, sediment transport, and subsurface structural changes, thereby linking observable terrain dynamics with the physical processes governing hazard initiation and evolution. The purpose of 3D mapping goes beyond the mere generation of digital images of the landscape. It is now possible to constantly track geological hazards in real-time due to the integration of advanced sensors, remote sensing technologies, and machine learning algorithms<sup>[8,9]</sup>. These types of systems can pick up mild variations in the environment that might be indicative of the beginning of a dangerous situation, e.g., a fault line shift, heightened seismic activity, or ground deformation. Having the capability of tracing evolving conditions over time, 3D mapping is becoming more and more pertinent in delivering early warning of disasters and making it possible to respond to them more effectively.

The purpose of this review article is to make a detailed discussion of the next-generation 3D mapping methods that have revolutionized geological hazard surveillance. The aim is to look at the development of 3D mapping technologies, their strengths, uses, and issues, and to determine the latest growth and future innovations.

The paper starts by discussing the historical evolution of 3D mapping techniques, when photogrammetry and laser scanning techniques were initially developed, and how these methods led to more advanced remote sensing technologies, including LiDAR, Structure from Motion (SfM) photogrammetry, and Synthetic Aperture Radar (SAR). This paper then proceeds to the state-of-the-art methods, which include the use of UAVs (Unmanned Aerial Vehicles) and satellite-based systems and ground-based monitoring technology in geological hazard assessment. The combination of various sensors and

data sources is given special consideration, as it allows forming more precise and valid 3D models, with the help of which the complex geological phenomena can be monitored<sup>[10–13]</sup>.

Also, the article explains the broad scope of the application of the 3D mapping technique in geological hazard monitoring, where the case studies revolve around earthquake, landslide, volcanic, and flood hazard measurements<sup>[14,15]</sup>. The constraints and challenges of these technologies are also covered, such as problems in the accuracy of data, computational load, and environmental limitations. To sum up, the review ends by discussing the future of 3D mapping in geological hazards monitoring with a specific emphasis on sensor technology development, real-time monitoring, machine learning, and self-driving mapping systems.

Providing the overall picture of the existing and coming technologies in the sphere of 3D mapping applications in geological hazard monitoring, the review will be a useful source of information to the audience of researchers, practitioners, and policymakers. The combination of recent technologies in 3D mapping in the sphere of geological hazard monitoring can be the answer to the considerable improvement of disaster preparedness, management, and mitigation, which eventually will allow saving lives and reducing the harm

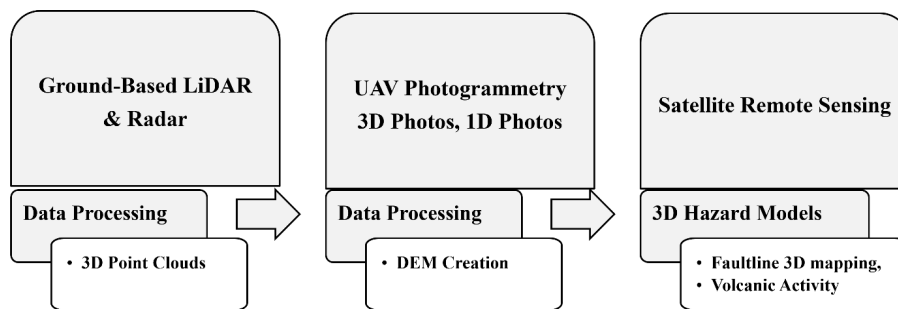
that geological hazards cause to the communities of nations worldwide.

## 2. Evolution of 3D Mapping Techniques

In the last several decades, the emergence of 3D mapping technologies and their application in geological hazard monitoring has registered a major shift in the use of 3D mapping technologies. Due to the ongoing development of technological innovations, the instruments used to be able to capture the complexity and dynamism associated with geological processes have become even more sophisticated<sup>[7,16]</sup>. This part discusses how 3D mapping methods evolved, from their inception to the most advanced and modern methods that are presently utilized in the assessment of geological hazards. Across the major 3D mapping modalities used in hazard studies, each offers a distinct balance among spatial resolution, operational constraints, and coverage scale, as summarized in **Table 1**. To frame the technical landscape, **Figure 1** provides an overview of contemporary 3D mapping modalities and the typical data-to-model pathway used in hazard monitoring.

**Table 1.** Comparison of representative 3D mapping techniques for geological hazard monitoring, highlighting strengths, limitations, and typical hazard-use contexts.

Technique	Description	Strengths	Limitations	Common Applications
Photogrammetry	Use of overlapping photographs to create 3D models	Low-cost, versatile, easy to deploy	Requires good weather, can be affected by light conditions	Terrain modeling, small-scale hazard assessments
LiDAR (Light Detection and Ranging)	Laser-based technology that measures distance to create 3D point clouds	High precision, works in low-light or dense environments	Expensive, requires specialized equipment	Landslide monitoring, fault zone analysis, and topography
Structure from Motion (SfM)	Uses multiple photographs taken from different angles to reconstruct 3D models	Low-cost, flexible, suitable for UAV integration	Can struggle with large areas or very high-resolution needs	UAV-based 3D mapping, volcanic craters, active faults
Synthetic Aperture Radar (SAR)	Uses radar waves to create 3D models from satellite data	Can operate in all weather conditions, and large-scale monitoring	Lower resolution may not detect fine-scale changes	Earthquake displacement, large-scale surface monitoring



**Figure 1.** Conceptual overview of 3D mapping technologies for geological hazard monitoring, illustrating data sources (ground, UAV, satellite) and the typical processing pathway to hazard-relevant 3D products.

## 2.1. Early Methods of 3D Geological Mapping

The idea of three-dimensional mapping of geological work began in the early 20th century when photogrammetry was among the earliest methods used to capture and display terrain in 3D. Photogrammetry, which entails the utilization of photographs taken from various angles to generate valid measurements of objects, enabled geologists to start generating three-dimensional illustrations of landscapes<sup>[17]</sup>. The early 3D maps were, however, labor-intensive, had restricted coverage, and had to be done manually by triangulating and stitching together photographs to make coherent models.

In 1990s, with the development of terrestrial laser scanning (TLS), 3D mapping to monitor geological processes made a big breakthrough in terms of 3D mapping. TLS offered an opportunity to obtain accurate topographical and surface data as point clouds. This technology enabled geological features, including fault lines, rock formations, and landslide-prone regions, to be scanned faster and in greater detail than through conventional photogrammetric processes. TLS provided higher resolution data, increased accuracy, and was able to operate in a broader environment. These advancements formed the basis of the modern procedures that are a routine in the monitoring of geological hazards<sup>[18,19]</sup>.

## 2.2. Advances in Remote Sensing Technology

The ultimate advancement of 3D geological mapping in the exploration of the Earth occurred when remote sensing technologies were advanced<sup>[20]</sup>. The technologies, especially LiDAR (Light Detection and Ranging) and Structure from Motion (SfM) photogrammetry, have transformed the capabilities of mapping in three dimensions and for geological hazards. The LiDAR technology relies on laser pulses to measure the distance, and it can be used to create 3D point clouds quickly and with high accuracy. LiDAR has also been the key to geology as it can give topographic data with millimeter accuracy even in problematic areas like dense forests or rugged mountain ranges, which the old systems may not be able to achieve.

Other technologies that emerged as key tools in geological hazard monitoring are SfM photogrammetry, which relies on overlapping photographs to develop 3D models with the help of computational algorithms, alongside LiDAR. Compared to LiDAR, which demands specialized equipment,

SfM photogrammetry may be performed with a general camera, and it has the secondary benefit of being relatively cheap and flexible. It finds special application in map-making of the geological features in distant and accessible places, in active fault areas, and in volcanic craters<sup>[21,22]</sup>.

These technologies have improved and therefore advanced their abilities. Not only did LiDAR and SfM make it possible to have more accurate and finer terrain models, but they also started to be used in the dynamic monitoring of hazards, so that real-time and continuous data could be collected. These remote sensing technologies have become the standard for 3D geology mapping in the modern world, and they have allowed the analysis of surface movements, terrain deformation, and geological hazards in more detail over time<sup>[8]</sup>.

## 2.3. Integration of Geospatial Data for 3D Mapping

The merging of geospatial information, which is obtained by a variety of means, has been one of the trends in the development of 3D geological mapping during the last few years. A combination of satellite imagery, UAVs (Unmanned Aerial Vehicles), ground-based sensors, and LiDAR has made it possible to develop very specific and dynamic 3D models, giving the complete picture of geological hazards. Geographic Information Systems have been instrumental in this integration because it provides a platform through which the collection, analysis, and visualization of geospatial data can occur<sup>[23]</sup>.

GIS can be used to superimpose 3D models with other data layers like soil structure and composition, seismic activity, and land use<sup>[5,24]</sup>. This allows viewing of geological hazards in a multi-dimensional manner, which considers the physical terrain as well as the human factor at stake. The predictive capability of geological hazard evaluations has been increased by the capability to combine these varied datasets into a single 3D model, making it possible to make risk modeling more accurate and to make better decisions during disaster management and mitigation planning.

Large-scale geospatial data integration has also become easier with the emergence of cloud computing and data storage solutions. Dynamic and updated 3D hazard maps can be accessed in real-time with the help of satellite images, UAV data, and monitoring systems, and are essential for re-

sponding to a natural disaster on a timely basis. The fact that real-time data can be provided, and that the 3D models can be constantly updated, is one of the most important aspects that signify the transition of the fixed hazard mapping to a more dynamic and responsive system<sup>[25]</sup>.

## **2.4. Automation and Machine Learning in 3D Mapping**

The second critical introduction in 3D mapping used in geological hazard observation is the implementation of machine learning and artificial intelligence (AI) to introduce automated analysis of complicated datasets<sup>[26]</sup>. Although the conventional 3D mapping methods had to involve a lot of human intervention to analyze the data and draw the necessary features, the use of AI and machine learning algorithms has simplified this task, as the geological features can be automatically identified and categorized. These algorithms are capable of processing huge amounts of data in a short period of time and finding patterns to forecast possible dangers like landslides, ground subsidence, or volcanic eruptions.

Machine learning models and especially those based on deep learning algorithms can now process point clouds of 3D data, as well as the outputs of remotely sensed measurements, to detect subtle topographical variations that could be a sign of geological events about to occur<sup>[27]</sup>. As an illustration, machine learning algorithms can track the patterns of surface deformation and mark regions where there are unusual changes in topography that are indicative of an imminent earthquake or landslide. This real-time detection capability has greatly improved the hazard forecasting and early warning systems.

Moreover, machine learning and AI-based methods have also been instrumental in the automation of the process of 3D model creation. The automated nature of feature extraction algorithms has simplified the process of processing data from different remote sensing technologies down into accurate and comprehensive 3D models with minimum human intervention. This automation will not only enhance the speed at which the mapping is done but also minimize the chances of human error, thereby leading to better and more reliable assessments of hazards<sup>[7,28]</sup>.

Technological progress, starting with the primitive photogrammetry and progressing through the most recent development of remote sensing techniques such as LiDAR and

SfM, has characterized the development of 3D mapping techniques in geological hazard monitoring. The combination of different geospatial sources of data, as well as the integration of AI and machine learning, has only increased the functions of 3D mapping to offer real-time and highly accurate hazard estimates. As the technologies keep on advancing, geological hazard monitoring at a more precise and faster rate is bound to reshape the disaster preparedness and risk management techniques across the planet. Not only are the next-generation 3D mapping methods tools of visualization, but they are also altering the mode of thinking of geologists, engineers, and policymakers regarding geological hazards monitoring and ultimately making risk mitigation processes more proactive and effective<sup>[29]</sup>.

## **3. Current State-of-the-Art 3D Mapping Techniques**

The accelerated methods in the 3D mapping technologies have resulted in a massive change in the monitoring and evaluation of geological hazards<sup>[30]</sup>. The modern 3D mapping technologies can be used to capture data of various types and quality in real-time, which may be ground-based, aerial, and satellite-based monitoring systems. Such contemporary methods offer greater detail and accuracy of the facts so that geologists and other disaster management professionals can interpret and respond to geological occurrences. This part delves into the advancement of the 3D mapping techniques that are being utilized nowadays in geological hazards monitoring.

### **3.1. LiDAR and Terrestrial Laser Scanning**

LiDAR (Light Detection and Ranging) is still one of the most popular and efficient technologies to use when capturing 3D information during geological hazard monitoring. The LiDAR systems, by sending laser pulses and measuring the time of bouncing back, can create point clouds that are highly accurate in 3D and in high resolution, and reflect the surface of the Earth with the precision of millimeters. The technology has been especially useful in geological surveying since it can produce detailed topographical maps that can show the slightest of elevation and surface alteration<sup>[31]</sup>.

LiDAR can also play an important role in geology hazards, wherein it can be utilized to monitor fault zones, land-

slides, volcanic craters, and other important geological aspects<sup>[30]</sup>. The fact that it can acquire massive landscape information within a brief duration of time comes in really handy in the detection of any ground movement that may be brought about by an earthquake or a volcanic eruption. Moreover, LiDAR can be put into use in numerous environments, such as forests and other thick vegetation, where the old surveying tools may fail. The more specific kind of LiDAR is the Terrestrial Laser Scanning, which is employed in the detailed scanning of smaller and localized geological aspects. TLS has gained enormous implications in the examination of the landslide-prone zones because it provides quite accurate information that can be utilized to estimate the stability of slopes and observe the changes over time<sup>[32]</sup>.

LiDAR has a major advantage in the fact that it is capable of giving very accurate three-dimensional representations of the landscape in a non-invasive way. LiDAR, in its high spatial resolution, allows identifying small-scale alterations in the terrain that might predetermine the initial phases of a geological hazard and timely intervene to mitigate the risk<sup>[33]</sup>.

### **3.2. UAV-Based 3D Mapping**

The Unmanned Aerial Vehicles (UAVs) or drone has emerged as a potent instrument in 3D geological mapping because they are flexible, cheap, and it is able to reach remote locations. The UAVs have high-resolution cameras, LiDAR, or multispectral sensors, which enable them to generate fine-resolution images and survey the terrain beneath into precise 3D models. They can cover extensive regions within a short time, and these systems can be used regularly to offer useful information that is capable of tracking geological risks over time<sup>[34,35]</sup>.

UAVs are found to be very handy in dangerous, remote, or otherwise inaccessible areas, which cannot be surveyed by human surveyors<sup>[36]</sup>. When it comes to landslides, as is the case, UAVs can be operated over precarious slopes where they can take real-time information on ground movement without jeopardizing the lives of humans. Likewise, volcano mapping has also shown many applications of drones, in which the dangerous conditions would not otherwise allow ground-based data collection. The 3D mapping of UAVs is also economical because it does not require the use of costly aerial surveys or satellite data.

When used in conjunction with photogrammetry and

LiDAR, UAVs can be used to produce very detailed, three-dimensional models that can be utilized to monitor changes that occur to the terrain over time. The models are important in offering important insights into the development of geological hazards, including a change in fault lines, volcanic activity, and slope stability. Besides, UAVs have GPS and inertial measurement units (IMUs), which complement the accuracy of 3D data collection and guarantee accurate georeferencing of the obtained imagery<sup>[37]</sup>.

### **3.3. Multi-Sensor Integration**

The combination of various sensors and data sets to form more complete and accurate models is one of the most promising trends in the current 3D geological mapping<sup>[7,38]</sup>. The integration of various technologies, including LiDAR, UAV-based photogrammetry, thermal imaging, and ground-based radar systems, will allow the researchers to get a more comprehensive picture of the geological environment. It is a multi-sensor method of monitoring a wide range of geological hazards, more integrated with other types of data that are complementary.

An example is that LiDAR is capable of delivering very detailed topographical information, whereas thermal imaging could detect temperature variations, which could indicate a volcanic eruption or a landslide. On the same note, ground displacement can be observed via radar-based systems, and this is essential in the detection of subsidence or fault movements. Combining all these types of data into one 3D model, scientists are able to obtain a better insight into the processes occurring in geology and are capable of making more precise predictions on what risks a specific hazard may present.

Multi-sensor integration also improves the capability of tracking real-time environmental variation<sup>[39]</sup>. Since the information from various sources is constantly being updated and combined, 3D models can be changed dynamically to support the latest state of affairs. This will enable real-time hazard maps to be created so that they will provide more current information on the changing geological threats to help to respond to the crisis more effectively and quickly. In addition to geospatial datasets, the integration of 3D mapping with environmental and climatic variables significantly enhances hazard interpretation. Variables such as precipitation, temperature, soil moisture, groundwater levels, and

atmospheric conditions provide critical context for interpreting observed terrain changes. For instance, coupling high-resolution 3D slope models with rainfall intensity and soil moisture data enables improved prediction of landslide initiation, while integrating temperature and gas emission data supports volcanic activity monitoring. This multi-domain data fusion allows the transition from purely geometric mapping to process-informed hazard analysis.

### **3.4. Ground-Based 3D Monitoring Systems**

Although airborne and satellite-based systems play a very important role in monitoring geology at a large scale, ground-based 3D monitoring systems are essential to monitor more localized, detailed data. Ground-based surveillance systems, e.g., GPS stations, radar systems, and terrestrial LiDAR, can be used to continuously monitor geological features with high accuracy<sup>[40]</sup>. These systems are found to be beneficial, especially in tracking ground movement, slope stability, and subsurface deformation in localities where aerial systems and satellite-based systems might fail.

As an example, a ground-based radar system will be able to detect even the slightest surface changes, which signal the beginning of a landslide or a volcano. Similarly, ground-based LiDAR may also be utilized to track the landscape changes at a very specific level, i.e., the alterations in the fault lines or slight deformations of the ground. Together with the real-time capability of data processing, it is now possible to know geological hazards as they occur, giving a warning of the possibility of catastrophic events that might occur<sup>[30]</sup>.

Ground systems are also essential in the validation and calibration of the remote sensing information. It is possible to use ground-based systems to enhance the accuracy of 3D models produced by airborne or satellite-based methods by using in situ measurements of geological features. This is due to the synergy between the ground-based and remote sensing technologies, which make geological hazard assessments as precise and dependable as possible<sup>[41,42]</sup>.

### **3.5. Satellite-Based 3D Mapping**

The 3D mapping, which is done on a satellite, has turned out to be a necessary tool in the extensive monitoring

of geological hazards<sup>[14]</sup>. Satellite-based monitoring technologies, e.g., Synthetic Aperture Radar and Interferometric SAR (InSAR), have allowed researchers to identify the surface movement of large areas with surprising accuracy. Such technologies are especially applicable in the detection of ground deformation, subsidence, and volcanic eruptions during earthquakes. Satellite-based 3D mapping is essential in determining hazards in a wide geographical area that could not be measured using limited ground-based coverage.

The first benefit of satellite-based 3D mapping being the possibility to track hazards in real-time, is one of the greatest benefits because the process covers geological events worldwide<sup>[43]</sup>. As an example, Sentinel-1 satellites of the European Space Agency have played a key role in monitoring ground movements after a seismic or a volcano has erupted. With the help of InSAR, researchers are able to form elaborate 3D maps of the surface of the Earth and can detect the slightest changes in the topography that could lead to an upcoming geological phenomenon. These satellites can cover remote areas and other areas that have low ground coverage; thus, this would be a very useful instrument in the overall assessment of the hazard.

The application of satellite-based 3D mapping is also very useful in monitoring long-term changes in the surface of the Earth, like the gradual tectonic movements or the development of landslides, which are very extensive. Having both the high spatial resolution and the global coverage, satellite-based monitoring is an inalienable instrument in large-scale hazard assessment and disaster management<sup>[14]</sup>.

With the incorporation of different advanced methods of 3D mapping, the geological hazard monitoring world has changed. All of the above have facilitated more precise, real-time, and large-scale monitoring of geological hazards by LiDAR, UAVs, multi-sensor systems, ground-based monitoring, and satellite-based technologies. They are very useful in understanding the deformations of the surface, the changes in the topography, and the possible risks that can occur, and increase our chances of predicting and reacting to the catastrophic geological phenomena. With the further development of these technologies, it is possible only to expand the scope of their application in geological hazards monitoring, which will provide additional opportunities in reducing risks, warning, and responding to disasters<sup>[44]</sup>.

## 4. Applications of 3D Mapping in Geological Hazard Monitoring

It is now possible to create 3D models that are very accurate and dynamic, thus radically changing how geological hazards are monitored and assessed. The 3D mapping applications in this area reach a very wide range of matters that are considered hazardous in geology, such as earthquakes and landslides, as well as volcanic eruptions and floods<sup>[15]</sup>. These applications not only offer minute information about the hazard

areas, but also help manage risk more efficiently and provide early warning devices, as well as emergency response plans. This part examines how the 3D mapping technologies have been applied specifically in the field of monitoring numerous geological hazards, and provides an example of how these technologies are already applied to reduce the risk and make the response faster. Because mapping requirements differ substantially among earthquake, landslide, volcanic, and flood contexts, the dominant 3D mapping technologies and their operational value by hazard type are synthesized in **Table 2**.

**Table 2.** Applications of 3D mapping in major geological hazards (earthquakes, landslides, volcanic hazards, flooding), indicating commonly used platforms and primary monitoring values.

Hazard Type	3D Mapping Technologies Used	Primary Benefits	Example Case Study or Application
Earthquakes	LiDAR, InSAR, UAVs	Real-time surface displacement monitoring, fault analysis	Post-earthquake surface rupture detection in fault zones
Landslides	UAVs, LiDAR, Ground-based radar	Continuous slope stability monitoring, early warning systems	Monitoring slopes in mountainous regions, like the 2014 Oso landslide
Volcanic Eruptions	UAVs (thermal imaging), LiDAR, SAR	Tracking lava flow, volcanic deformation, eruption prediction	Monitoring of Mount Etna and other active volcanoes
Flooding	LiDAR, UAVs, Satellite-based SAR	Accurate floodplain mapping, terrain-based inundation modeling	Flood risk assessment in coastal and river basin areas

### 4.1. Earthquake and Fault Zone Monitoring

The analysis of the earthquake faults and seismic activity is one of the most important contributions of the 3D mapping to geological hazards monitoring<sup>[45]</sup>. Surface displacements that usually go hand in hand with earthquakes can be recorded with 3D mapping tools, giving finer details about fault zones and regions of ground movement. LiDAR and InSAR (Interferometric Synthetic Aperture Radar) are useful specifically in recording the ground movements that materialize as a response to tectonic movements and providing high-resolution, precise illustrations of the manner in which the surface of the earth reacts to the seismic activity.

These 3D models play an important role in the long-term behavior of fault zones, particularly in areas that are highly prone to seismic activity. It is also possible to trace the activity along fault lines by recording the slightest movements of the line and being able to notice how they vary, and this could indicate the coming earthquake. Besides, 3D mapping enables the identification of the regions that are likely to experience surface rupture, which aids in disaster preparedness and infrastructure development. When there is a large-scale earthquake, a 3D mapping that utilizes satellites can be used as a fast response to the extent of the damage, facilitating response and recovery planning<sup>[46]</sup>.

UAVs and ground-based LiDAR further increase the possibilities of monitoring the activity of the fault zones and the surrounding landscapes in real-time, which allows for evaluating the risks of the seismic events<sup>[11]</sup>. These methods can be used to enhance the quality of hazard modeling and further enhance early warning systems by delivering timely and on-ground data.

### 4.2. Landslide and Slope Stability Monitoring

One of the most prevalent and devastating geological risks that occur especially in mountainous or hilly environments is landslides, which 3D mapping has proven to be very helpful in determining the stability of the slope, areas at risk of landslides, and observing the changes in the terrain that may signify upcoming failure<sup>[47]</sup>. LiDAR at high resolution, when used along with photogrammetry provided by UAVs, would make it possible to create detailed 3D representations of slopes and relief, as well as reflect the slightest topographic alterations, which could be an indicator of potential landslide occurrence.

Such 3D models will enable the extensive hazard evaluation process involved in the identification of steep slopes and unstable soil conditions, and other places with a high rate of erosion or past landslide occurrences. Geologists are

able to observe these regions over a time period to determine the slope stability, such as the shifting ground underlying the area or water build-up, which has the potential to cause a landslide. Moreover, 3D mapping gives an improved picture of the general landscape situation, and more informed predictions on the movement and possible effects of the landslide could be made<sup>[48]</sup>.

In the case of a live landslide, UAVs or LiDAR systems located on the ground can provide real-time information to monitor the movement of the landslide and evaluate its scale and possible influence. The data is critical in evacuation planning, infrastructure protection, and the realization of the extent of the damage after a landslide<sup>[35,49]</sup>.

### **4.3. Volcanic Hazard Monitoring**

The volcanic eruption is a highly dynamic and dangerous environment and requires constant data and constant checkups; 3D mapping procedures are essential in checking the development of the volcano craters, lava flows, and other forms of volcanic features over a long duration of time. LiDAR and UAV can be applied in mapping of volcanic landscapes and create detailed models of any volcanic landscape, and provide geologists a chance to trace the development of any volcanic crater, any moving lava flow, or any other changes that occur before, during, and after an eruption<sup>[50,51]</sup>.

The benefit of the 3D mapping on the volcano hazards surveillance is that a real-time measurement of the risk of an eruption of volcanoes can be done<sup>[52]</sup>. To provide an example, UAVs may contain high-resolution cameras or thermal sensors that will allow taking fine-grained images of the active volcanic sites, such as those where the lava is likely to flow, or where the pyroclastic eruption is soon to be expected. The hazard models that predict the path of the lava stream and the regions that might fall under the volcanic fallout can include these real-time streams of data.

The 3D images of the volcanic craters, as well as the landscape around the craters, can also help the researcher to identify the deformation of the surface of the ground as a result of the volcanic activity, and this can demonstrate the build-up of magma beneath the crust of the Earth. By monitoring the changes in the surface elevation with time, the scientists can ascertain the probability of eruption and the extent of its potential dangers, and this enables the scientists to devise early warning systems that may be utilized as a

means of saving the lives of those at risk.

### **4.4. Flood Hazard Mapping and Risk Assessment**

The most common and devastating natural hazard is flooding, which is usually aggravated by other causes like urbanization, climate change, and extreme weather conditions, where 3D mapping can be used to prepare a finer, more accurate map of floodplains, riverbeds, and also coastal areas<sup>[53]</sup>. By combining 3D topographic data with hydrological and meteorological variables such as rainfall intensity, river discharge, and storm surge conditions, researchers can simulate flood dynamics with higher accuracy. The integration of climatic drivers enables dynamic modeling of flood propagation under varying environmental scenarios, including extreme weather events and climate change-induced variability<sup>[54]</sup>. By producing digital terrain models (DTMs) of the terrain, the researchers can be able to forecast correctly the flow of water and come up with strategies for flood control and mitigation.

Flood risk assessment can be further improved with real-time monitoring systems, including those based on UAVs and satellite-based technologies that can provide updated models during storm events<sup>[55]</sup>. Such systems have the capability of recording the degree of flooding as it happens and will be crucial in sharing valuable data to be used in response planning, such as evacuation and infrastructure protection. The 3D mapping analysis of the post-floods can also help in the assessment of the damage and inform the strategies of recovery.

### **4.5. Coastal and Subsurface Monitoring**

Geological hazards like erosion, fault activity, and tsunamis are also very common in the coastal areas, and the 3D mapping techniques are increasingly being employed in the monitoring of these hazards, particularly in the face of the dynamically changing sea levels and the increasing storm activity owing to climate change<sup>[14,56]</sup>. The LiDAR and UAV-based technologies come in quite handy when it comes to mapping coastal erosion and monitoring the change of the shoreline with time. With these systems, changes in the topography of the coastline can be accurately measured, and this can offer information on long-term trends and assist

in predicting the areas that would most be affected by erosion or floods.

Besides coastal risks, 3D mapping is also needed in geological monitoring of the underground area<sup>[57]</sup>. The use of ground-based radar systems, integrating 3D LiDAR systems, is to map underground faults, seismic activity, and to locate the accumulation of pressure beneath the surface of the Earth. This information plays a very important role in knowing the risks that an underground phenomenon like a sinkhole, subsidence, or underground landslides could cause, which cannot be seen at the surface, yet could be disastrous.

#### 4.6. Summary of Applications

The application of 3D mapping in geological hazard monitoring extends beyond hazard identification to the interpretation of underlying environmental processes. By capturing high-resolution spatial and temporal variations in terrain, these technologies enable the analysis of geomorphic evolution, hydrological responses, and subsurface deformation processes. This process-based understanding is essential for linking observed surface changes to driving mechanisms such as rainfall infiltration, tectonic stress accumulation, and thermal or magmatic activity, thereby improving both hazard assessment and predictive capability<sup>[30]</sup>. Both in the case of fault line monitoring, landslide risk assessment, volcanic eruptions, and flood simulation, 3D mapping technologies

allow for better hazard identification, risk evaluation, and managing the disaster. With the further development of such technologies, the features of real-time data provision, using multiple sources of information, and developing highly detailed models of hazards will help to decrease the consequences of geological hazards and prepare for the occurrence of new incidents.

### 5. Challenges in 3D Mapping for Geological Hazard Monitoring

Although there are many benefits to the application of 3D mapping technologies in geological hazard monitoring, including the accuracy, real-time data collection, and better prediction of hazards, it is not without its challenges. These obstacles may include both technical constraints (like data quality and processing problems) and operational ones, which influence the possibility of implementing some mapping methods in dangerous or inaccessible locations. In this section, the principal issues of the field of 3D mapping of geological hazard monitoring have been discussed, along with the strategies that could be utilized to eliminate these problems. Despite strong performance gains, recurring constraints related to measurement fidelity, processing throughput, operational feasibility, and interoperability continue to limit deployment; these issues and typical mitigation pathways are consolidated in **Table 3**.

**Table 3.** Practical challenges in 3D mapping for geological hazard monitoring and commonly adopted mitigation strategies (data quality, computation, operational constraints, and data integration).

Challenge	Description	Impact on Monitoring	Potential Solutions
Data Accuracy and Quality	Environmental factors affecting data collection (e.g., dense vegetation)	Reduced precision, poor model quality	Improved sensor calibration, use of higher-resolution equipment
Computational Limitations	Large-scale datasets require high processing power and time	Delays in real-time hazard monitoring, slow data analysis	Cloud-based computing, optimization of algorithms
Environmental Constraints	Weather conditions (rain, snow, high winds) are affecting UAV performance	Limited operational windows reduced data reliability	Use of more robust UAVs, better sensor integration for all weather
Data Integration	Merging data from different sources (e.g., LiDAR, UAV, satellite)	Misalignment, data inconsistencies, and errors in final models	Development of standardized data formats, better integration software

#### 5.1. Data Quality and Accuracy

The quality and accuracy of the data collected are one of the greatest challenges in 3D mapping in order to monitor the geological hazards. Although 3D mapping technologies (LiDAR, UAVs, and photogrammetry) are currently in modern form, providing high-resolution data, the accuracy of the

results may be influenced by extraneous factors like sensor calibration, the environment, and the geological environment type<sup>[7,58]</sup>. As an example, vegetation will block LiDAR signals, or extreme weather conditions will cause incomplete or inaccurate data. Similarly, UAVS can experience problems of taking proper imagery during turbulent weather, including high wind velocity or heavy rainfall, which can compromise

the reliability of 3D models.

Moreover, various 3D mapping methods can result in data that is less accurate or more accurate. Although LiDAR is associated with high precision, photogrammetry with the help of UAVs may be characterized by the failure to stitch pictures well, especially when it comes to rugged terrain<sup>[59]</sup>. The possibility of data conflict between data resolutions or alignment on data from the various sensors or sources also presents the risk of having a poor quality of the 3D model.

Some of the strategies that should be implemented to resolve these problems include sensor calibration, data validation, and using high-quality equipment. Moreover, another way of enhancing the accuracy of the models is to use ground-truthing techniques where remote sensing data are compared with in-situ measurements. The fact that the data gathered using 3D mapping can be checked against the direct measures of the situation in the field allows scientists to make sure that the models reflect the real-life terrain and geological characteristics<sup>[58]</sup>.

## 5.2. Computational and Processing Limitations

Another challenge is the huge amounts of data that are produced by 3D mapping technologies<sup>[60,61]</sup>. LiDAR and UAVs, along with satellite systems, have the capability to provide large volumes of high-resolution information within a limited duration of time when scanning a large area or tracking a hazard over a long duration of time. This data takes a lot of computing power and storage space to process. The processing and work with point clouds, the creation of 3D models, and the synthesis of information from several sources require the use of complex algorithms. This is usually time-consuming, particularly in cases where dense datasets or large regions are involved.

Also, the fact that raw data has to be converted into an actual 3D model can only be done through specialized software, which is not always available to every researcher or organization, especially in resource-restricted contexts. The time taken to process such large datasets may add time to the creation of hazard models, which in turn slows down decision-making and response actions in emergencies. The processing and analysis of the data conducted in real-time may impede this process since they are important in early warning systems<sup>[62]</sup>.

As a way of surmounting these computational shortcomings, cloud computing and distributed processing are under development<sup>[63,64]</sup>. With the help of cloud solutions, the processing of the data may be transferred to a remote server of high power, and the analysis will be processed in a shorter time, and the local calculation capabilities might be used by other processes. In addition, machine learning computing and automated data processing methods are being developed to simplify the process of analyzing massive data volumes, and now it is possible to create the hazard models much faster and more precisely.

## 5.3. Environmental and Operational Constraints

Although the 3D mapping methods are very efficient in most geological environments, environmental and operational limitations still have the ability to restrain the use of this method. As an example, the usage of UAVs in remote or risky regions could be complicated because of the factors of accessibility, the type of terrain, and weather conditions. The required flight altitude or clear line of sight may not be realized in mountainous or highly vegetative areas, which would enable the UAVs to take precise data. Likewise, the weather may lead to unfavorable performance of UAVs or aerial platforms because of such adverse factors as heavy rain, snow, or high winds<sup>[36]</sup>.

As well, in high seismic activity or volcanic eruption, or in a region where the landslides are on the move, volcanic activity may be a significant issue to the safety of the field teams. A LiDAR or other surveying equipment deployed to such hazardous environments may present a risk to the personnel and may demand specialized equipment to be considered safe<sup>[65]</sup>.

In an effort to reduce such environmental and operational problems, scientists and professionals should be ready to address such contingencies by having appropriate contingency plans, including using remote-controlled or autonomous systems operating under dangerous environment. Those UAVs with infrared or thermal cameras, as an example, can be used to inspect any volcanic activity or a landslide area without endangering human lives. Likewise, the combination of real-time data streaming and automated monitoring systems will enable constant tracking of the hazards without the personal presence of personnel<sup>[66]</sup>.

## 5.4. Integration and Standardization of Data

One of the major problems of 3D geological hazard monitoring is the coordination and standardization of the information collected through various sources<sup>[7,67]</sup>. Most of the time, various technologies are used to collect data, including LiDAR, UAVs, and satellite systems, which all have their own formats and data structures. It may be challenging to combine these datasets into one 3D model, where one should make sure that the information provided by every sensor is correctly aligned and rescaled. Moreover, inconsistencies in the resolution of data, the accuracy, and the time frequency of various sensors may pose problems during the integration process.

To allow the dataset of various sources to be integrated and compared, data formats and protocols must be standardized<sup>[68]</sup>. Nevertheless, it is an ongoing process, and currently, there are no universally accepted standards in data interoperability in the field of 3D geological hazard monitoring. The inefficiencies, errors, and delays in the data analysis procedure may arise due to the absence of standardization.

To resolve this problem, the work on universal data standards, open-source data sharing, and integration is also a top priority. The collaboration between organizations and disciplines will allow the researchers to aim at developing uniform workflows by which the data provided by various sources can be easily connected and analyzed. Also, advances in machine learning algorithms to process data fusion are assisting in the automation of the process of aligning and integrating data across various sources, enhancing the efficiency as well as the accuracy of the hazard assessments<sup>[69]</sup>.

## 5.5. Financial and Resource Constraints

The other obstacle is the financial and resource limitations, which may restrict the adoption of 3D mapping technologies, especially in developing countries or in organizations with low budgets<sup>[70]</sup>. The devices needed to conduct 3D mapping, including LiDAR devices, UAVs and premium computing facilities might be costly to acquire and maintain. Besides initial cost, the operational costs are also likely to increase the cost burden, including data processing, storage and training the people involved.

Such financial limitations may prevent the extensive application of the 3D mapping technologies, particularly

in areas where geological hazards are most prone. These technologies must be made available to wider organizations and communities in order to achieve good global hazard monitoring and mitigation.

Collaboration and sharing of knowledge are two of the ways in order to deal with these resource issues<sup>[71]</sup>. The financial barriers to the accessibility of 3D mapping technologies can be reduced through the participation of the government in funding and the involvement of public-private partnerships, as well as international collaboration. Additionally, these technologies can be more affordable to organizations with a tight budget because cost-effective and open-source tools and platforms can be developed, leading to higher adoption and use in their hazard monitoring activities across the globe.

Although 3D mapping technologies have turned the world of geological hazards monitoring upside down, it is not without problems. Problems associated with data quality, limitations in computational resources, environmental limitations, data integration, and financial resources should be taken into consideration in order to achieve the best of these technologies. The field can address these three issues by coming up with new solutions, including new data processing algorithms, standardized data formats, and less expensive equipment, among others. Finally, once these obstacles are overcome, 3D mapping can become even more vital to enhance hazard forecasting, disaster management, and mitigation of risks on the global level<sup>[72]</sup>.

## 6. Future Directions and Emerging Trends

With the growth of 3D mapping technologies, there is a vast possibility of their use in geological hazards monitoring. New tendencies, which are promoted by technological advancement and interdisciplinary cooperation, are going to further increase the potential of the 3D mapping systems<sup>[73]</sup>. Here, we look to the future of 3D mapping in geological hazard monitoring with regard to the major developments of sensor technology, real-time monitoring, automation, and data integration, together with the wider trends that inform the area. Emerging directions are increasingly defined by sensor fusion, autonomous acquisition, low-latency analytics, and AI-enabled prediction; the core trends and anticipated hazard-monitoring impacts are outlined in **Table 4**.

**Table 4.** Emerging trends shaping next-generation 3D mapping for geological hazard monitoring and their anticipated impacts on observation, warning, and decision support.

Emerging Trend	Description	Potential Impact on Geological Hazard Monitoring	Examples of Technologies Involved
Advancements in Sensor Technology	Development of more precise, versatile sensors	Enhanced resolution, ability to operate in challenging environments	Next-gen LiDAR, miniaturized thermal cameras, multispectral sensors
Real-time Monitoring	Continuous monitoring of geological hazards using integrated systems	Improved early warning systems, real-time hazard detection	UAVs with live data streaming, sensor networks, and cloud computing
Autonomous Systems	Increased use of autonomous UAVs, robots, and drones for hazard monitoring	Safer, more efficient data collection in hazardous locations	Autonomous UAVs, ground robots, AI-powered systems
AI and Predictive Modeling	Use of machine learning and big data analytics to predict hazards	Enhanced ability to forecast geological events and risk modeling	AI-based predictive algorithms, real-time seismic data analysis

## 6.1. Advancements in Sensor Technology

The future of 3D geological hazard monitoring is highly related to the development of sensor technology<sup>[8]</sup>. With the further development of sensor technologies, they will be able to give even more accurate, efficient, and reliable data to monitor hazards. The LiDAR technology, as an example, is already reputed to be very accurate, but new-generation LiDAR systems are being developed with better range, resolution, and data capture speeds. These high-resolution LiDAR sensors will be capable of scanning bigger areas in shorter periods, more detailed, and with less loss of information, even in some of the most difficult conditions like dense forest or mountains.

Furthermore, 3D mapping systems are being equipped with sensors that can sense other environmental parameters, including temperature, gas emissions, and atmospheric pressure<sup>[74,75]</sup>. To illustrate, thermal cameras or multispectral sensors mounted on UAVs may be used to record the existence of heat in volcano craters, and this will be a valuable source of data regarding where exact eruptions are taking place. In the same manner, gas sensors could be used to monitor the emission of gases such as sulfur dioxide, which might be a sign of volcanic activity. LiDAR sensors combined with multi-spectral and radar sensors will enable monitoring geological hazards in a more in-depth manner, providing a better concept of the underlying factors and possible effects of such phenomena.

The other development that is likely to be beneficial is the miniaturization of sensors that will facilitate the deployment of 3D mapping systems in remote or dangerous areas<sup>[76]</sup>. The size and weight of sensors are small enough to be fitted into the UAVs or drones or even into mobile gadgets, allowing real-time access to the sensors in the areas

that were potentially challenging to reach, like the volcano hotspots or unstable hills.

## 6.2. Real-Time 3D Monitoring and Early Warning Systems

The transition to real-time monitoring and early warning systems is one of the most disruptive tendencies of the future of 3D geological hazard monitoring<sup>[8,77]</sup>. With 3D mapping technologies getting more and more competent to provide continuous streams of data, they can be incorporated into dynamic monitoring systems that will offer real-time hazard assessment. Indicatively, fault lines, landslides, or volcanic activity may be monitored 24/7 using real-time data of UAVs, LiDAR, and ground-based sensors, which may give early signals of a possible seismic occurrence or natural catastrophe.

Special attention should be paid to the integration of 3D mapping with early warning systems in the case of such hazards as earthquakes, tsunamis, and volcanic eruptions, where a timely response to hazards can save lives. These systems will be able to provide timely warnings based on real-time data to track the change in terrain or seismic activity status and thus provide authorities and local populations with an opportunity to evacuate or take other proactive measures. This is particularly critical during high-risk zones, where chances of a disaster are higher and evacuation or mitigation interventions will go a long way in saving lives<sup>[14,78,79]</sup>.

The creation of low-latency communication networks, including 5G, will also play an important role in the implementation of real-time hazard monitoring systems, which will make it possible to transmit essential information provided by remote sensing systems to decision-makers faster<sup>[80]</sup>. With the increased connectivity, creating inte-

grated hazard monitoring networks will become achievable, which will connect sensors, data processing systems, and emergency response teams to reduce the lack of coordination and response to the disaster.

### 6.3. Autonomous and Collaborative Mapping Systems

Self-driven systems, such as UAVs, robots, or drones, are likely to be more significant to geological hazard monitoring in the near future<sup>[34,81]</sup>. These systems are programmable to perform complicated mapping functions without necessarily involving human operators, and it is therefore easier and safer to observe dangerous environments without involving human lives. LiDAR, radar, or thermal sensors installed on autonomous UAVs can be used to fly over hazardous areas or active volcanic locations and generate high-quality data without human pilots being on the ground. Also, autonomous ground-based systems may be applied in tracking slopes, fault zones, or underground situations, and provide constant surveillance of geological risks.

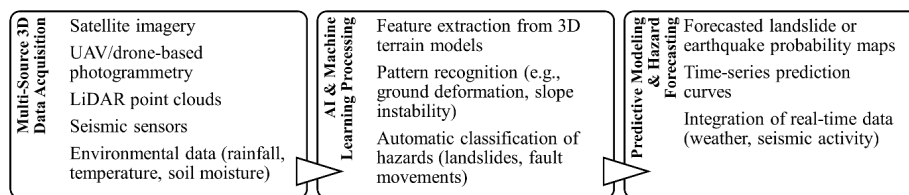
Another developing yet strong form of monitoring to help with hazard monitoring is collaborative mapping systems<sup>[82]</sup>. Such systems use the synergistic capability of multiple UAVs/satellites/ground sensors to produce comprehensive and real-time 3D images of risky regions. With the coordination of the work of several independent systems, a task of large-scale geological monitoring can be performed more effectively, and it is possible to have real-time access

and integration of the data. An example is a fleet of UAVs being able to map an area of a volcano in a variety of angles at the same time, using the data with satellite data and ground-based LiDAR to produce a very detailed, recent 3D hazard map.

The further development of the autonomous and collaborative systems on geological hazards monitoring also involves AI algorithms that will be able to streamline the work of the aforementioned systems. These machine learning models would have the capability of coordinating the operation of a number of UAVs or robots so that data collection would be carried out as effectively and efficiently as possible.

### 6.4. Big Data, Machine Learning, and Predictive Modeling

Another way that the future of big data-driven 3D geological hazard monitoring is promising is the combination of machine learning, predictive modeling, and big data analytics<sup>[83,84]</sup>. The amount of data produced by 3D mapping technologies, including satellite imaging, UAV-measured data, the data on seismic activity data, and environmental data, can offer unprecedented information on geological threats. The problem is, however, to analyze and interpret such a great amount of information. Beyond automation of model generation, AI is increasingly used to infer precursors and forecast hazard evolution from multi-temporal 3D signals, as conceptualized in **Figure 2**.



**Figure 2.** AI-enabled hazard prediction concept using multi-temporal 3D mapping inputs, illustrating data ingestion, feature learning, anomaly/precursor detection, and probabilistic forecasting outputs.

The application of machine learning algorithms and AIs is becoming more common in processing large data sets, finding patterns, and predicting possible geological hazards. An example is to train machine learning models to detect minute indicators of ground movement that can be an early warning of a landslide or an earthquake. Through the analysis of previous data and identification of patterns in the change of terrain, these models can give early notifications or even predict the

possibility of an event. These models have the capability of incorporating terrain conditions together with environmental and climatic variables, including precipitation patterns, temperature variations, soil moisture, and atmospheric pressure. The integration of such variables enables predictive models to capture the complex interactions between environmental forcing and geological responses, thereby improving the reliability of hazard forecasts under both current and fu-

ture climate scenarios. On the same note, AI algorithms may also be utilized to automatically process and interpret 3D data using LiDAR or photogrammetry to accelerate the data processing and hazard analysis of the results<sup>[85,86]</sup>.

With the help of predictive modeling tools, along with the information provided in real time by 3D mapping systems, scientists will be able to model and predict geological events with increased accuracy. These models have the capability of incorporating information about the conditions of a terrain, seismic, weather forecast, and other environmental conditions, and this makes the assessment of hazard risks more accurate. Such predictive models will be improved in the long run to alleviate the effects of disasters and enhance emergency preparedness activities.

### **6.5. Integration of 3D Mapping with Other Hazard Monitoring Technologies**

The combination of 3D mapping and other hazard monitoring devices in the future, including seismic sensors, weather forecasting, and social media data, would be highly important in enhancing disaster preparedness and response. For example, weather data can be dynamically integrated with 3D terrain models to assess how extreme rainfall events influence slope stability or flood propagation. Similarly, coupling seismic data with 3D deformation models allows better interpretation of tectonic processes, while climate projections can be incorporated to evaluate long-term hazard evolution under changing environmental conditions<sup>[87]</sup>. It will become possible to produce more comprehensive and precise models of possible geological hazards by combining information from a variety of sources. As an example, seismic information would be utilized in automated UAV flights in the active fault areas, and weather data would be embedded in flood risk models to determine how heavy rainfall affects the areas at risk of landslides.

Social media and crowdsourcing of data are also becoming a new trend towards improving geological hazard surveillance<sup>[88,89]</sup>. Local populations can also help, local populations such as reporting of tremors, landslides, or volcanic ash, which can be used in combination with 3D mapping systems to give more context and enhance the accuracy of hazard models. Such merging of a wide range of data will allow gaining a more detailed and up-to-date picture of the geological events.

The future of 3D mapping in geological hazard monitoring is rather exciting, as sensor technology, real-time monitoring systems, machine learning, and predictive modeling are set to open up a way to achieve more efficient and effective hazard detection and response<sup>[30]</sup>. The 3D mapping systems will provide more functions to monitor diverse geological hazards, such as earthquakes and landslides, volcanic eruptions, and floods, as they become more autonomous, collaborative, and integrated. The developments are bound to enhance early warning facilities, enhance the precision of forecasting hazards, and eventually save lives by facilitating more coordinated and proactive disaster management activities. It is the constant development of these technologies that will reframe the manner in which we perceive and react to the changing and unpredictable geological processes occurring on the Earth.

## **7. Conclusion**

The assimilation of the next-generation 3D mapping tools into geological hazard monitoring is a paradigm shift in the method we evaluate, forecast, and control the consequences of natural calamities. These new technologies, such as LiDAR, UAVs, ground-ground surveillance, and satellite surveillance, offer unmatched processing and precision in the dynamics of the earth's surface. 3D mapping as a hazard assessment and disaster management tool has become inevitable due to the provision of real-time and highly accurate geological features like fault lines, volcano craters, landslides, and floodplains.

The development of sensor technology, including the increasing powers of machine learning, data fusion, and predictive modeling, is changing the form of geological hazard monitoring. The innovations make it possible to constantly and in real time monitor the high-risk regions and develop early warning systems that will help to save lives and minimize the economic and social consequences of geological events. The combination of several sources of data into coherent 3D models allows for a better overall picture of the complicated interactions among different geological hazards, which, in turn, results in better-informed decision-making and risk management.

Nevertheless, there are still difficulties with the complete exploitation of these technologies. The problem of data

quality, computation, environmental issues, and multi-source data integration is still seen as a major challenge. The only way to overcome such challenges is to move on with the progress of sensors and data processing algorithms, as well as global cooperation to establish standard protocols of data sharing and integration. In addition, the issue of financial and resource constraints will need to be handled to ensure that 3D mapping technologies can be introduced in high-risk as well as resource-limited areas.

In prospect, the 3D mapping of geological hazards has massive potential in geological hazard monitoring. With the constant development of technologies, it is possible to see even more advanced systems that will combine real-time data, self-directed systems, and AI-based predictive frameworks. These systems will not only help us better monitor geological hazards but also predict their occurrence more accurately and allow us some time, which is extremely vital in preparing and responding.

To sum up, the future of geological hazard surveillance has a closer relationship with the further evolutionary advancement and implementation of newer 3D mapping technologies. Through these tools, we can better understand geological processes, improve the early warning system, and ultimately, the human and economic cost of natural disasters. Through ongoing inventions, teamwork, and investment, 3D mapping will lead to the creation of a better, more resilient future in geological hazards.

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The author declares no conflict of interest.

## AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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