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Geologic Risk and Seismic Hazard Assessment in the Southeastern Caucasus Using Remote Sensing Data

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1. Abstract

This study was devoted to the legacy geologic information on the geology, seismicity, infrastructure and mud volcano hazard of the Southeastern Caucasus. Caucasus region is home to a large number of the world's mud volcanoes, which are some of the most mobile, and potentially destructive to infrastructure, geologic features. Because, the seismic events have a much greater impact on this region than on most other regions of the world. In this connection, has been used several major remote sensing tools to provide base hazard maps for assembling the geologic and geophysical information about the South-eastern Caucasus for public policy use. It was focus on using Landsat, set of Synthetic Radar aperture (SAR) interferometry and spectral imaging tools such as ASTER to map and monitor the mud volcanoes and fault structures in the Caucasus region. This study will be of extreme importance to siting and maintaining of pipelines, roads, and other infrastructure, as well as for assisting with the mud volcano hazard planning for the Southeastern Caucasus in particular.

2. Introduction

Mud volcanoes are part of the natural landscape, and offer opportunities to investigate some of the forces that both form or reshape the surface and present hazards to humanity. From a scientific perspective, it is important to understand the cycles of mud volcano activity and the relationship between eruptions and landscape formation. There is both scientific and practical value in observing changes in mud volcanoes during the days, weeks, or months prior to an eruption, using available measurements of surface deformation, seismicity, and gas emissions. Space-based observations, including radar or lidar mapping of surface deformation, remote sensing of gas plumes and surface temperature, offer the only practical means to monitor all active mud volcanoes. In conjunction with seismic and other in situ measurements, space-based observation provide the role of gases and other fluids in volcanic processes, volcanic breccia and their mobilization, and eruptive cycles.

The natural springboard from which to launch application-oriented short-term studies focused on assessment of vulnerability to natural hazards such as landslides, mud volcano eruptions, and earthquakes. Fundamental understanding of landscape-forming processes is essential to reconstruct the history and evolution of dynamic geologic systems and thereby extend the time-frame far beyond the bounds of direct observation of contemporary phenomena. Detailed observations of the processes associated with natural hazards often exist only for a few decades, a time span much too short to encompass the range of hazardous events. Understanding the long-term behavior of natural systems is the pathway to assessing current risks of catastrophic events. Unraveling these interactions is a fundamental first step toward finding efficient ways to conduct human activities, taking into account available resources and potential hazards.

Local deformation and mud volcano studies aim to understand and predict the behavior of earthquake fault systems. Intensive studies in areas such as Southeastern Caucasus is conducted to deduce both the recurrence intervals and magnitudes of displacements along known faults, as well as measure and monitor the contemporary accumulation of strain. The Southeastern Caucasus is located in the mobile Alpine-Himalayan tectonic belt. The basin is restricted by the Greater Caucasus and Balkhan ridge in the north, and by the Lesser Caucasus, Talysh ridge and Elborz Mountains in the south (Shikalibeyli,1996; Jackson, 1992).

Geologically, this region is located in the mobile Alpine-Himalayan tectonic belt and is characterized by high strains resulting in a large number of earthquakes. Every year within the region tens of earthquakes of significant magnitude are recorded.(More than one hundred earthquakes with K>10, including a number of adequate strength to cause significant destruction, are recorded annually. The epicenters are situated mainly at intervals of 10-20 km (Philip et al., 1989; Priestley et al., 1994; Shevchenko et al., 1999; McClusky et al.,2000; Jackson et al., 2002).In addition, a number of geological factors facilitates development of mud volcanism in this region.

The thickness of the sedimentary pile reaches 30km, the upper 10 km being composed of the Pliocene-Quaternary dominantly clayey sediments deposited at extremely high sedimentation rates (up to 1300m/m.y.). Among the special features of the basin are low heat flow, abnormally high formation pressure, and a high degree of dislocation and seismicity. Using space geodesy and remote sensing techniques, predominantly the Landsat and Synthetic Aperture Radar (SAR) Interferometry data, we can provide monitoring of extensional deformation in this region which is related with mud volcanoes. Mud volcanoes are well-developed in the South-Eastern Caucasus (Fig. 1) , comprising more than 30% of those known worldwide. In excess of 300 mud volcanoes have been detected on land and beneath the Caspian. Many of these mud volcanoes are particularly large (up to 400m high) with a variety of forms and eruption frequencies.

Many of the mud volcanoes are quite active and periodically erupt, ejecting huge quantities of mud, clastic rocks, and gases. The gases often flare up to major fires spewing from the ground. During the last several years, tectonic activity has included the abrupt raising of the Caspian Sea level; intensification of seismic activity; and eruptions from previously dormant mud volcanoes. On 25th November 2000, an earthquake with a magnitude of 6.3 on the Richter scale occurred in Baku, resulting in destruction of property as well as injury and loss of life. After this event, up to presence occurred 16 mud volcano eruptions in this region (Kechaldag, Buzovna, Lokbatan, Keyreki, Sangi-mugan, Bozdag-Gezdek, Shikhzagirli, Cheildag etc.)

History has shown that earthquakes and mud volcanoes can create major dangers to people, industrial objects, marine infrastructure, pipelines, rail lines, etc. For example, an earthquake destroyed the Mashtaga region in the northern part of the Apsheron peninsula in 1842. In addition to the November earthquake of three years ago, on March 7th of 2000 a large landslide occurred in the Bayilovo district of the Apsheron peninsula. There was also significant damage as a result of the eruptions of mud volcanoes both onshore and offshore (Garasu, Khere-Zire, Sangi-Mugan islands, and others). Related to these occurrences are many sources of oil, gas and water seepage as a result of instability in the earth's crust.

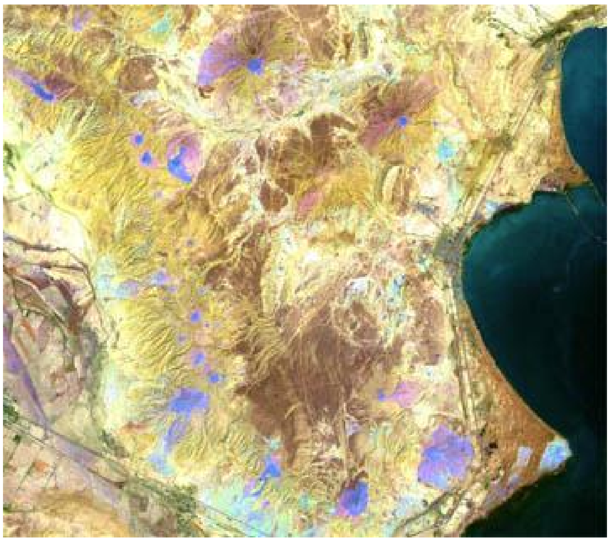

Fig. 1. Southeastern Caucasus, showing more than a dozen mud volcanoes from Landsat 7 data (2004) with their radial patterns and blue centers. Infrasturcutre like roads, pipelines, buildings are all in danger from this rapidly erupting material when it moves.

3. Methodology

The principal new tools brought by space-based observation to the study of regional geology are capability to deduce surface composition over large geographic regions using multispectral imaging and the capability to produce precise, high-resolution, global topographic maps. The first type of information is provided by a suite of past and current moderate-to-high resolution multispectral imaging radiometers, such as the Thematic Mapper on the Landsat satellite series. For geologic applications, basic imaging data have already been acquired for most of the world and the main issue is one of data access.

Methods to analyse Landsat MSS and TM imagery have been developed an attempted to map steeply diping active faults and distribution of mud volcano breccia, which correspond in the field to abrupt scarps, in order to obtain indormation about fault throws. Landsat scenec were selected because, they have high ground resolution and covers a large areas. On remotely sensed images, geological structures do not have a characteristic pattern of reflectance. Therefore, methods of classification using multispectral data are of little use them visual perception is not sufficient to systematially detect all significant landforms, practically geomorphological indicators of strike-slip faulting. In contrast, computerized methods are able to process systematically and small details are enhanced everywhere the same way (Callot et al., 1994; Prost, 1997; Sabins, 1997).

The methodology of filtering detailed here has been tested on Landsat MSS and TM composite scene in Azerbaijan, which was served here as an example to explain the image processing. Structural interpretation, which consists of selecting continuous dark lines corresponding to fault scarps from features, is easy to do by visual observation. However, in other part of same scene, the pattern is more complex and needs some suitable filtering to extract at least the relevant lines which underlined by shadow. Filtering techniques are generally used to assist visual interpretation. In the studied case, we had resource to morphological and geodesical transformations (Zeynalov, 2000; Banerjee and Mitra, 2004). Systematic exploitation of Landsat stereoscopy, good ground resolution, and more specialized processing techniques permitted the discovery of large and detailed structures that previously were unknown in the study area. Many important results and interpretations concerning subsurface structures and mud volcano distribution problems were obtained, including the fracturing pattern, basin faulting and fault inversion, evaluation of the thrusting as a cover detachment, and amount and direction of strike-slip movements. These results were part of the assessment of the efficiency of our methodology.

4. Discussion and Results

Mud volcanoes are mainly formed along faults where the critical stress of breakthrough is less than the abnormally high pore pressure in the volcanic kitchen. Formation of the mud volcanoes may be triggered by a break of equilibrium of the system by such factors as seismic and tide waves. Because this occurs so quickly in geologic time, the current imaging and mapping capabilities available to governments and companies is extremely inadequate to respond to changes in the crust and potentially disasterous movement of the crust. Buried faults are particularly challenging since they show no surface rupture and can only be inferred indirectly from geomorphic, stratigraphic, geopotential, and geodetic data. Although volcanoes may lie dormant for centuries and become sites of intense human presence, they can erupt into catastrophic activity, sometimes on short notice. The problem is to identify the geologic properties and processes that govern the recurrence of volcanic eruptions, how eruptive events develop, and how past eruptions have affected the surrounding landscape. Many (perhaps most) volcanoes experience significant changes in the days, weeks or months prior to eruption, including surface strain, seismicity, ground temperatures, and gas emissions. Capturing these ephemeral signals can be challenging. Systematic observation from space considerably enhances our capability to collect data that may be used to provide a long-term perspective on mud volcanic activity. Remote sensing techniques provide only partial information that complements field data on the age, breccia composition, sequence, and character of past eruptions, as well as structural aspects of likely eruptive sites.

Considering these dangers and complexities, the use of every available tool to evaluate geologic-geophysical conditions is designed to enhance our understanding of the regional extensional deformarion peculiarities of the South-Eastern Caucasus, and the relation of mud volcanoes with the different natural processes that are occurring. It was also provided a rational estimate of the relative level of danger within this region for the civilian population, for industrial sites and for transportation facilities including pipelines. Given the importance of this region from energy as well as a political standpoint, along with the extreme complexity modern-day activity of the geology, it would be hard to imagine a more critical project of this type anywhere in the world.

Strike-slip tectonic environments with extensional and compressional bends tend to be dominated by a lengthy fault system in which individual episodes of fault rupture do not extend along the whole length of the fault. In the vicinity of such faults, high-angle fractures will be subject to alternating episodes of compressional and extensional strain according to the location and geometries of the individual episodes of fault rupture in the Southeastern Caucasus. These fault lines are not fully mapped, nor is their relative stress and strain measured or understood completely.

Up to now, remote sensing data have been used in structural modeling of this region partly. In particular, remote sensing where multiple data sets are fused together has not been available to the general scientific community. Different geologic and geophysical surveys have been used for different localities, but a lack of standardization makes the synthesis of this data for regional planning extremely difficult to nearly impossible. Mud volcano hasard has not yet been studied by special investigations, so that knowledge of the effect of earthquakes on the people and infrastructure of the region is woefully lacking (Fig. 2.)

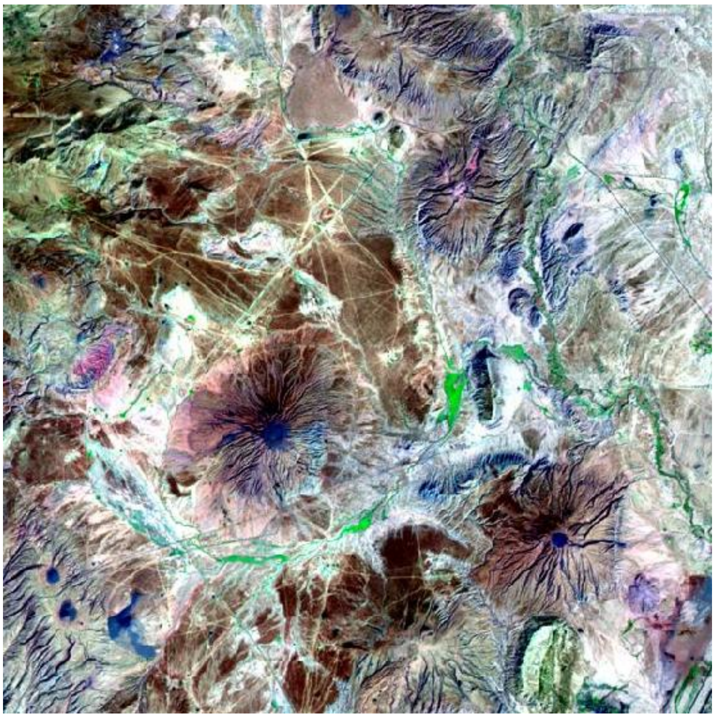

Fig. 2. Bands 7,4,2 of mud volcanoes. Image is 17.7 km across. Notice infrastructure crossing major structures.

Incorporation of remote sensing data, namely Landsat, SAR and ASTER Imagery, in assessment of extensional deformation significantly helped understanding mud volcano hazard issues of the South_Eastern Caucasus. The research was contributed significantly to an understanding of the structural development of this region and the understanding the processes that are actively changing the region. The results of this study should help with prediction of where earthquakes will strike and where mud volcano will most likely erupt. Other geologic phenomenon related to public safety and the siting and design of industrial and transportation projects and facilities are also imaged with Landsat-ASTER type imagery. This will be accomplished through the use of available remote sensing data for enhanced modeling of the fault systems associated with earthquakes and mud volcanoes and other geologic challenges. These data sets will be combined with real-time remote sensing such as with the available seismic arrays, SeaWiFS and MODIS imagery to provide data to compare to existing data sets and map changes.

5. Conclusion

This is an extremely valuable study because it is critical for the improved understanding of extensional deformation model of the South-Eastern Caucasus for the determination of relative seismic safety zones for people, and for public and industrial facilities. This research is attempted to detail the active fault systems and facilitate their monitoring for prediction of earthquakes, mud volcano eruptions, landslides and other geologic phenomenon. In spite of little remote sensing data has been used for such structural modeling, we can predict mud volcano eruptions interdependence with the active fault systems, and their displacement for this region and the importance of its seismic safety, makes the funding and completion of this study extremely critical for the planned Baku-Tbilisi-Ceyhan pipeline running through the region.

Fig. 3. Bands 742 (RGB) of Landsat 7. Stream appears to be flowing through a small shudder ridge, which is formed by parallel strands of major strike-slip fault. Image is approximately 17 km across. Located along the proposed Baku-Ceyhan pipeline route.

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