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Mitigating the consequences of extreme events on strategic facilities: Evaluation of volcanic and seismic risk affecting the Caspian oil and gas pipelines in the Republic of Georgia

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ABSTRACT

In this work we identify and quantify new seismic and volcanic risks threatening the strategic Caspian oil and gas pipelines through the Republic of Georgia, in the vicinity of the recent Abuli Samsari Volcanic Ridge, and evaluate risk reduction measures, mitigation measures, and monitoring. As regards seismic risk, we identified a major, NW-SE trending strike-slip fault; based on the analysis of fault planes along this major transcurrent structure, an about N-S trend of the maximum, horizontal compressive stress ($\sigma 1$) was determined, which is in good agreement with data instrumentally derived after the 1986, M 5.6 Paravani earthquake and its aftershock. Particularly notable is the strong alignment of volcanic vents along an about N-S trend that suggests a magma rising controlled by the about N-S-directed $\sigma 1$.

The original pipeline design included mitigation measures for seismic risk and other geohazards, including burial of the pipeline for its entire length, increased wall thickness, block valve spacing near recognized hazards, and monitoring of known landslide hazards. However, the design did not consider volcanic risk or the specific seismic hazards revealed by this study.

The result of our analysis is that the Baku-Tbilisi-Ceyhan (BTC) oil pipeline, as well as the Baku-Tbilisi-Erzerum South Caucasian natural gas pipeline (SCP) were designed in such a way that they significantly reduce the risk posed by the newly-identified geohazards in the vicinity of the Abuli-Samsari Ridge. No new measures are recommended for the pipeline itself as a result of this study. However, since the consequences of long-term shut-down would be very damaging to the economies of Western Europe, we conclude that the regionally significant BTC and SCP warrant greater protections, described in the final section of or work. The overall objective of our effort is to present the results in a matrix framework that allows the technical information to be used further in the decision-making process, with the goal of reducing the uncertainty in the final decision. This approach is applicable to the study of risks in other pipeline systems.

1. Introduction

Volcanic hazard assessment typically evaluates the risks posed to humans and the environment. However, the risk of volcanic activity to strategically-important human infrastructure must also be considered in hazard assessments. The volcanic risk posed to strategic pipelines, for example, was dramatically demonstrated by the 2002 eruption of Reventador Volcano in Ecuador. Lava flows from the volcano severed a Petro-Ecuador oil pipeline, producing a major oil spill and disruption of supply. The event also disrupted construction of the Oleoducto de Crudos Pesados pipeline in the same region (Porter et al., 2005). The Caspian region has the potential to become one of the major oil and gas producing areas in the world. Much of the production will come from the Baku region of Azerbaijan, in particular from the giant Azeri-Chirag-Gunashli (ACG) oil field that lies about 100 km off the coast of Baku, with about 5.4 billion barrels of recoverable petroleum.

The Republic of Georgia, situated in the central part of the Caucasian region, between the mountain ridges of Greater and Lesser Caucasus, provides a natural transportation and pipeline corridor from the Caspian region to the west. The Baku-Supsa (BS) and the Baku-Tbilisi-Ceyhan (BTC) oil pipelines, as well as the

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Baku-Tbilisi-Erzerum South Caucasian natural gas pipeline (SCP) traverse the Caspian region through the Republic of Georgia (Fig. 1). Along this corridor through Georgia, both the BTC and SCP were designed to withstand seismic events. However, there is also a potentially significant volcanic and volcano-seismic hazard (Lebedev et al., 2003; Kuloshvili and Maisuradze, 2004), and recent data indicate that the hypothesis of a renewal of volcanic activity in the area cannot be ruled out (Chernyshev et al., 2006). Lava flows, tephra fall, landslides, and other volcanic hazards differ in their effect on surface facilities from the risks analyzed in the original design.

The likelihood of future volcanic, seismic, and related geohazards along the right of way for these strategic pipelines threatens these vital energy links. In addition to the risk of interrupted oil and gas supply, accidental releases could affect the springs and groundwater that supports the Borjomi bottled water industry in the area, as well as significant flora and fauna resources in the support zone of Borjomi-Kharagauli National Park (Blatchford, 2005).

Despite these threats, the nature of the volcanic and seismic hazard and corresponding mitigation measures have not yet been developed and understood. During a NATO-funded, two-year research project, we attempted to fill this critical gap through an international scientific cooperation aimed at assessing the volcanic and seismic risk in the Georgian section of the Caspian oil and gas pipelines and evaluating the need for additional protective measures for mitigating the consequences of potential volcanic and seismic events. We conducted our assessment of volcanic and seismic hazard in key areas of the active Abuli Samsari Volcanic Ridge (southern Georgia) by integrating the data derived from previous geologic, volcanologic, petrologic, radiometric and remote sensing works with our own data, collected during field surveys aimed at identifying the control of tectonics on the evolution of volcanism in the area.

The potential for an awakening of volcanic activity along the Abuli Samsari Ridge was not considered in the pipeline design, and the potential magnitude of seismic event and failure planes were not known with certainty. More recent study has identified the potential for both volcanic and seismic events at the northern end of the Abuli Samsari Ridge, and this study brings together the data in order to evaluate the adequacy of the existing pipeline protective measures to withstand the consequences of these events.

The potential need for enhanced pipeline design features or additional risk mitigation measures is frequently derived from analysis of compilations of accident data (for example, US DOT, 2005), supplemented by negotiated agreements with stakeholders and government agencies. This was the approach followed by BP in the design and construction of the BTC and the SCP pipelines (Blatchford, 2005). This approach is also well illustrated by the work done to support design and construction of the Trans-Alaska Pipeline (Johnson et al., 2003; Cluff et al., 2003) and the Sakhalin pipeline (Sakhalin Energy, 2010). These studies considered seismic risk and other geohazards, including post-construction pipeline evaluation following large earthquakes. This paper proposes a more transparent risk communication method for presenting the results of risk assessments, which allows a greater use of scientific information in the final decision-making process regarding acceptability of risks and consequences. The overall objective of this paper is to quantify the volcanic and seismic risks based on the previous literature and new field information, and to provide a risk management tool consisting of a matrix that ranks risks and mitigation strategies to reduce risks that is applied to re-evaluate the adequacy of the design and operation of the pipeline in light of the new risk assessment.

2. Geological and structural framework

The Republic of Georgia and nearby territories of Armenia, eastern Turkey, and northwest Iran represent a seismically active, geologically complex area located in the Alpine–Himalayan fold-thrust belt. From north to south, this area includes the following structural domains: The Greater Caucasus, the Transcaucasus, the Lesser Caucasus suture zone, the Izmir–Ankara–Erzincan suture zone, the east Anatolian microplate, the Bitlis-Zagros suture zone, and the Arabian plate (Fig. 1). The formation of this complex domain is related to the convergence and continental collision between the Arabian and Eurasian plates; some studies suggest that this continental collision began as recently as 10 Ma (Sengör and Kidd, 1979) or 5–3.5 Ma (Philip et al., 1989). The collision resulted in the lateral ejection of the Anatolian block westward and the Iranian block eastward (Ketin, 1948; McKenzie, 1972; Sengör and Kidd, 1979; Jackson and McKenzie, 1984; Dewey et al., 1986; Taymaz et al., 1991). Along with this process of lateral extrusion,

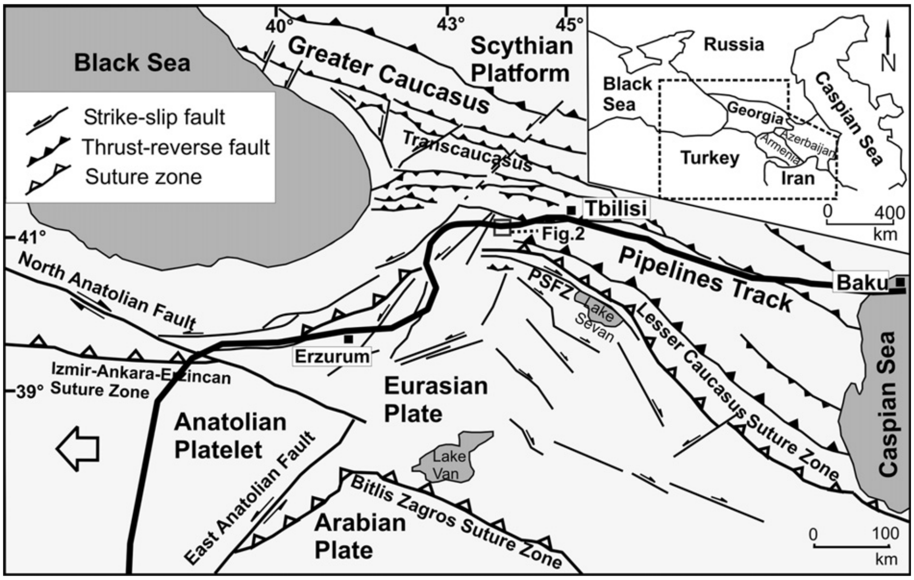

Fig. 1. Geodynamic framework of the Caucasian area with indication of BTC and SCP pipelines track. PSFZ = Pambak-Sevan Fault Zone. Redrawn after Koçyigit et al. (2001).

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there has been the compression of the region placed between the northern tip of the Arabian plate to the south and the Eurasian plate to the north. A few studies based on the estimated sum of the seismic moment of earthquakes (Kostrov, 1974; Molnar, 1979) yielded an average value of 1.3 mm/year shortening rate in this sector of the Alpine belt (Philip et al., 1989; Jackson, 1992). In comparison with the Arabian–Eurasian convergence rate (estimated at 20–30 mm/year), it can be suggested that 80–90% of the deformation is a seismic (Chase, 1978; Minster and Jordan, 1978; De Mets et al., 1990).

One of the characteristics of the Caucasian region is the complexity of its present-day tectonic setting, dominated by an association of both compressive E-W striking thrusts and folds and N-S directed normal faults and dykes, accompanied by Neogene to Quaternary volcanism. Moreover, there are also NE-SW left-lateral, and NW-SE right-lateral strike-slip faults (Rebaï et al., 1993; Koçyigit et al., 2001).

The dominant tectonic structure in the Lesser Caucasus is the Pambak–Sevan Fault Zone (PSFZ in Fig. 1), a 300 km long, 10 km wide and NW-SE trending dextral strike-slip fault zone located along the southern front of the Lesser Caucasus (Philip et al., 2001). One of the best-known and recently active compressional structures in the Lesser Caucasus is the Spitak reverse fault, located just south of the west-northwestern sector of the PSFZ (SP in Fig. 1). It is a 20 km long, 70° NE-dipping fault that produced the M 7 Spitak earthquake in December 1988 that devastated northern Armenia. According to Trifonov et al. (1990), the rupture was up to 37 km long, with maximal vertical and lateral offsets of about 1.8 m each.

Considering the study area in the Lesser Caucasus for this paper, the 2500 km^2 Javakheti plateau is located in the central part of the Lesser Caucasian mobile belt and forms a 1500–2000 m highland, with up to one hundred major and minor volcanic centers (Tutberidze, 1994; Lebedev et al., 2003; Kuloshvili and Maisuradze, 2004; Chernyshev et al., 2006). The youngest volcanic system in the Javakheti plateau is the centrally-located, 40 km long, Abuli Samsari Volcanic Ridge. This ridge includes more than 20 volcanic centers (Lebedev et al., 2003).

Rebaï et al. (1993) investigated the relationship between tectonics and recent volcanism in the Lesser Caucasus including the Javakheti area, bordered to the south by the PSFZ and composed of the Javakheti Ridge and the Abuli Samsari Volcanic Ridge (Fig. 2). Through observation of SPOT images, they identify the main structures in the Abuli Samsari Ridge and describe N-S directed dip-slip faults, NW-SE striking right-lateral strike-slip faults, as well as NE-SW directed faults, which they assume to be left-lateral strike-slip ones.

3. Design of the Caspian pipelines

The BTC and SCP pipelines traverse the same route through the Republic of Georgia along a section of 248 km (Fig. 1). They are parallel, separated by approximately 20 m. For 70 km of this route, the pipelines lie within the northern part of the Javakheti recent volcanic province. Four pipeline corridors were considered through Georgia during the siting studies. The primary environmental concern through the selected route is the Borjomi area, which is a world-famous area for natural spring water; an oil spill may reach the Borjomula River, which would cut off community water supplies and have ecological impacts between the spill site and the river.

Owing to the water quality concern of the Borjomi area, and the biological resources in the support zone of Borjomi-Kharagauli National Park in the segment between Tskhratskharo Pass to Kodiana Pass, the typical protections provided in pipeline design were enhanced. The Abuli Samsari volcanic ridge is also included in this pipeline segment. During the design phase of the BTC and SCP pipelines, including discussions with the Government of Georgia, the following additional safety measures were provided in this segment:

1. Double the number of block valves required by international pipeline construction codes to isolate sections of the pipeline.
2. Increased pipe wall thickness.
3. Use of trench backfill consisting of rounded granular material to allow flexure.
4. Enhanced sensor systems (wavy wire and fiber optic sensors) to detect any earth movements, illegal excavation, or damage by third parties.
5. Additional route markers.
6. The use of marker tape in the trench with an electronic alarm to detect breakage/interference to alert people digging near or on the pipeline.
7. A permanent local security presence, equipped with all terrain vehicles and communications systems, to conduct daily monitoring and horse patrols.
8. All weather access roads for daily monitoring and emergency response.
9. Locally recruited, internationally trained oil spill response personnel and permanently located equipment.

Field inspection of the facilities conducted by our team verified that these components were in place and active.

At the time of pipeline design and construction, the Abuli Samsari Ridge was thought to be inactive, posing only a general seismic risk and landslide risk. However, recent work has shown that the area is volcanically active, and that the most recent flow is adjacent to one of the valve stations of the BTC pipeline.

4. Structural analysis and seismic hazard assessment

Some observations on the study area are described in the work of Koçyigit et al. (2001). They propose that the neotectonic regime of the area is marked by a strike-slip-dominated compressional-extensional regime, which started in the Pliocene. According to the authors, the major structures are represented by NW-SE to NE-SW trending conjugate sets of right-lateral and left-lateral, strike-slip faults, N-S to NNW-trending normal faults, fissures, and associated Plio-Quaternary volcanoes.

We focused most of our attention on a major, NW-SE striking fault which we were able to trace in the field for a length of about 25 km, as illustrated in Fig. 2. Three natural dam lakes formed along the fault; two of them are dried up, whereas Sagamo Lake (Fig. 2) is still present. This fault was first recognized on SPOT images by Rebaï et al. (1993) who observed, on the southeastern extremity of the fault, the shift of two rivers suggesting, in terms of morphostructural evidence, a major right-lateral, strike-slip component. The cumulative horizontal offset of stream channel measures about 1 km. However, Rebaï et al. (1993) did not conduct detailed structural surveys of the fault. We performed structural field surveys aimed at recognizing the evolution of the fault kinematics and deriving stress tensor orientations. We made measurements of the fault at several stations (continuous observation of the fault was hindered by the thick vegetative cover); we provide here the results of the two structural stations where the clearest fault planes were exceptionally well exposed and could be measured in extreme detail. The stations numbered as 1 and 2 in Fig. 2 are located at the SE and NW tips of the fault zone, respectively.

At station 1 we observed very steep fault planes with slickensides revealing two components of movement: an older normal component (with striation pitches close to 90 °), upon which

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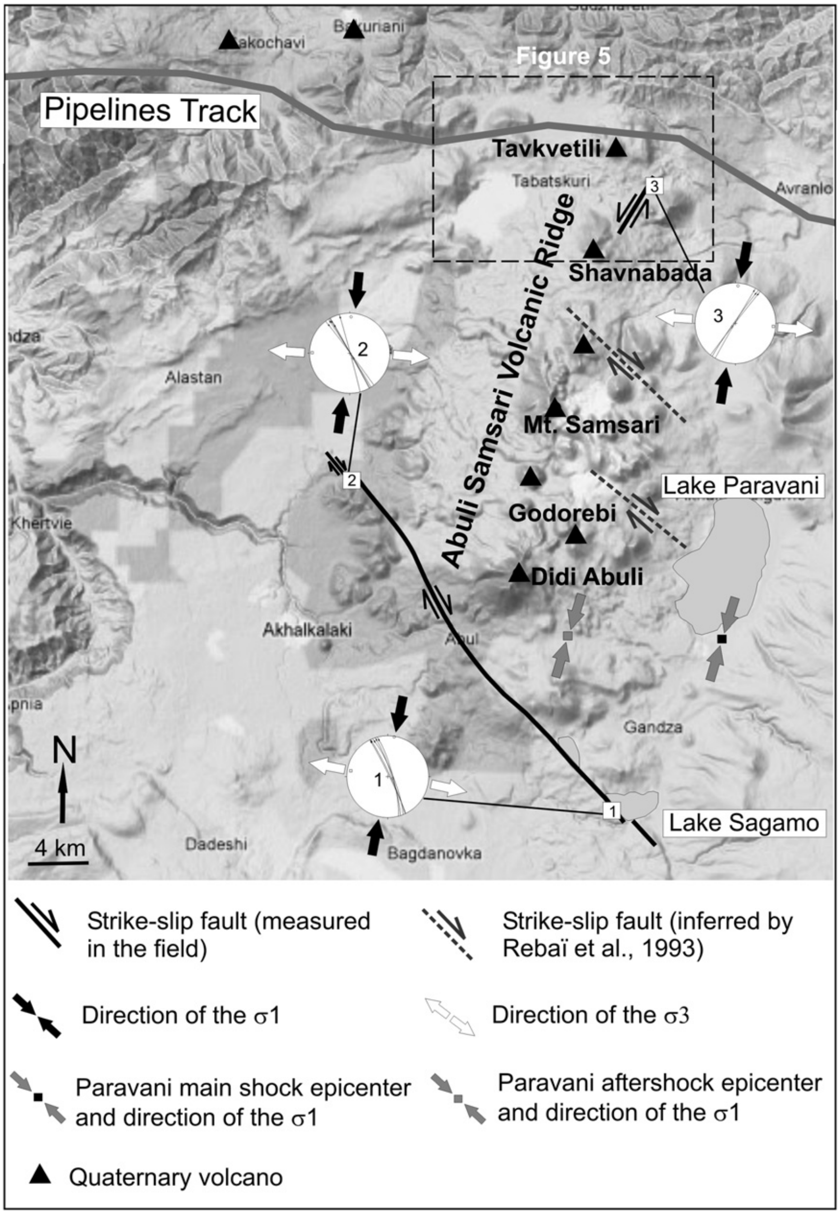

Fig. 2. Map of the Abuli Samsari Ridge showing fault plane stereograms along the main faults with indication of the related stress regime; it is possible to observe the about N-S trending alignment of the Quaternary volcanoes, correspondent to the inferred direction of the σ1. The numbering in the stereograms refers to the structural field stations where data were gathered.

a younger, right-lateral, strike-slip one is superimposed. Stereogram 1 in Fig. 2 shows stress tensor calculations based on the younger striations found at station 1, that indicate almost pure strike-slip movements on the fault plane.

At station 2, we found outstanding evidence of strike-slip movements along the fault, expressed through a series of major fault planes (Fig. 3) that indicate, according to the freshness of the slickensides, recent activity. Stress tensor computations (stereogram 2 in Fig. 2), indicate an approximately N-S directed σ1. We were not able, due to the lack of suitable outcrops, to confirm the continuation of this structure NW of station 2. However, the observation and interpretation of a Digital Elevation Model of the area allows us to suggest the NW-ward prolongation of the fault track based on morphological evidence (Fig. 4).

Moreover, in the Tavkvetili area, which is closer to the pipeline track (3 km away from it) we measured a NE-striking strike-slip fault (station 3 in Fig. 2), which was already recognized by Rebaï et al. (1993) based on SPOT image observations. Our measurements on the steep fault planes with clear striations indicate that this is a left-lateral, strike-slip fault. The related horizontal compressive stress (σ1) (stereogram 3 in Fig. 2) is again in good agreement with the results from the NW-directed, right-lateral fault.

The results of our computations from the three stations (Fig. 2) may be related to the direction of the maximum horizontal compressive stress instrumentally derived from the Paravani earthquake of May 1986 (and its aftershock), as reported on the World Stress Map (WSM) database (Heidbach et al., 2008). The WSM database provides, for this earthquake and its aftershock, a trend of the maximum σ1 that is about N-S directed (Fig. 2). The average direction of the σ1 derived from stress computations on our structural stations is hence in very good agreement with the WSM data. The M 5.6 Paravani earthquake, with a source depth at

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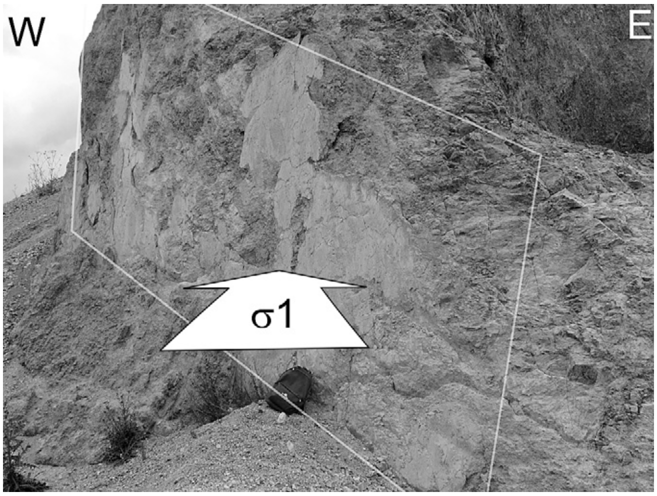

Fig. 3. Station 2. Picture of the NW-directed fault plane and indication of the σ1 direction. Backpack for scale. The lava unit displaced by this fault plane was dated (Lebedev et al., 2003) to 760,000 yr. Immediately north of this outcrop, the fault affects alluvial sediments that are most likely Holocenic in age.

12 km and produced by a strike-slip tectonic regime (WSM data, Heidbach et al., 2008), is the largest historical event in the Abuli Samsari area. The triggering fault for this event has not been defined (Borissoff, 1988). We believe that a structure belonging to the fault system we documented in Figs. 2–4 might be regarded as the cause for the seismic event of 1986, based on the following considerations: i) the Paravani lake area, where the earthquake and its aftershock (Fig. 2) were recorded, is less than 5 km from the main fault segment we identified in the field; ii) no other fault in the area is comparable to this system both in terms of persistence in length (45 km from the Sagamo Lake area to its NW, inferred tip in Fig. 4) and freshness of the fault planes (e.g., Fig. 3). In Fig. 2 we have drawn also another two, lesser fault segments close to the Paravani Lake, which have been identified by Rebaï et al. (1993) based on SPOT image observations and interpreted as right-lateral, strike-slip faults. These might also be regarded as possible triggering structures of the Paravani Earthquake; if this was the case, their trend and kinematics are once again compatible with an about N-S directed σ1.

We believe this strike-slip stress regime (and the related trend of the σ1) can indeed be regarded as the one affecting at present the pipeline area. Moreover, if our inferred 45 km long fault (Fig. 4) should rupture along its entire length, it would produce a much greater event in terms of magnitude, than the Paravani earthquake. By using the Regressions of Rupture Length and Magnitude for strike-slip faults, as indicated by Wells and Coppersmith (1994) we calculate a moment magnitude 7 for this worst-case scenario earthquake. We discuss the implications of this scenario in section 6.1.

5. Volcanic evolution and hazard assessment

The studies of Neogene-Quaternary volcanism of Lesser Caucasus have a long history (Gamkrelidze, 1949; Skhirtladze, 1958; Tutberidze, 1994; Kuloshvili and Maisuradze, 2004; Chernyshev et al., 2006). In the study area, two main phases of volcanic activity built the Pliocene-early Pleistocene Javakheti plateau, composed of basaltic lava flows, about 300 m thick, and the superimposed late Pleistocene-Holocene Abuli-Samsari Ridge (Fig. 2). The most prominent volcanoes in this range are Didi Abuli (3300 m asl) and Samsari (3284 m asl) (Fig. 2). The products erupted are mainly lavas (andesite to dacite) and very subordinate pyroclastics. Some isolated volcanic centers with geochemical characteristics and age similar to the Abuli-Samsari Ridge were active in the Bakuriani-Borzhomi area, north of the main volcanic chain (Fig. 2; Lebedev et al., 2009).

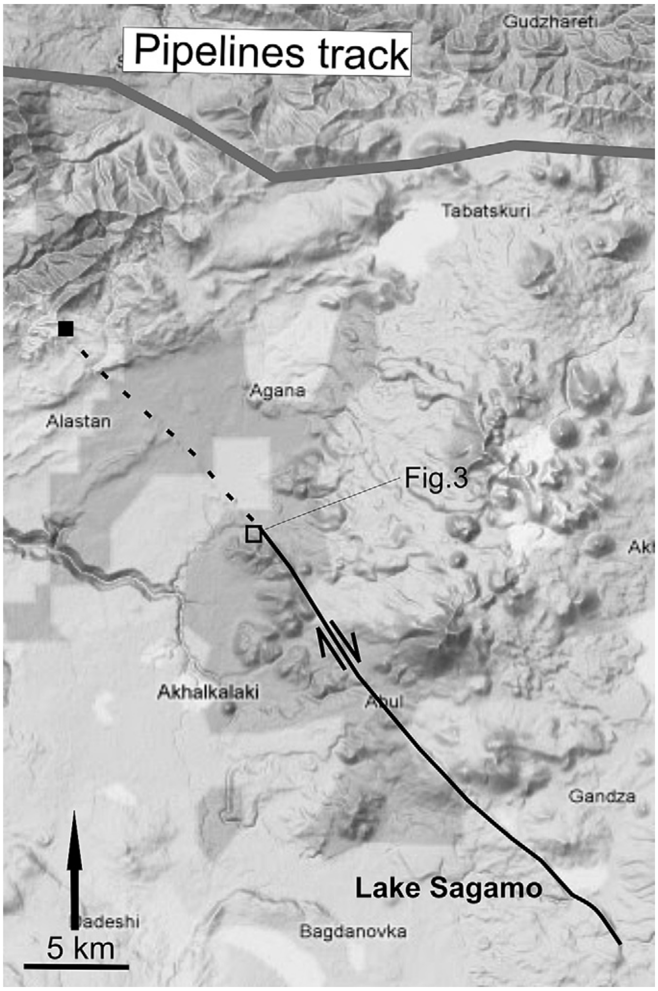

Fig. 4. Digital Elevation Model of the area with morphological evidence of the NW-ward prosecution of the main, right-lateral, strike-slip fault. Dotted line depicts the inferred prosecution of the fault. Black square indicates the worst-case scenario epicenter. See section 6.1. for explanations.

Based on K-Ar dating, Lebedev et al. (2003) identified four intervals of late Pleistocene-Holocene volcanic activity on the Abul Samsari Ridge: (I) 800–700 ka; (II) 400 ka; (III) 320–170 ka, and (IV) Late Pleistocene-Holocene (less than 50 ka) comprising the youngest Tavkvetili volcano (younger than 30 ka) (Figs. 2 and 5). The main structural characteristic of the Abuli-Samsari Ridge is the strong alignment of volcanic vents along an about N-S trend (Fig. 2) that suggests a magma rising controlled by the about N-S-directed maximum horizontal stress (σ1) inferred by our stress analysis on the fault planes measured in the field.

At the northernmost edge of the Abuli-Samsari Ridge, extremely close to the pipeline corridor, particularly notable are Tavkvetili and Shavnabada volcanoes (Figs. 2 and 5). Tavkvetili volcano is a scoria cone, up to 2582 m asl in elevation, with a well-preserved summit crater, 200 m in diameter. Several lava flows were outpoured from the vent and flowed northward and southward as far as 4 km away from it (Fig. 5). Tavkvetili dacite is aphyric with a glassy black groundmass; the lava flows are a few decimeters to meters thick. These textural characteristics suggest that this lava had a low viscosity during emplacement. Shavnabada volcano is located 6 km

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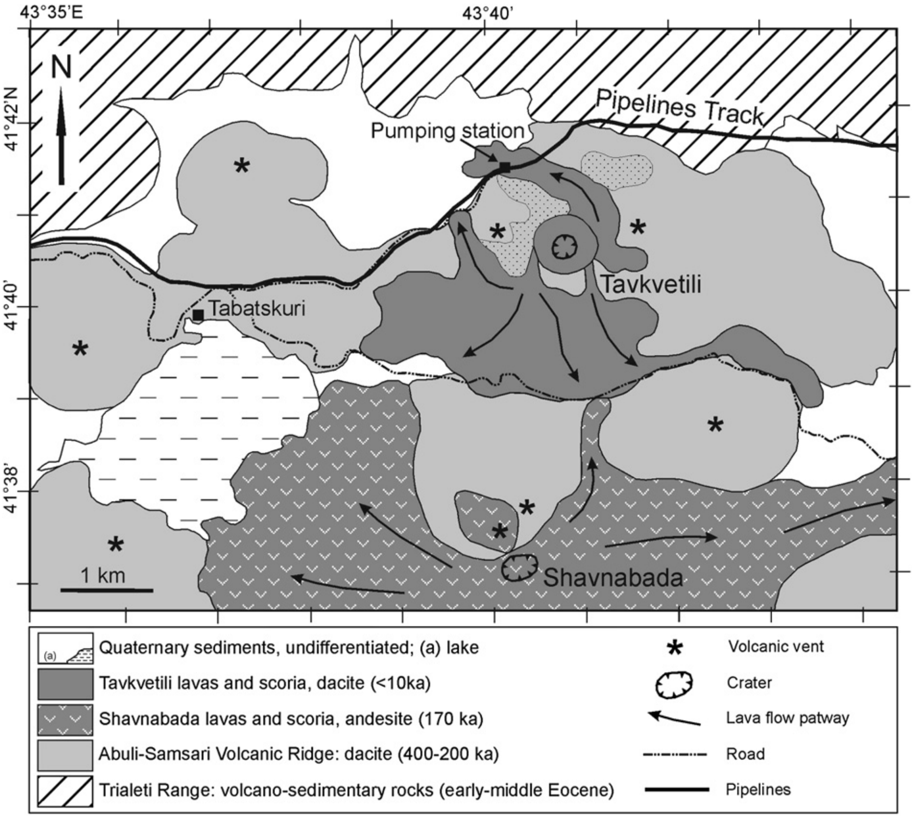

Fig. 5. Geologic map with local track of the pipelines, location of the pumping station, Tavkvetili volcano and its more recent lava flow. Ages from Lebedev et al. (2003).

south of Tavkvetili and shows two vents (Fig. 5). The northern vent produced a scoria cone, up to 2929 m asl in elevation. The southern vent is a small shield cone with a distinguishable summit crater and radial lava flow field. Shavnabada andesite is also aphyric with a glassy black groundmass. Tavkvetili and Shavnabada are among the youngest volcanoes of the Abuli-Samsari Ridge (Lebedev et al., 2003). Also our geomorphologic observations indicate the absence of periglacial activity on slopes and the well-preserved summit craters suggest that volcanic activity probably postdates the last glacial retreat (<10,000 a BP).

Based on the results of our structural study, we believe the about N-S directed σ1 has major implications for volcanic reactivation, that might occur in the form of fissural eruptions and successive growth of localized vents along an about N-S tectonically-controlled direction. Since the pipeline right of way is immediately north of Tavkvetili Volcano, there could be increased volcanic risk that was not addressed in the initial design.

6. Risk response measures

The original design of the BTC and SCP pipelines included mitigation measures for geohazards, including the additional measures described in Section 3 for the segment between Tskhratskharo Pass to Kodiana Pass, which includes the Abuli-Samsari volcanic ridge. However, the original design of the pipelines did not consider volcanic risk, or the specific seismic hazards revealed by this study. This section presents a framework for considering the newly-identified geohazards to the existing pipelines, and for determining the need for additional mitigation measures.

Most geohazard risk assessments have converged to the approach of identifying the likelihood of an adverse event, and the consequence of that adverse event occurring (Ball and Floyd, 1998; Sweeney, 2005; Rizkalla, 2008). Design measures, mitigation measures, or contingency plans are developed that can address these consequences, and the decision whether or not to implement them is typically a group decision made by the builder/operator of the infrastructure, government agencies with jurisdiction over the project, and local stakeholders including national or international non-government organizations (NGOs). The objective of this section is to present the results of the risk assessment for this section of the BTC and SCP pipelines in a framework that allows the technical information to be used further in the decision-making process, with the goal of reducing the uncertainty in the final decision. Here we work toward simplifying the presentation of results, enhancing their use in resolving stakeholder disputes with technical analysis rather than argument.

The most common tool for this type of risk assessment is the frequency-consequence, or FN, curve (Ball and Floyd, 1998). FN curves are developed as log–log plots with the abscissa (*x* axis) representing the scale of the consequence in terms of number of fatalities or some other harm, and the ordinate (*y* axis) representing the frequency with which the number of fatalities (or other harm) occur. Although widely used, it is generally accepted that FN curves can be difficult for the general public, and indeed non-risk experts, to understand (Ball and Floyd, 1998). Societal risk decisions are of crucial importance because they shape the location and design of strategic infrastructure, and as such the risks that society is willing to accept. We agree with Ball and Floyd (1998) that at this time more attention should be paid to improving the utility of scientific and technical data in decision making, before the mathematical basis is pushed further.

For this geohazard risk analysis, we explore the use of a risk matrix for presenting the results of the hazard assessment. This approach ranks the risks according to the likelihood and

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consequences of an event by a simple scale, such as extreme, medium, or low. Each threat is assigned to a cell of the matrix based on its likelihood and consequence. Effects with both a high likelihood and a high consequence receive a higher priority for risk reduction, mitigation measures, or monitoring. Although the use of the matrix is a simplified approach, the approach presents an easy-to-understand framework for decision making.

6.1. Geohazard and mitigation risk matrix

The following new geohazards, not previously considered in pipeline design in the Caucasus, have been identified in the Abuli Samsari Ridge area:

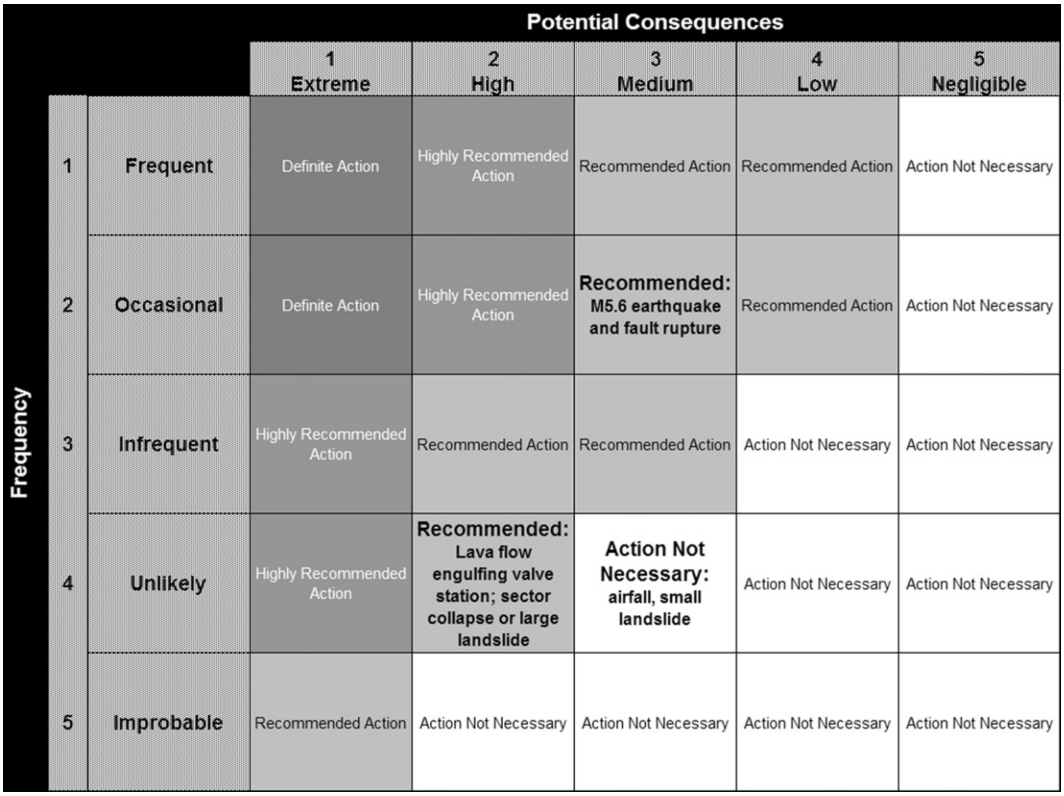
a) Seismicity, including shaking, fault rupture, liquefaction, and subsidence.
b) Volcanic activity.
c) Landslides/mass movement.

For these identified hazards, various types of responses are available, as follows:

a) Risk Reduction Measures: Design measures that reduce the likelihood of an adverse consequence.
b) Mitigation Measures: Infrastructure or design features that reduce the consequence of a geohazard.
c) Monitoring Measures: Monitoring activity to determine when an adverse event is happening, or is imminent. Monitoring measures frequently have contingency measures that can be implemented once an event occurs.
d) Further Analysis and Field Investigation: More detailed study to better quantify the risk before requiring any measures.

For this analysis, we have used a matrix approach to evaluate the need for additional mitigation measures on the Caucasus Pipelines traversing the Abuli Samsari Ridge (Fig. 6).

The vertical axis of Fig. 6 represents the frequency of a particular hazard, with 1 corresponding to a frequent event (repeatedly within 100 years), 2 corresponding to a occasional event (once within 100 years), 3 corresponding to a infrequent event (once within 1000 years), 4 corresponding to an unlikely event (once within 10,000 years), and 5 corresponding to an improbable event (greater than 10,000 years). The horizontal axis corresponds to the consequences of a possible event, with 1 corresponding to extreme consequences, 2 corresponding to high consequences, 3 corresponding to medium consequences, 4 corresponding to low consequences, and 5 corresponding to negligible consequences. Rating consequences differs for effects to humans, to the environment, to physical structures, or to the reliability of water, electricity, and fuel delivery. Finally, within each cell of the matrix, the priority of action recommended to mitigate the potential consequences is presented, rated as Definite Action, Highly Recommended Action, Recommended Action, and Action Not Necessary. The level of action recommended is a function of both the frequency of occurrence of an event, and the potential consequences. For example, a frequent event with extreme consequences is a definite priority for mitigation, while an improbable event with medium consequences would not require mitigation. In general, Definite and



			Potential Consequences				
			1 Extreme	2 High	3 Medium	4 Low	5 Negligible
Frequency	1	Frequent	Definite Action	Highly Recommended Action	Recommended Action	Recommended Action	Action Not Necessary
	2	Occasional	Definite Action	Highly Recommended Action	**Recommended: M5.6 earthquake and fault rupture**	Recommended Action	Action Not Necessary
	3	Infrequent	Highly Recommended Action	Recommended Action	Recommended Action	Action Not Necessary	Action Not Necessary
	4	Unlikely	Highly Recommended Action	**Recommended: Lava flow engulfing valve station; sector collapse or large landslide**	**Action Not Necessary: airfall, small landslide**	Action Not Necessary	Action Not Necessary
	5	Improbable	Recommended Action	Action Not Necessary	Action Not Necessary	Action Not Necessary	Action Not Necessary

Fig. 6. Risk/Consequence Matrix. The vertical axis represents frequency of a particular hazard, with 1 corresponding to a frequent event (repeatedly within 100 years), 2 corresponding to a occasional event (once within 100 years), 3 corresponding to an infrequent event (once within 1000 years), 4 corresponding to an unlikely event (once within 10,000 years), and 5 corresponding to an improbable event (greater than 10,000 years). The horizontal axis corresponds to the consequences of a possible event, with a 1 to 5 range of consequences. Finally, within the matrix, the priority of action recommended to mitigate the potential consequences is presented, rated as Extreme, High, Medium, and Low. In this assessment, the seismic risk and the risk of a lava flow or large landslide engulfing the valve station is a medium priority, and small landslides and airfall are rated a low priority.

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Highly Recommended actions would be implemented, and Action Not Necessary would not be implemented. Recommended Action may be implemented depending on the outcome of discussions among the pipeline operator, government agencies, and stakeholders.

In addition, the consequence analysis can be modified by considering vulnerability (Fell et al., 2005). Vulnerability is the degree of loss to infrastructure within the areas affected by geohazards. Vulnerability of a pipeline element, for example, is an expression of the element's capacity to withstand a hazard occurrence. This term is taken into account in order to determine whether or not a particular hazard occurrence is of sufficient magnitude to affect pipeline element integrity. When considered together with the frequency of a geohazard, the susceptibility of the pipeline to damage from a geohazard results.

For the newly-identified volcanic hazards along the Abuli Samsari Ridge, the frequency of volcanic eruption is approximately one in 10,000 years, corresponding to an unlikely event. Most events, such as volcanic airfall of tephra, small volcanic-induced landslides, and low-magnitude earthquakes, have a medium to low consequence. In addition, the block valves, including the ones in the vicinity of Abuli Samsari Ridge, are housed in bunkers referred to as local equipment rooms (LER) that protect the gears, monitors, and valves. The LER would also provide protection against light ashfall from the adjacent active Tavkvetili volcano. Therefore existing, enhanced, risk reduction measures on the BTC and SCP pipelines (buried, increased wall thickness, bunkers over block valve stations) reduce the vulnerability of the pipeline to these types of volcanic risks, and reduce the consequence to low. However, a lava flow reaching the pump station or large-volume sector collapse would have medium to high consequences. In the event of a lava flow or landslide burying or destroying the valve station, existing valves would close and shut off the pipeline. These existing mitigation measures would place the pipeline in a safe condition with respect to consequences to humans or the environment. However, oil supplies passing through the area would be interrupted until such time as the affected portion of the pipeline could be re-routed. This reconstruction of the pipeline could last for months, but probably less than a year. Therefore, the pipeline is only moderately susceptible to long-lasting damage from the geohazards newly-identified in this paper. These events would lead to a Recommended Action priority of applying mitigation, and is considered further in the next section.

The seismic risk would correspond to an event up to moment magnitude 7. If the rupture was triggered from the norwestern tip of the newly-mapped fault (black square in Fig. 4), the vicinity of the epicenter to the pipeline track would be 12 km. Using the empirical relationships provided in Newmark and Hall (1987) results in a predicted horizontal ground acceleration of 3.9 m/s^2 and oscillatory motions ranging from 0.1 to 0.3 m at the pipeline's nearest point to the epicenter. The frequency of this event is not known with certainty but is likely to be once in approximately 100 years (Borissoff, 1988). The consequence of this event would be triggering the automatic block valves and shutting the pipeline until inspection and repairs are made. In addition, the existing, enhanced risk reduction measures on the BTC and SCP pipelines reduce the vulnerability to the seismic risks. Given the enhanced risk reduction measures, the distance between the pipeline and receptors of concern (Blatchford, 2005), as well as the close block valve spacing in this pipeline segment provided to reduce the size and therefore consequence of a spill, we rate this a medium consequence.

6.2. Use of risk matrix to determine need for additional risk reduction or mitigation

Current standards for pipeline design require mitigation measures for known hazards that may occur during the working life of the pipeline. For example, third-party damage can be expected during the life of the pipeline, and to protect against the damage that results from an oil spill, designers usually place automatic block valves at river crossings and population centers to allow rapid shut-down of the line and minimizing the volume of oil lost. The design may also increase the wall thickness to withstand some strain from a seismic event, reroute the pipeline, or apply other mitigation techniques (Cluff et al., 2003; Johnson et al., 2003; Sakhalin Energy, 2010). As described in Section 3, the BTC and SCP were constructed with numerous safety enhancements beyond those required by current standards of pipeline design.

The result of this analysis, described in the previous Section, is that no additional mitigation measures for the pipeline itself are recommended to address these newly-identified geohazards. The existing design incorporates the elements that may have been recommended for the seismic risk or the volcanic risk of airfall and small landslides (increased wall thickness, increased number of block valves, high-quality access roads for response, and protective structures covering the block valves, among others) have already been implemented and are in good order based on our review.

Although the risk assessment does not recommend additional protections for the pipelines, the scenario of a lava flow or large landslide engulfing the valve station is prioritized as a Recommended Action. Typically, this priority would not necessarily require action. However, loss of this strategic pipeline corridor for up to a year as a result of a volcanic eruption may not be an acceptable outcome. As regards seismic rupture, this would have less of a supply impact in terms of the longevity of consequences, because repair works could start immediately. In the former case, we would recommend actions to shorten the time during which the pipeline is out of service. This mitigation measure would be to enhance the road network to support reconstruction. The existing pipeline service road system is well-maintained and currently adequate for this purpose. However, the road system leading to the service roads would require upgrading to support the necessary equipment. This upgrade could be conducted in the near future, or be considered as part of the contingency measure to be implemented in the event of loss of this section of the pipeline to a volcanic or seismic event.

7. Conclusions

This study has identified and quantified new seismic, volcanic and related geohazards along the Abuli Samsari Ridge that were not specifically considered in the original design of the BTC and SCP pipelines. The age of volcanic centers in the Abuli Samsari Ridge is younger toward the north, and hence toward the pipelines. A young, <10,000 y lava flow from Tavkvetili Volcano is adjacent to an automatic block valve station for the BTC. Our study has shown that the section of the pipeline route in the Abuli Samsari Ridge area is subject to risk from new seismic and volcanic activity that was not previously recognized in the design of the pipelines.

The result of the analysis is that the BTC and SCP were designed in such a way that the risk posed by the newly-identified geohazards in the vicinity of the Abuli-Samsari Ridge was reduced significantly. No new measures are recommended for the pipeline itself as a result of this study. The regionally significant BTC and SCP may warrant greater protections, since the consequences of long-term shut-down in the event of a lava flow or large landslide engulfing the valve station would be very damaging to the economies of Western Europe. The additional protections recommended in this case would include an upgrading of the road system that leads to the pipeline service roads, in order to allow construction equipment and materials delivery. This upgrade could happen in the near future, or be considered part of the overall response action

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after a volcanic or seismic event leads to a loss of this section of the pipeline.

To our knowledge, the risk communication in this paper has not been applied to volcanic and seismic risk assessments. We believe that once the risks, damages, and costs are framed in a quantitative way, then simplified displays such as those provided here can help foster meaningful discussion about mitigation measures and provide a firm support for decisions. Moreover, we think the proposed methodology has wide applications, well beyond the geographical area we have addressed in our research.

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