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The Sivas Gypsum Karst - Implications for Routing, Construction and Operation of the Trans Anatolian Natural Gas Pipeline

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Abstract

The TANAP route runs 92 km through one of the world´s largest gypsum karst terrains, covering an area of 2140km² (Günay 2002; Doğan & Yeşilyurt 2019) located in the Turkish Province of Sivas. A fantastic place for the geologist but a big challenge for the routing and construction of a pipeline.

Based on the morphology a karst classification, comprising of 5 karst types, was set up. The development of a genetic karst model enabled the assignment of specific hazards to each of the identified karst types. These hazards comprise of collapse dolines, subsidence sinkholes, internal erosion and pinnacled bedrock. Each karst type required a specific risk mitigation depending on type and severity of the hazard, to be considered either by routing or by applying technical measures.

Construction finally proofed that the karst model was correct. This was also underlined by the discovery of a large cave on the right of way during grading works within one of two short route sections with a predicted high risk of large cavities. Detailed ground investigations were necessary to assess the irregular shape of the cave and to move the alignment to safe ground.

Experience from BTC and Nabucco Projects which also cross this gypsum karst area on different routes were highly beneficial for the successful completion of the task.

1. INTRODUCTION

TANAP aims to convey natural gas from the Caspian region via Turkey to Europe. It is part of the Southern Gas Corridor, which consists of three main elements: the South Caucasus Pipeline (SCPX) running form Azerbaijan's giant Shah Deniz gas field through Georgia to Turkey, TANAP which traverses Turkey from East to West between Posof at the Turkish-Georgian border and Ipsala at the Turkish-Greek border and the Trans-Adriatic Pipeline (TAP) starting from the Greece/Turkey border, passing through Albania and being tied to Italy through the Adriatic Sea.

The pipeline has a length of 1811 km and crosses various forms of landscapes from coastal plains to high altitude mountain ranges, climbing to an altitude of 2,750 m above sea level. The pipe diameter is 56" for the first 1338 km and 48" for the remaining 455 km up to the Greek border. The Sea of Marmara is being crossed North of the Dardanelles Strait by 2x36" pipes each having a length of 18 km. In its final extension, the pipeline system will comprise of 7 compressor stations and produce 31 bcm/a gas throughput with a design pressure of 95.5 barg.

The various landscapes encountered along the pipeline route as well as the geotectonic position of Turkey at the boundary between the converging Eurasian and African Plates and its geological history make this country almost unique in terms of type and number of terrain and ground related geohazards, including landslides, active faults, seismicity, liquefaction, lateral spreading, karst and sinkholes, soil erosion, flooding, and fluvial erosion.

This paper gives an overview over the karst types encountered along the pipeline route between the town of and focusses on the challenges of routing and construction of TANAP in the Sivas gypsum karst, one of the world´s largest gypsum karst terrains.

2. GEOLOGIC SETTING

The Sivas basin developed after the closure of the North Tethys Ocean in Upper Cretaceous to Lower Tertiary ages (Yılmaz & Yılmaz 2006). After the sedimentation of flysch like deposits in the Palaeocene and Eocene further crustal shortening resulted in uplift and the deposition of continental strata and massive gypsum which was deposited in a sabkha type environment (Hafik Formation) during the Oligocene (Ciner et al. 2002). The gypsum deposits reach a thickness of up to 500 m (Doĝan & Yeşilyurt 2004).
A number of large salt springs and diapiritic structures indicate significant salt bodies at depth. The gypsum strata are overlain by Miocene marine and Pliocene continental formations.

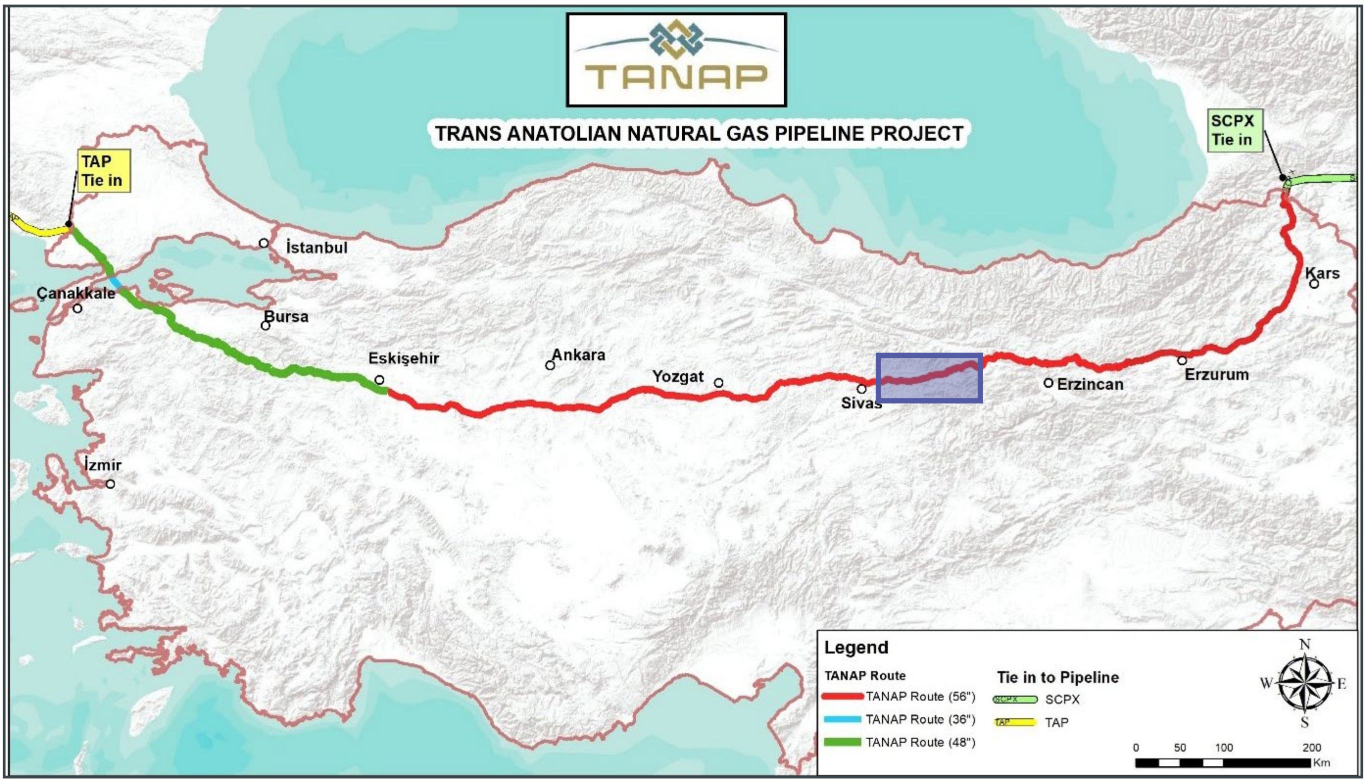

Figure 1: Overview of the TANAP route. The section where TANAP runs through the gypsum karst is marked by the blue rectangle

At present much of the gypsum outcrop is bare rock, usually weathered and fractured to a depth of several meters while large areas are covered by plastic residual clays which have been left by surface dissolution of the impure gypsum.

3. GENETIC KARST MODEL

The term karst describes landforms derived by the dissolution of soluble rocks such as limestone, dolomite, gypsum or rocksalt. Karst terrains typically have an underground drainage system. Due to the high solubility in water the karst evolution in gypsum is, unlike limestone karst, a very dynamic process.

The Sivas gypsum karst is exposed on a 280 km long and up to 55 km wide ENE-WSW trending stretch (Doĝan & Yeşilyurt 2020). Three major rivers, Kızılırmak and its tributaries Acısu and Acıçay drain the area. They act as the receiving streams for all karst groundwater of the region and thus set the base level for karstification processes. The evolution of the Sivas gypsum karst is inextricably linked with the spatio-temporal development of these rivers. Understanding the geologic history which led to the present karst topography proofed to be crucial for assessing the karst risks.

Karst formation started after the erosion of the Miocene cover sediments with the exposure of the gypsum strata. Through fissures and fractures surface water made its way underground forming a large number of solution dolines on the surface and phreatic caves at the groundwater level. Thousands of solution dolines, separated by a polygonal net of low interfluve ridges developed on the gypsum platforms (polygonal karst).

The Proto - Kızılırmak and its tributaries which had their sources outside the karst terrain went underground as soon as they reached the gypsum. They were able to dissolve large cave chambers in massive gypsum, especially if the caves were completely water filled.

Where cave chambers exceeded a certain size and where the overburden was limited, collapse dolines formed. By the time these collapse structures expanded and eventually coalesced with nearby collapse dolines due to continued dissolution, undercutting and a long sequence of progressive breakdown failures.

The next stage of karst evolution is represented by the formation of poljes either due to expanding and coalescing collapse dolines or long lasting dissolution processes at the karst margins. Poljes can grow to huge landforms, frequently several kilometres wide. Often they contain lakes which are mostly fed by underground streams. It has to be assumed that Proto - Kızılırmak was flowing through a series of poljes which were separated by gypsum plateaus but hydrologically connected by cave systems.

Figure 2: Large river cave in the Sivas Gypsum karst

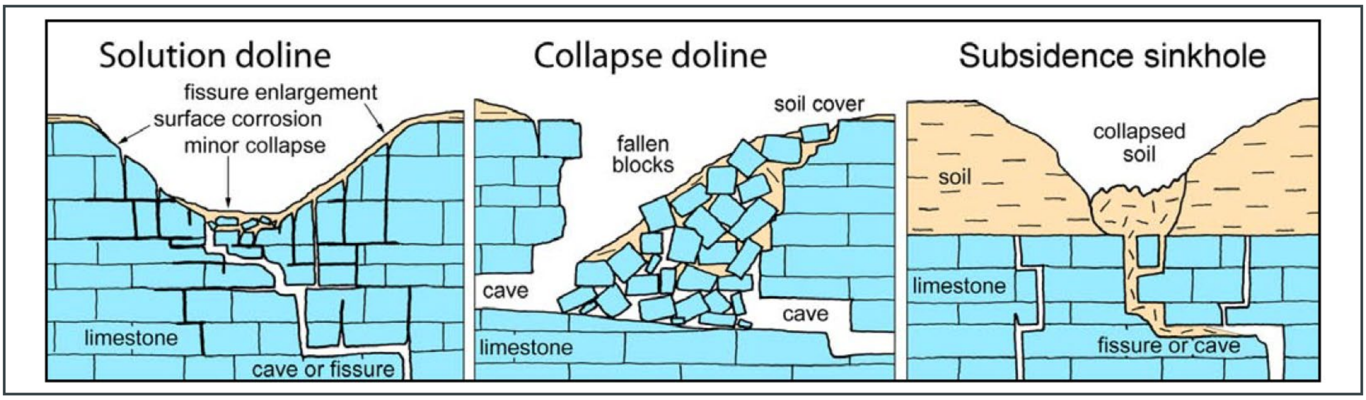

Figure 3: Main types of sinkholes found in the Sivas gypsum karst (Waltham 2013)

Continued dissolution along the active parts of these cave systems led to the last stage in the karstic surface lowering which is represented by alluviated basins hosting the current course of Kızılırmak.

Within the project area karst evolution did not take place simultaneously and at the same pace so that today all stages of karstification are present within short distance.

Based on this genetic model and the present day karst morphology a karst classification could be created which enabled the assignment of specific hazards to each of the identified karst types.

4. KARST FEATURES AND HAZARDS

4.1 GENERAL

The main geohazard in karst is represented by sinkholes, also known as dolines. The hazard is related to the development of new sinkholes which can form suddenly without any warning signs anywhere within karst terrain but also to ground movement in existing sinkholes. Pinnacled rockhead beneath the pipeline, transfer of bedding / padding material into open karstic voids and groundwater with high concentrations of sulfate and chloride are further hazards to be considered in gypsum karst.

The Karst hazard is very often not recognized or underestimated. The USGS (United States Geological Survey) estimates that sinkhole damages in the USA over the last 15 years cost on average at least $300 million per year. Much of these damages could have been avoided if a proper karst assessment had been carried out and mitigation measures taken.

4.2 SINKHOLES

Within the Sivas gypsum karst three types of sinkholes or dolines can be distinguished.

- SOLUTION DOLINES
  Solution dolines form by the dissolution of gypsum around the drainage outlet, a relatively slow process which typically lasts over several tens of thousands of years. The doline floors are frequently covered by cohesive residual soils. Commonly surface water is discharged into narrow karst fissures. Even in very old and large solution dolines the width of these fissures rarely exceeds half a meter. Thus the hazard to the pipeline is considered to be low.

Figure 4: TANAP is passing on the upper side of a large solution doline

- COLLAPSE DOLINES
  Collapse dolines occur when large, near surface cave chambers get instable and collapse. As opposed to limestone karst, caves in gypsum usually form smaller chambers. Nevertheless there are examples of more than 40 metres wide cavities in gypsum. Field mapping showed that initial collapse dolines may be up to 20m across and further widened by subsequent phases of progressive wall collapse.


Figure 5: Initial stage of a subsidence sinkhole close to the right of way (left) and an old collapse doline (right)

Such collapse events are very rare but in general impossible to predict. In addition most of these cave systems have not been explored yet and lack any surface expression.

- SUBCIDENSE SINKHOLES
  Subsidence sinkholes are being formed by a process called suffosion, i.e. the internal erosion of soil and transport into karst fissures. In cohesive soils voids of several metres across can develop. Dropout sinkholes, a special form of subsidence sinkholes may form if such a void collapses.

  In granular soils dropout sinkholes are less likely. Instead settlement will be observed on the surface. Depending on the amount of water being drained such sinkholes can develop to very large structures within short time.

  Subsidence sinkholes are common features in soil covered karst areas, especially if drainage patterns and groundwater levels are changed by construction or agriculture.

4.3 PINNACLED ROCKHEAD

In sections where the pipe trench is located within gypsum rock bedding and padding material might be washed into open voids resulting in intolerable pipe stress and dents.

5. KARST CLASSIFICATION AND KARST HAZARD MITIGATION MEASURES

Based on the genetic karst model and the geomorphological features identified through evaluation of orthophotos as well as field mapping, five karst types could be distinguished in order to define the nature, extent and scale of the prevailing karst geohazards and their impact on design, construction and operation of TANAP.

On its more than 90 km long route through the Sivas gypsum karst TANAP crosses four out of the five identified karst types.

5.1 KARST MARGIN (KG1)

This karst type occurs as narrow strips up to a few hundred metre wide along the karst margins, either at the border of poljes or along non-karstified areas where surface drainage enters the karst, forming a large number of caves and dissolution notches which undercut the steep gypsum slopes at the karst margin.

Undercutting, enhanced cave development and cliff collapse as a result of lateral dissolution processes constitute a significant geohazard.

The hazard mitigation philosophy focused on finding a safe route by assessing and avoiding potential instable cliff areas and by minimizing the crossing length of kg1 karst.

5.2 POLYGONAL KARST (KG2)

Polygonal karst is characterized by a large number of closely spaced solution dolines, in general 100 to 400 metres wide, which are separated by a polygonal network of low bedrock ridges. Typically the doline floors are covered by up to 10 metre thick cohesive soils.

Dissolution rates are low and irrelevant when compared to the lifetime of the pipeline.

Class	Karst Type	Karst Geohazard	Mitigation Measures
kg1	**Karst margin**, narrow zone along cliff line boundary	Caves and notches undercut steep slopes, increasing slope failure hazard	Minimize length within hazard zone
kg2	**Polygonal karst**, array of solution dolines separated by a polygonal net of low interfluve bedrock ridges (“egg-box” topography)	Moderate hazard of settlement and suffosional soil loss on doline floors, formation of subsidence sinkholes	Avoid crossing doline floors as far as practical, control drainage during construction, install trench breakers and seal the pipe trench bottom,
kg3	**Plateau karst**, upland and high ground with no surface drainage, with scattered large, old collapse dolines	Very small hazard of initial collapses of up to 20m wide. Higher risk on plateaus bordered by active or former poljes /alluviated basins	Control the drainage, increase pipe wall thickness to allow spanning a new collapse, ground investigations
kg4	**Immature karst,** generally on mixed rock sequences	Very small hazard, rare subsidence sinkholes	Not on TANAP route
kg5	**Mantled karst**, upland areas with thick soils over the gypsum, favored by impure gypsum or interbedded siltstone and sandstone layers, also some basins on kg3 plateaus	Small hazard of subsidence sinkholes which may grow to 10m across, pinnacled rockhead	Control the drainage, avoid hollows with internal drainage, increase bedding thickness to mitigate hazard from pinnacled rockhead

Table 1: Karst types along the TANAP route

Figure 6: Large collapsed cave at karst margin bordered by a polje

Settlement within the doline soils due to suffosion and formation of new subsidence sinkholes constitute the main geohazards within the polygonal karst. Also pinnacled rockhead has to be accounted for and, as in all other karst types where the pipe trench was excavated in gypsum rock, geotextile was used to prevent the bedding / padding from being washed into karstic voids.

The pipeline was preferably routed along the ridges between the dolines or on the doline flanks.

Where doline floors had to be crossed measures to control the drainage were implemented to mitigate these hazards.

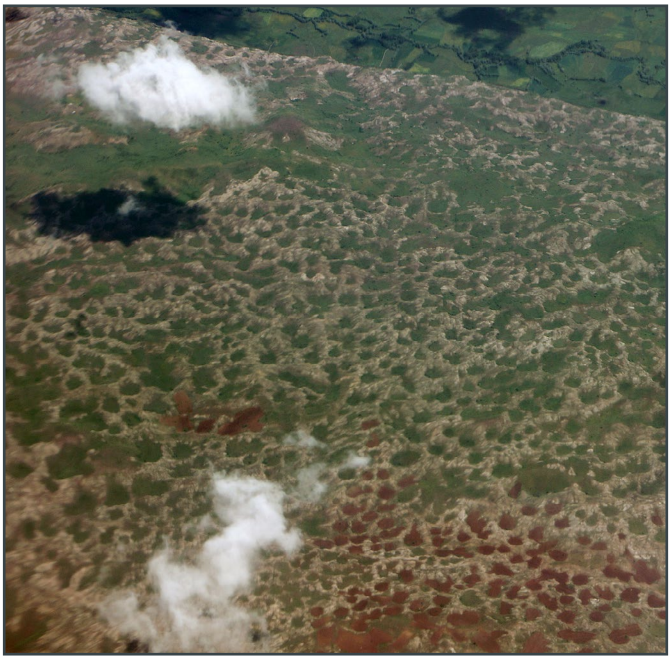

Figure 7: Polygonal karst, aerial view

Mitigation measures comprised of trench breakers to prevent water from concentrating in the trench and flowing down the internal doline slopes where it could accelerate suffosion processes and the installation of impermeable material at the trench bottom which should impede excessive water infiltration and reduce suffosion significantly.

New subsidence sinkholes within the doline soils are typically only a few metres wide at their initial stage and could be safely spanned by the pipeline.

The danger coming from pinnacled rockhead was mitigated by increasing the bedding thickness.

5.3 PLATEAU KARST (KG3)

Large collapse structures are the most striking features of these karst plateaus. The collapse dolines which are scattered over the plateau karst are up to 400 metres across and up to 50 metres deep. These are very old features, though some are still active and have lakes on their floors corresponding to the wider karst water table and the water level of the major receiving streams. Field assessments indicate that initial surface failure did not exceed 20 metres across. These collapse dolines give a good testimony of the cave chambers that have existed and most certainly still do exist in kg3 karst. They are the remnants of large water filled cave systems which originally interconnected poljes. Apart from the collapse dolines these caves have no surface expression. A new collapse could occur anywhere on these plateaus.

Large collapse events are assumed to be extremely rare. Waltham (2013) suggests that the chances of a collapse 20 metres in diameter developing beneath the pipeline during a hypothetical 200 year pipeline lifetime are no more than

Figure 8: Polygonal karst near Imranlı

1 in 2500.

Based on the genetic karst model and geomorphologic studies, areas with an elevated risk of large cavities could be identified and investigated by boreholes. Experience from the BTC pipeline which is also crossing the Sivas gypsum karst and other projects such as the Nuremberg – Ingolstadt high speed railway line (Germany) showed that the detection of cave chambers by means of geophysical methods comprising of seismic methods, geo-electric, gravimetry, geo-radar) is not very reliable. In the best case brecciated rock mass or sediment filled voids could be detected. Therefore a geophysical investigation was not taken into consideration.

Pipe stress analysis performed for all credible scenarios proofed that in the unlikely event of a cave collapse the pipe will be capable of spanning 30m wide gaps which is far beyond the maximum credible initial collapse width of 20m.

Mitigation measures aimed at avoiding karst plateaus located between active or former poljes. Where this was not possible boreholes were drilled to investigate potential large voids. During the right of way clearing and grading works near the town of Hafik it turned out that at one location the boreholes missed a large cave chamber just by a few meters.

The cave was investigated using ground penetrating radar that was limited by the high clay content and a total of 107 percussion probe drillings. Performing a survey inside the cave was not permitted for health and safety reasons.

After the cave had been opened and partly backfilled the alignment of the pipeline was shifted several metres to the North where the cave dimensions decreased and the thickness of the cave roof clearly exceeded the size of the void beneath.

Figure 9: Large cave on the right of way after grading works (left) and after it had been opened (right)

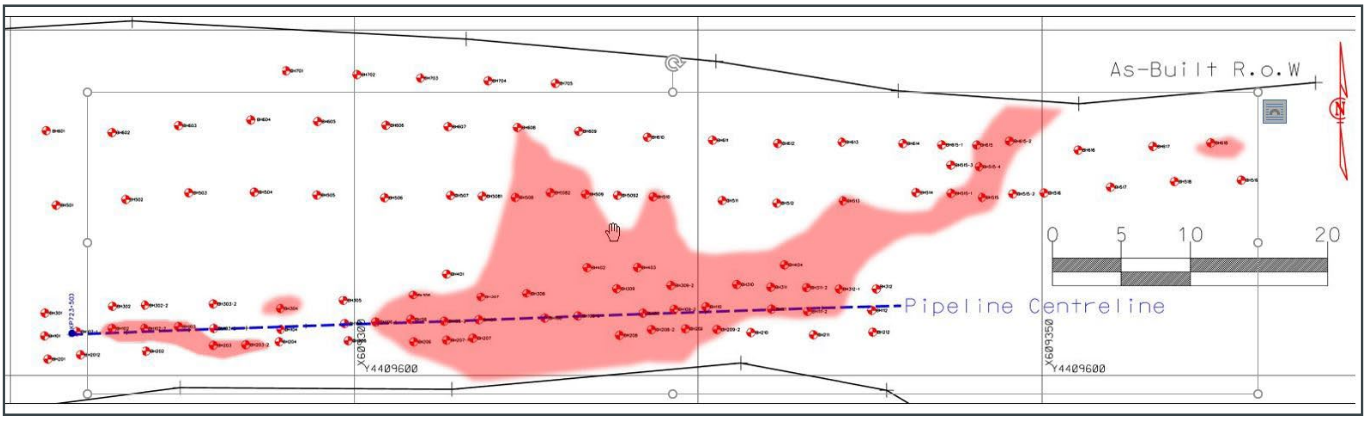

Figure 10: Approximate footprint of the cave based on the results of 107 percussion probe drillings. Red dots indicate borehole locations

5.4 MANTLED KARST (KG5)

Large areas of the Sivas gypsum karst have a thick sediment cover, either residual clays or alluvial sediments. Subsidence sinkholes are rare. Pinnacled rockhead is an issue where the soil cover is reduced.

Avoiding topographic low points with internal drainage by routing and drainage control were the most important measures applied.

6. CONCLUSIONS

The TANAP pipeline crosses one of the world´s largest gypsum karst terrains on a length of more than 90 kilometres. A genetic karst model could be developed through extensive geomorphologic studies in the field and desktop. A karst classification was set up distinguishing five karst types.

Both, genetic karst model and karst classification, served as a basis for a karst hazard assessment and the resulting mitigation measures.

Hazards mainly arise from subsidence sinkholes and to a smaller extent from collapse dolines which, despite their extremely rare occurrence pose a risk due to their potential consequences while solution dolines are irrelevant to construction and operation.

Mitigation measures ranged from avoiding areas of higher risk by routing as much as practical to simple technical solutions such as use of geotextiles to prevent bedding material from being transported into open voids or increase of bedding thickness in sections with pinnacled rockhead. Most important was the drainage control. This included measures inside the trench which should prevent the trench from becoming a new conduit as well as measures on the right of way to reinstate the original flow pattern as far as possible and to divert surface runoff away from the right of way.

Large collapse events affecting the right of way are highly unlikely to occur within the design life of the pipeline whereas the development of smaller subsidence sinkholes has to be expected. Both, collapse dolines and subsidence sinkholes are well within the spanning capability of the pipeline and will not lead to a failure.

Regular karst surveys which are carried out after snow melt and severe rainfall events in the operation phase of the pipeline shall identify potential subsidence and sinkhole development at an early stage so that remediation actions can be taken in a timely manner if required.

ACKNOWLEDGEMENTS

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