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Detecting Unstable Ground by Multisensor Remote Sensing

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Summary: Underground mass movement can cause subsidence, collapse sinkholes, and landslides at the earth's surface. We have used satellite and airborne remote sensing to investigate subsidence and collapse-prone ground resulting from the dissolving of salt in the Eisleben district in the German federal state of Saxony-Anhalt. Because the electromagnetic radiation utilized by remote sensing cannot penetrate the ground, early detection of hazardous ground by remote sensing will require "diagnostic features" which can serve as surface markers of subsurface situations, and which can be recorded by satellite and airborne sensors. We have tested the extent to which surface features can indicate subsurface mass movement. Integrated processing and interpretation of high-resolution aerial photography, airborne laser scanning and satellite imagery revealed surface features that are associated with fracturing, subsidence, and weakened rocks. Analysis of data recorded by the different types of sensors produced results with less ambiguity than obtained with a single sensor.

Zusammenfassung: *Multisensor-Fernerkundung zur Untersuchung instabiler Geländebereiche*. Unterirdische Massenbewegungen können Geländeabsenkungen, Erdfälle oder auch Hangrutschungen verursachen. Flugzeug- und Satellitendaten wurden genutzt, um durch Subrosion in Steinsalz verursachte Massenbewegungen und ihre Folgen an der Geländeoberfläche zu untersuchen. Testgebiet war der Raum Eisleben in Sachsen-Anhalt. Da die von der Fernerkundung benutzte elektromagnetische Strahlung nicht in den Boden eindringen kann, müssen zur fernerkundlichen Früherkennung von gefährdeten Bereichen so genannte „diagnostische Merkmale" herangezogen werden, welche Rückschlüsse auf die Situation im Untergrund zulassen, und von Satelliten- und Flugzeugsensoren erkannt werden können. In dieser Arbeit wurde untersucht, in wie weit unterirdische Massenbewegungen bzw. Geländeauflockerungen durch typische Oberflächenmerkmale indirekt angezeigt werden können. Durch kombinierte Verarbeitung und Interpretation von hochauflösenden Luftbildern, Flugzeug-Laser-Scanning Daten und Satellitenbildern konnten charakteristische Oberflächenmerkmale sichtbar gemacht werden, die mit einer Auflockerung oberflächennaher Gesteinsschichten und mit Geländeabsenkungen in Verbindung stehen. Die Anwendung eines Multisensoransatzes erbrachte zuverlässigere Ergebnisse als Daten eines einzelnen Sensors.

1 Introduction

The events leading to underground mass movement are various. Collapsing underground mines can lead to weakening of overlying rocks, and eventually to collapse sinkholes and land subsidence. Further reasons for the occurrence of sinkholes, subsidence and landslides are collapsing cavities formed by dissolution of soluble rocks, e.g., rock salt, gypsum or limestone. Collapse sinkholes form suddenly, whereas subsidence is a slow and mostly long, continual process. In many cases, collapsing ground and

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land subsidence cause severe damage to buildings and urban infrastructure. Prominent incidents in the recent past were the Lassing disaster in Austria in 1998 and a sequence of collapse sinkholes near the Federal Highway 180 south of Eisleben, Germany, in 2001 and 2002.

Especially in cases with disastrous consequences, questions about the efficiency of early warning systems arise. Traditional monitoring of collapse-prone ground uses field surveying methods that are based on testing and sampling at single points or along lines. The most frequently used observation method is ground-based levelling. Levelling provides precise subsidence rates for each observation point, but limited coverage of potential disaster areas. Moreover, the traditional ground-based investigations, such as levelling, drilling or other means of sampling, and geophysical surveying, often cannot be used because they would require entering hazardous areas, or the results are unreliable because the methods have to be applied from outside the area of investigation.

Adding remote sensing to the complex of observation methods would offer a chance to improve the early detection of subsidence and collapse-prone ground. In contrast to the limited field of view of a ground-based observer, remote sensing takes advantage of the overall-coverage of observation areas provided by satellites and airplanes. Furthermore, recording remote sensing data does not require entering the investigation area.

The Federal Institute for Geosciences and Natural Resources (BGR) has been working on remote-sensing-based disaster monitoring since the mid-eighties. Selected case studies on the application of multi-sensor remote sensing for detecting unstable ground above abandoned tin, potash and lignite mines have been described (KUEHN et al. 1988, 1997, 1998 und 1999). In the previous studies, we have demonstrated how distinctive alterations of the terrain, visible in remote sensing data, can be used to detect collapse-prone ground. By combining data from different sensors, we can improve the reliability of the data interpretation. In this paper we report on results of the detection and characterization of unstable ground caused by subsurface mass movement resulting from subrosion of rock salt.

Remote sensing utilizes electromagnetic radiation from the visible portion of the electromagnetic spectrum up to the microwave portion. Radiation in this part of the spectrum has wavelengths from about 400 nm to several decimetres, and therefore cannot penetrate the ground. The aim of the present study was to clarify to what extent surface features can indicate subsurface mass movement, and to test whether airborne and satellite sensors can be used to record and recognize such features. Early detection of hazardous ground by remote sensing will require "diagnostic features" which can serve as surface markers of subsurface situations, and which can be recorded by satellite and airborne sensors. Such diagnostic features are lineaments, fractures, small scarps, hummocky terrain and depressions, moisture anomalies and altered vegetation (PETERS 1988 and 1993, SINGHROY 1988, WATSON & KNEPPER 1994, KUEHN et al. 1988, 1997, 1998 and 1999). In most cases, mass movement starts at depths ranging from a few meters (e.g., near-surface mining, karst) to several 100 meters.

The initial stages of subsidence and collapsing ground are commonly indicated by the occurrence of very faint fractures in near-surface rocks. Minimal subsidence rates can often be observed over a relatively long period, before caving through to the surface finally forms a collapse sinkhole. In order to serve as an early-warning system, remote sensing sensors have to be able to detect subsidence and weakening of subsurface rock formations at the earliest stages, long before it can be observed at ground level.

2 Investigation Area

Fig. 1 shows a simplified scheme of the situation in our study area in the German state of Saxony-Anhalt (Eisleben area), where subsidence and collapse-prone ground are widespread. In the past, rock salt of the Zechstein domed up beneath the area of to-

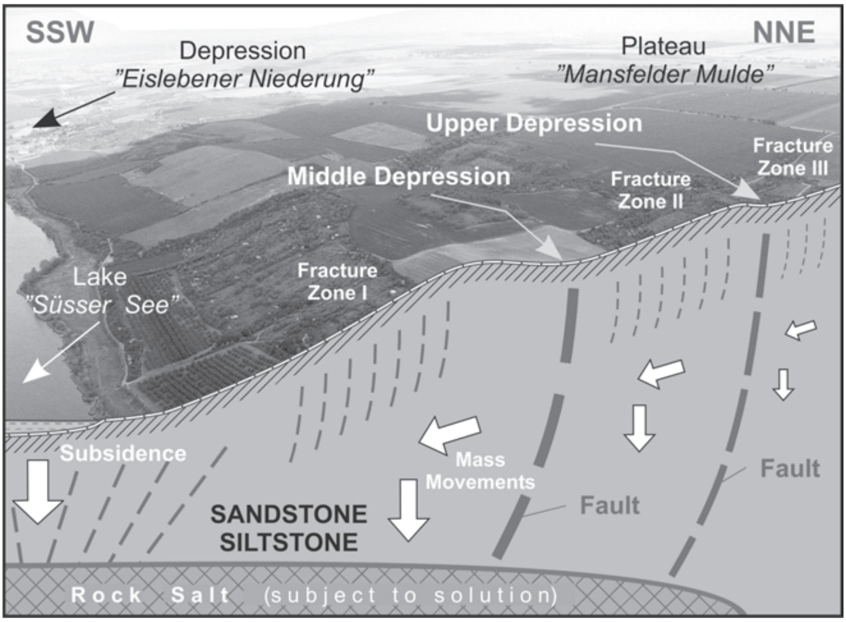

Fig. 1: Combination of an oblique aerial photograph and a simplified geological section of the study area; subsidence triggered mass movement and fracturing on the sloping ground between the ,,Eislebener Niederung'' subsidence area and the elevated ,,Mansfelder Mulde'' area (geologic section modified after v. Hoyningen-Huene 1959).

day's Eislebener Niederung. Since then, fresh water influx through fractures and abandoned copper mines has been continually dissolving salt from the top of the diapir, leading to subsidence and the formation of the Eislebener Niederung depression. The Süsser See lake is also a result of subsidence. In the elevated area of the Mansfeld syncline (,,Mansfelder Mulde") in the northeast, the rock salt is at greater depth than beneath the Eislebener Niederung and no dissolution and subsidence are apparent. The higher elevation of the Mansfelder Mulde area appears to be in contradiction to its name. The term refers to its structural-geologic character, before the subsidence of the adjacent Eisleben area led to relief inversion.

Between the subsidence area of the Eislebener Niederung and the elevated area of the Mansfelder Mulde, there is a tension zone. This tension field has affected the stability of the sandstones and siltstones northeast of the subsidence area. Fractures of different lengths and widths have formed parallel to the strike of the slope between the two areas. Blocks of rock have broken off, tilted and slid slowly towards the Süsser See subsidence area. This has resulted in an intensively fractured zone about 30 km long parallel to the top of the slope (Fig. 1). Two long, narrow depressions have developed on the sloping ground above the Süsser See depression. The first one above the lake is called the ,,Mittlere Senke" (''Middle Depression'') and contains widely opened fissures and sinkholes (Fig. 2A). The youngest fractures, mostly still closed, are on the upper shoulder of the ,,Obere Senke" (''Upper Depression'') (Fig. 2B). A still older ,,Untere Senke" (''Lower Depression'') may have existed in the past. The fractures are grouped into Fracture Zones 1–3.

3 Remote Sensing Data

To characterize this extensively fractured area, we have chosen an integrated approach using data recorded by various sa-

Fig. 2: Field photographs showing (*a*) a collapse sinkhole in fracture zone 2 and (*b*) fractures causing damage to a road in fracture zone 3.

tellite and airborne sensors. The following data were acquired, processed, and evaluated to determine their suitability for detecting terrain features that indicate unstable ground:

- **satellite images** (Landsat TM/7, SPOT, and IRS-1C/D) to map lineaments, moisture and vegetation anomalies, and illumination effects associated with faults and subsidence-related fracturing;
- **aerial photographs** (high-resolution stereo photographs) to map faint fractures, morphological features, moisture and vegetation anomalies;
- **airborne laser scanning (lidar) data** to recognize faint depressions and linear terrain features;
- **satellite radar data** (ERS-1/2) for interferometric SAR (InSAR) to measure subsidence rates.

In the following section, we will concentrate on data recorded by Landsat 7, Spot XS, airborne laser scanning, and on aerial photographs. The data were processed and interpreted using standard methods. The InSAR results were not satisfying in this study. We assume that this was due to the extremely small rates of subsidence and the extensive rural character of the study area, where the ground is mostly covered with vegetation.

Airborne laser scanning for high-resolution Digital Terrain Modelling (DTM) was included to the complex observation methods in order to be able to correlate fracture features delineated in traditional stereoscopic aerial photographs and satellite images with terrain alterations identified with the help of "high-resolution" elevation data. In this way, we expected unstable ground to be detected more efficiently and at an earlier stage of development than is possible by the evaluation of traditional remote sensing data alone. Detailed information about airborne laser scanning method has been described by ACKERMANN (1999), BALTSAVIAS (1999a/b), WEHR & LOHR (1999), and others in the airborne laser scanning volume 54 of the ISPRS Journal of Photogrammetry & Remote Sensing.

The laser scanning survey was flown on February 11–12, 2000, before the beginning of the growing season. This flight time was chosen in order to minimize the influence of vegetation. The study area was scanned by the laser beam on a $2.5\,\text{m} \times 2.5\,\text{m}$ grid (flight altitude: 2100 m, FOV $\pm 11°$, ground illumination cell: 70 cm). In this way, the laser scanned about 35 million ground reflection points in the 120 km^2 of the test area. In the derived DTM, each point is precisely characterized by its coordinates and elevation, e.g., x (easting): 4470038.31, y (northing): 5750872.45, and z (elevation): 78.47 m. For further processing, the DTM was converted from ASCII into raster format. Standard image processing was then applied to

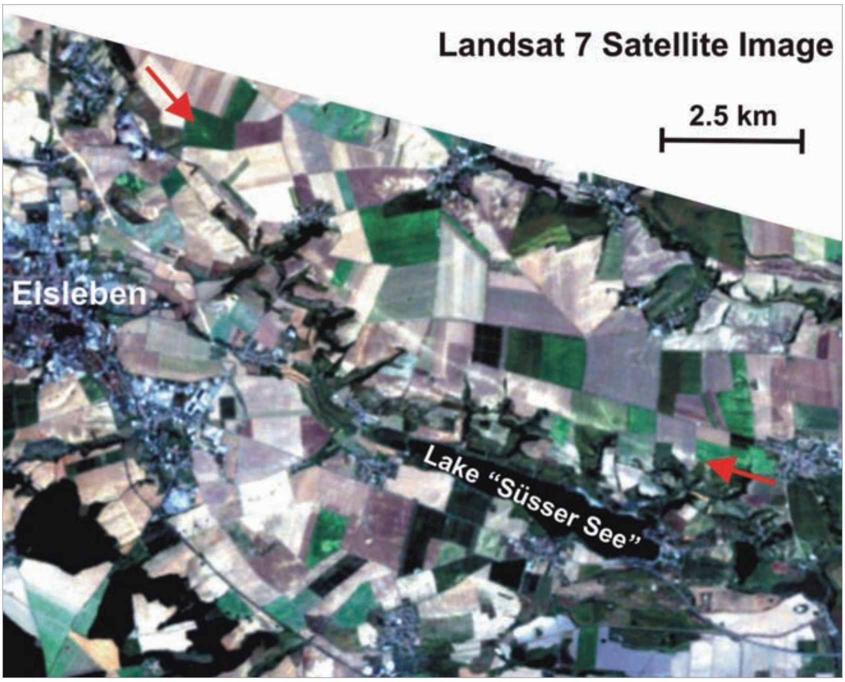

Fig. 3: Landsat 7 image from September 4, 1999, as a color composite image ETM1/red, ETM2/green, ETM3/blue, showing the study area in near-natural colors; in this image, the Upper Depression (*red arrows*) appears as a curvilinear feature.

enhance features that indicate depressions, fractures, landslides, etc.

The high resolution in elevation measurements is the essential gain from airborne laser scanning. However, the accuracy of the elevation measurements at any single point of the grid depended on the general surface roughness. The laser beam detects terrain alterations indicating both slightly displaced ground at fractures and faint depressions, but it also detects the plowing pattern and the natural unevenness of the surface. Digital filtering of the DTM data helped enhance features related to mass movements. It was possible to detect faintly displaced ground indicating fracturing and land subsidence with a limit of detection below 10 cm.

4 Case Studies

To demonstrate the applicability of the various remote-sensing methods we used, we have selected imagery which displays fractured ground between the Eislebener Niederung subsidence area and the elevated area of the Mansfelder Mulde. We focused on the Upper Depression and Fracture Zone 3. In this area, fractures are small and mostly closed and hardly visible in the field. Therefore, this area is best suited to study the performance of satellite and airborne remote sensing for early detection of unstable ground.

Fig. 3 shows a section of the Landsat 7 image taken on September 4, 1999. The image depicts a typical rural area in central Germany, with extensive farmland and only a few small towns and villages. The Eislebener Niederung subsidence area with the Süsser See lake is visible in the lower right of the image. North of the lake, a large and prominent curvilinear feature (between the red arrows) marks the location of the Upper Depression. This feature reflects poor vegetation growth and low topsoil moisture content typical of a well drained terrain. The

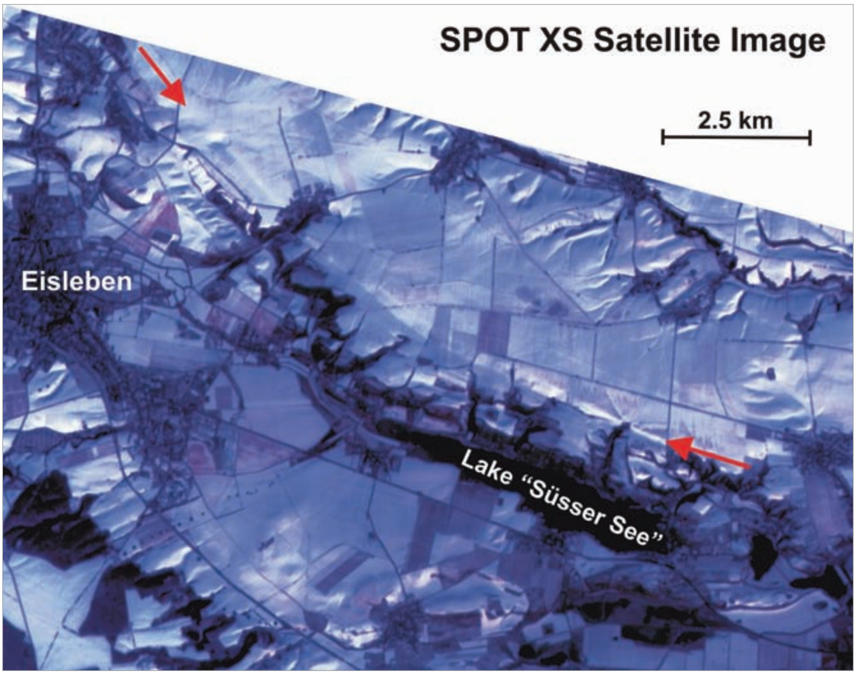

Fig. 4: Spot XS winter image from February 15, 1999, as color composite image, Band3/red, Band2/green, Band1/blue, with contrast enhancement (Gausian); the Upper Depression is enhanced by reflections and shadows on uniformly snow-covered terrain (*red arrows*).

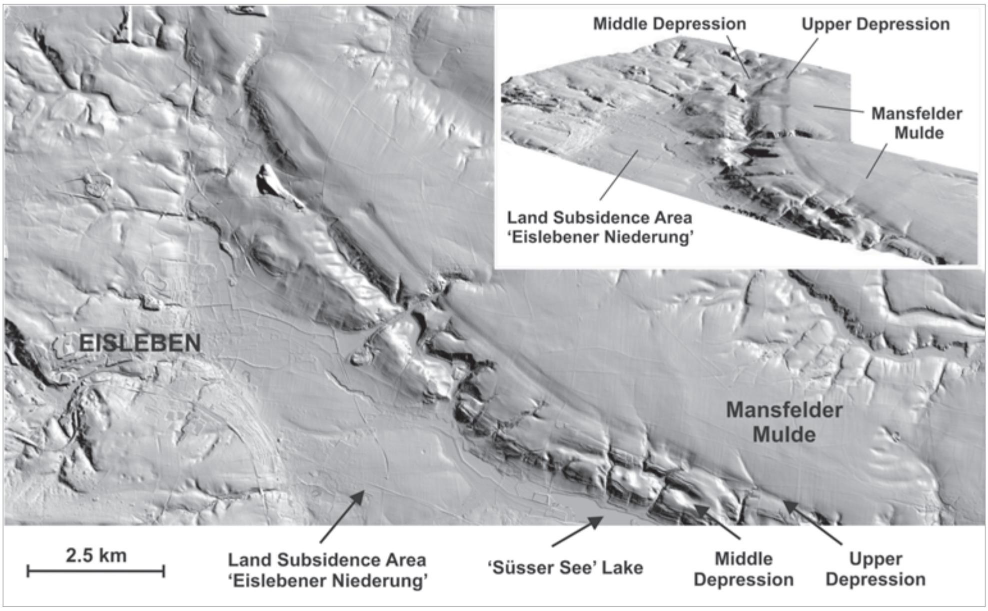

Fig. 5: ''Laser Image'' showing the major morphologic units of the study area; the vertical view is the rasterized DTM as ''shaded relief map'' (sun elevation: 45°, azimuth: 45°); the inset is a 3D view of the ''shaded relief map''; both fault troughs can clearly be seen northeast of the ,,Eislebener Niederung'' subsidence area.

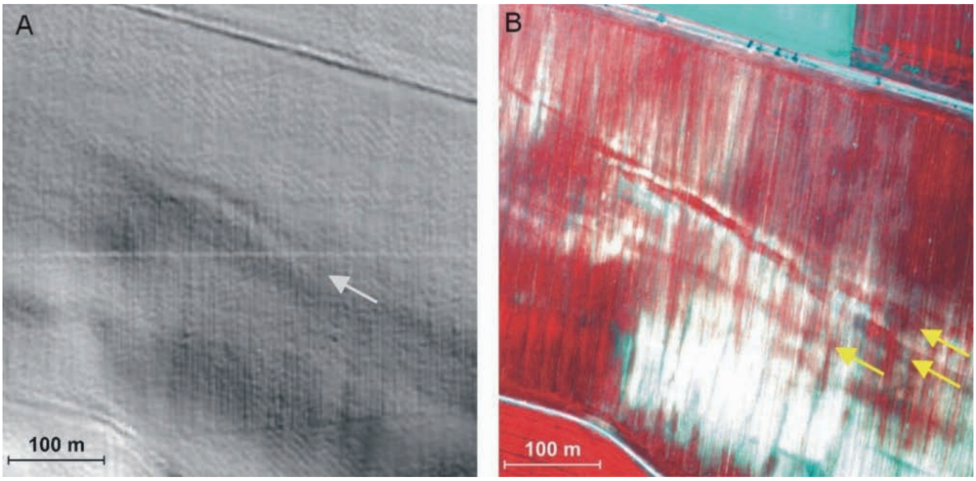

Fig. 6: ''Laser Image'' (A, shaded relief map – sun elevation: 45°, azimuth: 45°, and B Color infrared (CIR) aerial photograph of the same part of the Upper Depression; faint morphological linear features in the zoomed laser image and linear to curvilinear features in the CIR aerial photograph (*yellow arrows*) are surface expressions of fractures that make up ''Fracture Zone 3''.

good drainage is due to the highly fractured rocks of this depression.

Further indications of a fault along the depression can be seen in the Spot XS image recorded on February 15, 1999, at 10:35 GMT (Fig. 4). Because of the snow cover, different colours of surface objects and of the vegetation that usually dominates snow-free images are not visible here. Owing to the low angle of the sun from the south and the thin, uniform snow cover, unevenness in the terrain is more pronounced, leaving a light-coloured trace of the gentle south-facing slope of the depression.

The occurrence of mass movement in this area is moreover supported by airborne laser scanning data. The laser images in Fig. 5 are shaded relief maps showing the major morphological units of the study area. The shaded DTM relief map was prepared using a simulated illumination from 45° elevation, 45° azimuth, which makes the details of the morphology appear more pronounced. The land subsidence area of the Eislebener Niederung and both depressions are now visible as prominent landscape units. Two visualizations of the DTM displayed in Fig. 5 provide an idea of how large blocks of rock became separated from the rocks of the southwest limb of the Mansfelder Mulde. As result of the sliding of the blocks towards the Süsser See depression, the Middle Depression has developed broad crevasses parallel to the slope. The prominent curvilinear morphological feature of the Upper Depression can be seen in both views in Fig. 5.

An enlarged section of the laser image and a section of a Colour Infrared (CIR) aerial photograph of the same area are shown next to each other in Fig. 6. The CIR aerial photograph was taken on April 21, 2000, and shows a field of young grain (Fig. 6B). Due to the spectral sensitivity of the film, red colouring indicates healthy vegetation. In this photograph, the intensive red indicates advanced growth of the young plants. The vigour of the plants is due to the presence of a fertile soil, composed of thick loess, accumulated in open fractures. Accordingly, the red lines in the aerial photograph mark the individual fractures. Narrow linear depressions that are visible in the laser image (Fig. 6A) suggest that parts of the ground are already subject to displacement. Both images in Fig. 6 corroborate the existence of a Fracture Zone 3 associated with the Upper Depression. It can moreover be inferred that the area of weakened ground is slowly expanding to the northeast. The existence of Fracture Zone 3 has been verified in the field. Since this area is still used for farming, potential hazards to people, road traffic, and to farm machinery have to be taken into consideration.

5 Discussion

Most geological information obtained by remote sensing is the result of interpretation, and therefore has to be treated as circumstantial evidence until it has been verified in the field. To ensure the reliability of remote-sensing-based information, field checks are essential, but typically only spot checks are made, since in most cases it is impossible to fully verify remote-sensing-based information. Therefore, highly reliable information derived from remote-sensing data is essential when hazardous ground is investigated.

A prerequisite for reliable remote-sensing-based detection of hazardous ground is the identification of terrain features associated with hazardous ground in data from several methods at different times. Hence, we combined satellite imagery, high-resolution aerial photography, and airborne laser-scanning data to detect different surface features that indicate fractures and depressions. These appear as faint variations in terrain features in high-resolution imagery, or as regional-scale features that can be recognized best in small-scale satellite imagery (Figs. 3 and 4).

When the observation distance is reduced from several 100 kilometres (satellites) to one to two kilometres (airplanes), the degree of generalization decreases, while the spatial resolution of the images increases, and fine details of the terrain become visible. The high-resolution aerial photograph shown in Fig. 6B revealed that the large prominent curvilinear feature, which marks the Upper Depression in the satellite images (Figs. 3 and 4) is the summarized effect of numerous small fractures. Our multi-sensor remote sensing approach showed that most vegetation and soil moisture anomalies visible in satellite images and aerial photographs coincide with uneven and partly displaced ground that is apparent in the DTM images derived from the laser data. This was observed in regional fracture zones (Figs. 3, 4 and 5), as well as for smaller individual fractures (Figs. 6A and 6B).

The performance of the multi-sensor approach significantly benefited from the combination with airborne laser scanning. In contrast to conventional remote-sensing data, the laser-based DTM is a result of a quantitative measurement and therefore less affected by subjective views of the interpreter. The identification of surface features indicating unstable ground at different times and with various techniques, and the measurement character of laser-scanning data reduced interpretation errors and increased the reliability of the multi-sensor approach.

One factor that may limit the ability of remote sensing methods to detect hazards is an obstructed view of the ground, as is the case in densely forested or urban areas. Moreover, the possibility of using vegetation as a marker for certain subsurface situations depends on seasonal conditions.

In this study, multi-sensor remote sensing proved to be an efficient and reliable method for detecting and characterizing unstable ground resulting from mass movement after dissolution of salt from rock salt formations. The coupled interpretation of satellite and airborne remote sensing data is thus shown to be applicable to the early detection of potentially affected sites and associated risks. A prerequisite is that the subsurface mass movement affects the ground surface in a typical way.

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