Application of remote sensing methods in geological mapping

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Abstract. Aerial photographs are a source of geological information that may be unobtainable elsewhere. If the fullest use is to be made of this information for the purpose of geological mapping, there must be a planned integration of the photogeological work with the field and laboratory investigations. The appearance of the first satellites for civil purposes on the beginning of the 1970s (such as ERTS – Landsat series), of most land areas of the Earth has provided new opportunity for photogeologists. Many areas can now be studied and mapped geologically for which neither adequate maps nor vertical aerial photograps were available. The advantages of the present satellite systems and examples of their application by specialists of the Polish Geological Institute are presented in this paper.

Nowadays, it is practically impossible to imagine performing geological mapping without application of remote sensing data and analysis. Development of new technologies is very fast and new borne techniques are coming like permanent scatter interferometry, laser scanning etc. However, we should always remember, that they are only very useful tools to help geologists in their field mapping art and practise.

Key words: *geological mapping, photogeology, remote sensing*

Geologic mapping is the principal method used by geologists to understand the geologic nature of the planet. Geologic mapping in a given area involves an understanding of the character and nature of the landforms (geomorphology), the lithologic characteristics and stratigraphic age of the rocks, and the structural and tectonic setting of the rocks.

Aerial photographs have been used by most field geologists ever since they became available. The first aerial photographs taken from an airplane for geologic mapping purposes were used to construct a mosaic covering Benghazi, Libya, in 1913. In general, the earliest uses of airphotos were simply as base maps for geologic data compilation, especially as applied to petroleum exploration (Lillesand & Kiefer, 1999). Some interpretive use of aerial photographs began in the 1920s. Since the 1940s, interpretive use of airphotos for geological mapping and evaluation has been widespread.

Photogeology is the name given to the use of aerial photographs in geological studies (Allum, 1969). Aerial photographs are a source of geological information that may be unobtainable elsewhere. If the fullest use is to be made of this information for the purpose of geological mapping, there must be a planned integration of the photogeological work with the field and laboratory investigations. It includes, amongst the other things:

- ❏ the geological interpretation of aerial photographs;
- ❏ the compilation of these interpretations into maps;
- ❏ the use of aerial photographs in the field;
- ❏ the use of aerial photographs for the production of the final geological map.

The first aerial photographs in Poland for military and civil services as well as for research institutions were taken by “FOTOLOT” acting within the Polish airlines LOT enterprise (Graniczny, 2002). Between 1932 and 1939, 150 000 km^2 of the country were covered by aerial photos (Sobczyński, 2000). In the early 1930s the aerial photos and photomaps from the Polesie Region and the Narew River Valley were interpreted in the Polish Geological Institute. Professor Edward Rühle, long term researcher and later director of the Polish Geological Institute, should be recognized as precursor of the application of aerial photos for geological purposes in Poland.

After World War II, there were some limitations with using aerial photos for non-military purposes. Most of the aerial photos were classified and acquisition of the photos required a long and difficult procedure. The situation essentially changed at the beginning of the 1990.

Multispectral aerial photos (taken with MKF-6M and MB-490 NAC cameras) have been applied for updating of the geological mapping in the Mosina region (near Poznań, Central Poland).

The photogeological analysis has enabled expanding information concerning geological mapping, especially of the Warta River Valley. It was also possible to obtain important new information regarding evolution of the river in the vicinity of Mosina (Graniczny & Doktór, 2000).

The aerial photos have been also a very effective tool for observation of recent development of the Vistula outlet near Świbno. On the southern coast of the Gdańsk Bay, forms and sediments occur which are related to the three mouths of the Vistula River which existed in historical times. Until 1840, the Vistula flowed into the Bay of Gdańsk near Gdańsk. During the night 31st January/1st Februrary 1840, during a very high water level on the Vistula, with an ice-jam in its mouth and a high water level and a strong storm on the Baltic, the flood banks and dunes separating the Vistula river-beds from the sea broke. The Vistula formed a new mouth ca. 10 km away from Gdańsk. In 1895, a new artificially dug mouth of the Vistula was opened near Świbno, 20 km away from Gdańsk. Since then, most of the Vistula’s water and sediments have been transported to the Bay of Gdańsk by means of this artificial channel called the Vistula Cross-cut. During the last 100 years large quantities of sediment were deposited here, which formed the currently active front of the delta and the pro-delta. The sediments of the head of the delta form a river-mouth fan and they are developed mainly in the sand facies. The thickness of the sand sediments of the river-mouth fan is a maximum 11–13 m. The sediments of the pro-delta occur on the forefield of the river mouth ran at a depth zone of 12–16 m and also underlie the fan sediments (of the delta head). The thickness of these sediments ranges from 0 to about 10 m.

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Aerial photos from 1947, 1958, 1964, 1978 and 1997 have been compared. The photograps were processed using ER Mapper 6.2 software into a orthophotomap format. The Gauss-Krüger map projection was used on a WGS–84 geocentric ellipsoid and the 1992 geographic co-ordinate system. Additionally, measurements of the coast line changes using GPS equipment were performed in October 2001, March 2002 and September 2002. Position of the coast line in the years 1947, 1958, 1964, 1978 in the background of the orthophoto from 1997, as well as high resolution IKONOS satellite image, registered in 2002, from the same area are presented in the Fig. 1.

Many excellent books and articles are available on the use of aerial photographs for geologic mapping projects (Ray, 1960; Miller, 1961; Lattman & Ray, 1965; Allum, 1969; Mekel, 1970; Ciołkosz at. al., 1978; Ostaficzuk, 1978).

The appearance of the first satellites for civil purposes on the beginning of the 1970s (such as ERTS–Landsat series), of most land areas of the Earth has provided new opportunity for photogeologists. Many areas can now be studied and mapped geologically for which neither adequate maps nor vertical aerial photographs were available. Current satellite systems have following advantages:

❑ Very extensive global coverage;

❑ Temporal character — capability of recording the same scene every few days in different seasons;

❑ Possibility of the image registration in wide range of the electromagnetic spectrum — visible, infrared and microwave;

❑ Synoptic nature of the imagery (e.g., one Landsat image covers an area 185 × 185 km what is an equivalent to 1600 aerial photos at the scale 1 : 20,000.

❑ Excellent cartographic accuracy and projection (UTM in the case of the Landsat satellites).

❑ Capability for digital enhancement of images and further processing, including generation of the GIS thematic composition and hybrid compositions using DTM (Digital Terrain Model).

❑ Variety of useful formats for analysis and display of data.

❑ Better and better spatial resolution of images — from 15 meters in case of Landsat ETM+ to 0.5 meter in case of Quick Bird.

❑ Limited possibility of getting stereoscopic effect.

❑ Unrestricted availability and low cost of data.

The Landsat and SPOT images are most frequent used satellites systems in Poland (Ciołkosz & Kęsik, 1989; Graniczny, 1998a). First satellite from the Landsat series (MSS) has enabled mapping of geological elements (mostly regional tectonic structures) in the scales 1 : 1,000,000 — 1 : 200,000. Further satellites (TM) made possible mapping at the scale 1 : 100,000 and ETM+ mapping at the scale 1 : 50,000 (similar possiblility offered French satellite SPOT). Finally, high resolution satellites, like IKONOS or Quick Bird made mapping possible in the scales 1 : 25,000 — 1 : 10,000.

The fundamental principals of the photogeological analysis of satellite images are practically the same as in the case of aerial photos. The essential difference is in the degree of generalization and the size of the analyzed area.

Multistage image interpretation is typically utilized in geologic studies. One may begin by interpretating satellite images (medium and low resolution) at scales 1 : 1,000,000 to 1 : 200,000, then examining high resolution satellite images or high altitude stereoscopic aerial photos at scales from 1 : 100,000 to 1 : 50,000. For detailed mapping, very high resolution satellite images or stereoscopic aerial photos at the scales 1 : 25,000 to 1 : 10,000 may be utilized.

Small-scale mapping often involves the mapping of *lineaments*, regional features that are caused by the linear alignment of regional morphological features, such as streams, escarpments, and mountain ranges, and tonal features that in many areas are the surface expression of fractures or fault zones. Major lineaments can range from a few to hundreds of kilometers in length. Although monoscoping viewing is often suitable for lineament mapping, *lithologic mapping,* the mapping of rock units, is greatly enhanced by the use of stereoscoping viewing. The process of rock unit identification and mapping involves the stereoscopic examination of images to determine the topographic form (including drainage pattern and texture), image tone, and natural vegetative cover of the area under study. In barren areas, most lithologic units are distinguishable on the basis of their topographic form and spectral properties. In vegetated areas, identification is more difficult because the rock surface is obscured by plants, and some of the more subtle aspects of changes in vegetative cover must be considered. Unfortunately, such situation pertains to nearly the whole territory of Poland.

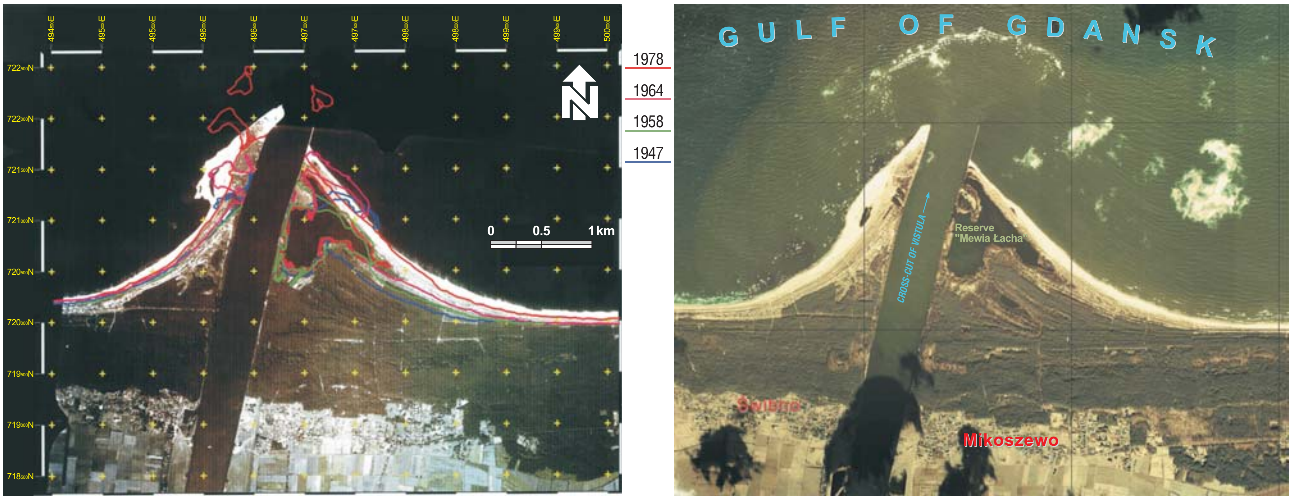

Fig. 1. Position of the coast line near Vistula Outlet in the years 1947, 1958, 1964, 1978 against the background of an orthophoto from 1997 and high resolution IKONOS satellite image, registered 8th March 2002 from the same area

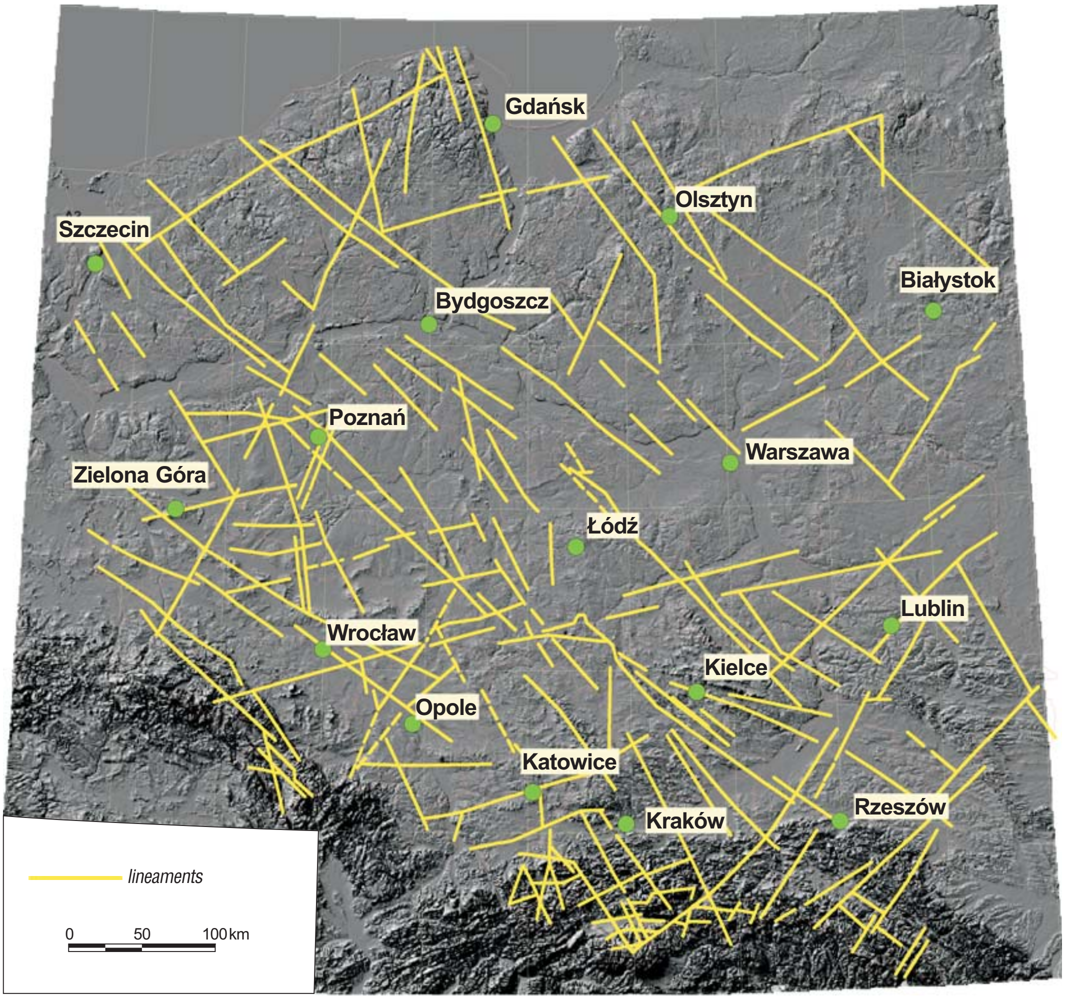

Fig. 2. The main lineament zones interpreted at the satellite images of Poland and surrounding countries superimposed on the Digital Elevation Model. DTM compiled by the Polish Military Cartographic Service, processed by Z. Kowalski and Z. Kordalski

One of the first geological interpretation of the satellite images of Poland was presented in the *Photogeological Map of Poland in the scale 1 : 1,000,000* (Bażyński et al., 1984). The publication of this map enabled geologists to get acquainted with new materials, different from those used before. In this map the results of satellite images interpretation are shown against the background of geologic and tectonic units of Poland. The diagrams of lineament directions of each geologic units are shown. For the area except Carpathians and Sudetes the main directions are within the following intervals: 60–80° (ENE–WSW), 120–140° (NW–SE) and 30–40° (NE–SW) as less important. Changeability of lineaments directions can be observed in Carpathians but it is possible to divide them into three principal intervals: 140–150° (NW–SE), 0–10° (N–S) and 30–40° (NE–SW). Main directions of lineaments in Sudetes and in Carpathian Foredeep are similar and the basic azimuth intervals are: 20–30° (NNE–SSW), 130–150° (NW–SE) and 70–80° (ENE–WSW).

There are many indications that the zones of lineaments may be treated as elements of a planetary rhegmatic network, its surface symptoms. Yet the picture of this lineament network does not quite correspond to the commonly quoted regularity of the orthogonal and diagonal systems. It is much more complex and a characteristic fact is that in the whole analyzed area there is not a single place in which complete systems would be present. The established relationship between the particular lineaments with individual faults as well as with other geological structures, such as salt crests and plugs, fold lines or tectonic grabens, points to the polygenetic character of these structures.

Photogeologic elaboration of the Carpathians comprising the whole of Polish and Slovakian Carpathians and surrounding areas has been compiled at the scale 1 : 500,000 and presented in the “Geological Atlas of the Western Outer Carpathians and their Foreland — Photolineament Map” (Doktór et al., 1988–1989). In the satellite images of the Carpathians two main types of linear elements may be distinguished. The first type is connected with fold structures and lithological differences. The second group of lineaments is connected with different discontinuous deformation. The main characteristics of the lineaments are a big diversity of azimuths and variability of lengths. In the eastern part of the Carpathians, the NE–SW and close to N–S directions prevail, while in the central and west parts the NW–SE, N–S and ENE–WSW directions dominate. Several regional lineaments zone were distinguished for the first time. Some of the lineament zones extend 400 km, e.g., Myjava (ENE–WSW), Hron (ENE–WSW), the distances of the other lineaments are very close to it: Murań

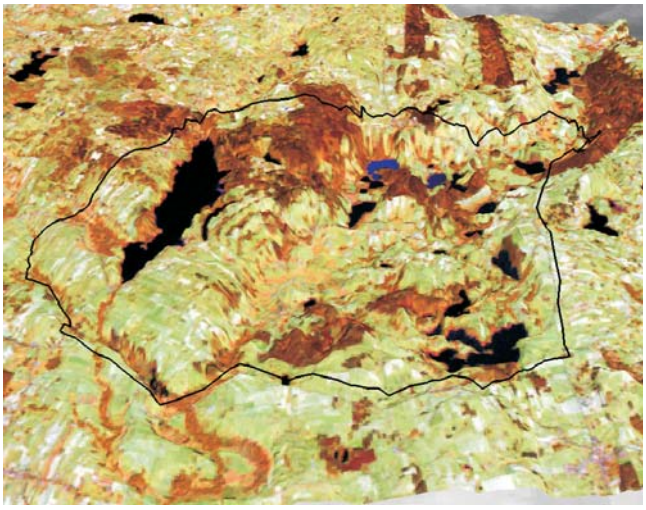

Fig. 3. The Landsat ETM+ data (bands 8, 5, 2) registered 11th September 2002 superimposed on the DTM compiled by the Polish Military Cartographic Service and processed by Z. Kowalski, from the territory of the Suwałki Landscape Park its and vicinity. Differentiated geomorphological forms are clearly enhanced, the Hańcza Lake is visible in the left upper corner and Suwałki town in the right lower corner of the image

(ENE–WSW), Przemyśl (NE–SW), Northern Tatra (W–E). On the basis of further studies model of deep geological structure of the Polish Carpathians was presented according results of complex remote sensing — geophysical analysis. Computer transformation and correlation of various data, including interpreted lineaments from satellite images, gravimetric and magnetic data were used, as well as obtained magneto-telluric information. Elaborated maps of structural linear elements in the Carpathians refer to tectonic model of the Carpathians, presented by R.Unrug (Doktór et al., 1990). He proposed explanation of strike–slip faults in the flysch Carpathians by rotation of a fanwise dispersed tectonic block. In such meaning, the zones forming middle Carpathian block pass along the lines: Łysa Polana–Nowy Targ–Brzeźnica and Muszyna–Jasło (Murań lineament). These marked tectonic zones show connections between tectonic structure of deep subflysch basement and recent neotectonic movements of the Earth crust in the Carpathians area.

Numerous remote sensing studies have been performed at the territory of the Sudetes Mts. On the basis of interpretation of Landsat MSS and COSMOS satellite images and aerial radar TOROS images , the "Photogeological Map of the Sudetes Mts." have been compiled at the scale 1 : 200,000 (Bażyński et al., 1986). One of the most conspicuous tectonic feature, northeastern Marginal Sudetic Fault (NW–SE), cutting Sudetes Mts. from their foreland is clearly visible in the remote sensing data. Besides, it is also visible that this feature is cut by numerous transverse faults, oriented ENE–WSW. The analysis of the lineaments has revealed existence of two main tectonic systems in the Sudetes: ENE–WSW, extending the Ohre Continental Rift onto the Polish territory (Doktór et al*.,* 1991), and NW–SE indicating main tectonic graben of the Sudetes (Oberc, 1991). The main lineament zones interpreted at the territory of Poland and surrounding countries superimposed on the Digital Elevation Model (DTM) are presented in the Fig. 2.

A complex correlative analysis of remote sensing and geophysical data for determining tectonic structures have been made for the territory of the Polish–Lithuanian cross-border area — Suwałki Anarthosite Massifresulting in five maps in 1 : 100,000, scale i.e., sheets Przerośl, Wiżajny, Olecko, Suwałki and Sejny (Graniczny, 1998b).

The topography of Lithuanian-Polish cross-border area is characteristic of the glacial morainic upland in the northeast and glaciofluvial outwash plain in the south (Atlas, 1997). The glacial advance of the Late Weichselian maximum formed the relief. The topographic altitudes vary between 130 and 298 m above sea level. The morainic upland is formed by marginal moraines, dead ice moraines, kames and kame terraces, eskers, and melt water erosion channels and other forms. During the deglaciation, glaciofluvial streams from the northern part of the upland flowed to the south and southwest forming the Augustów outwash plain, which is built of gravel and sand. Thickness of glacial and aquaglacial deposits, accumulated during repeated

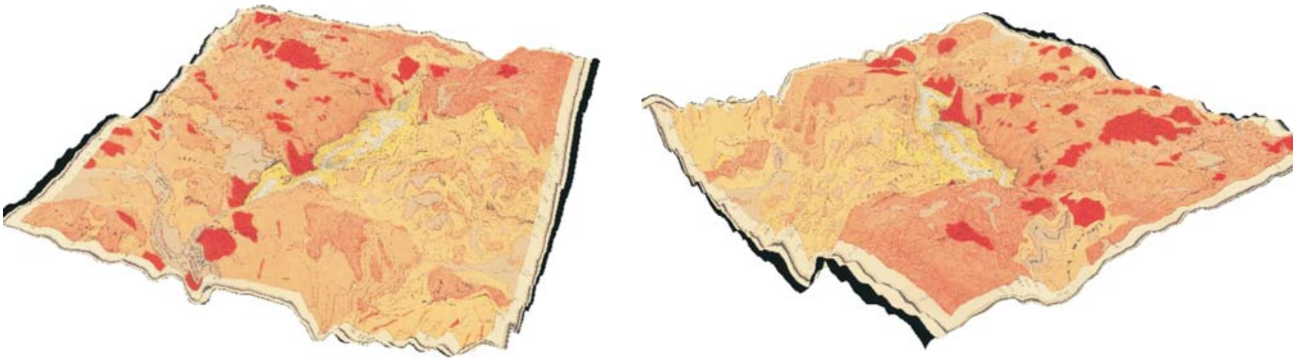

Fig. 4. The geological map of the Hańcza Lake and vicinity made by Edward Rühle (1932) in the scale 1 : 25,000 superimposed at the DTM. The analysis of this comprehensive product indicates clearly that the extent of sediments of the mapped end moraines should be corrected. DTM compiled by the Polish Military Cartographic Service and processed by Z. Kowalski

Pleistocene glaciations of the reach up to 281 m in the paleoincisions of the sub-Pleistocene surface in the northern part of the project area, while the smallest thickness (about 112 m) is known to occur in the south-eastern part of the Augustów Plain. In the central part of the area the thickness of the Quaternary cover is approximately 200 m.

The character of an individual lineament in the young glacial area is generally very complex. For instance, one of the lineaments, traced at a 50 m distance, is revealed by a high plain margin, a lake trough, a boundary of forest complex or meadow-swamp vegetation in depressions, individual moraine hills, etc. There also exist parts of regional lineaments which have no directly impact on the morphology or geological structure of shallow rocks. Based on the interpretation of the subsurface that occurs beneath the Quaternary sediments in the Suwałki region, Ber (1988) described two systems of inferred faults. One featured by the NNW–SSE direction and the other by two parallel lines extending across the whole area. The comparison of faults described by Ber with the lineament image provides no basis for direct conclusions. No matter how these NW–SE lineaments are interpreted, none coincides with the inferred NNW–SSE fault. No parallel zone have been found in the satellite images. However, numerous ENE–WSW zones can be noted. They distinctly refer to the subsurface that underlies Quaternary sediments. The satellite image interpretation can be also used for correction of the Ber's map in which fault strikes are approximately determined. On the other hand, the conclusions may be drawn on the origin of lineaments; they cannot be referred only to aforementioned Quaternary subsurface, but also to the deeper basement.

Generally, nearly meridional (NNW–SSE) and parallel (primarily ENE–WSW) discontinuities are most distinctly marked. In addition, NW–SE, and scarcely NE–SW directions are observed; west of the Żytkiejmy–Suwałki line NW–SE directions are prevalent, whereas east of it — NE–SW directions predominate. The analysis indicated that Krzemianka ore deposits occur at the intersection with meridional and NW–SE discontinuities (tectonic knot). The Udryń ore deposit also occurs in the tectonic knot marked by NE–SW and NW–SE discontinuities.

To define the land use and trace its changes in the Polish–Lithuanian cross-border area two Landsat MSS satellite images have been acquired of 1979 and of 1992. They have been processed using PCI (EASI/PACE) software in the Polish Geological Institute. Land use has been analysed by supervised and unsupervised methods (Atlas, 1997). According to satellite images classification, six land use classes have been distinguished: 1) coniferous forests, 2) mixed forests, 3) cultivated lands, 4) wetlands and pastures, 5) lakes, 6) nonclassified.

The analysed satellite images have been taken in the month of September, that of 1979 in the first and that of 1992 in the second decade. The analysis revealed that considerably bigger changes of land use in period 1979–1992 are noted in the Lithuanian territory. In 1979, due to intensive land cultivation by soviet type collective farms, arable land occupied 48.5% of Lithuanian side of the cross-border area, while cultivated land occupied 28.8% of the Polish area, at the same time. It is noteworthy that in the period between 1979 and 1992 cultivated lands in Lithuania decreased by nearly 20%, while in the Polish part, cultiva-

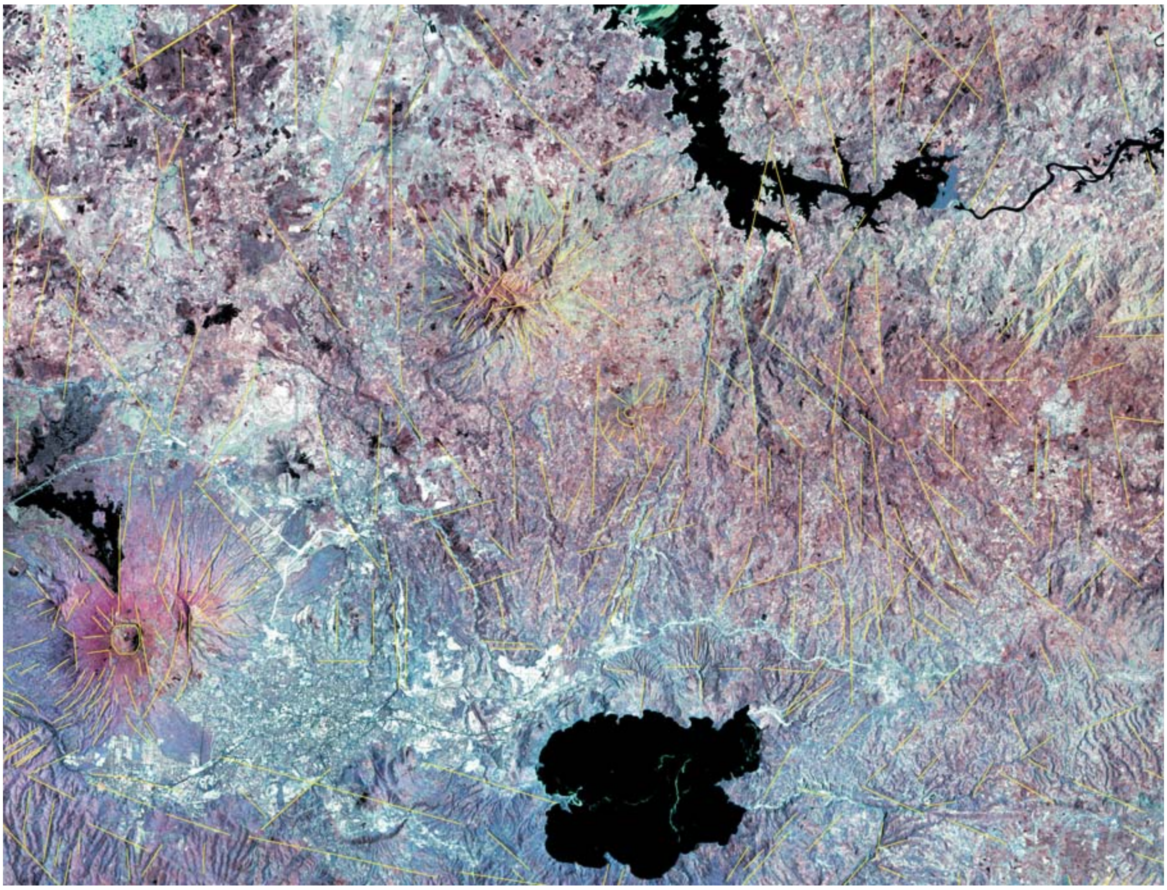

Fig. 5. The lineament interpretation of the Landsat ETM+ image of El Salvador taken on 14 April 2003. The interpreted area covered vicinity of the El Salvador city and Ilopango Lake (former caldera)

ted land area increased by almost about 3%. This dramatic change of land use in Lithuania has been caused obviously by the collapse of collective farms after reestablishment of independence of Lithuania and the resulting economic transformation.

The detailed analysis of the satellite images (Landsat TM) of the Suwałki area have not permitted for direct identification of the lithological differentiations (Graniczny, 2002). There are several reasons for that: great differentiation of the geological lithological complexes within relatively small area, dense vegetation cover and agricultural activity. Indirectly, it was possible to obtain some information on the basis of the terrain relief analysis. Especially, the "negative" forms are clearly visible at the satellite image, e.g., glacial tunnel valleys, depression formed due to the ice exaration and ice melting, bottoms of the river valleys and erosional river valleys. It was also possible to recognize the belts of moraine hills due to the characteristic texture — Fig. 3 (Graniczny, 2002).

Verification and updating of the geological maps is also possible thanks to the analysis of the Digital Terrain Model (DTM). The geological map of the Hańcza Lake and vicinity made by Edward Rühle (1932) in the scale 1 : 25,000 was superimposed onto the DTM. The analysis of the comprehensive product indicates clearly that the extent of sediments of the mapped end moraines should be corrected — Fig. 4. Such analysis should be a very effective tool for updating of older geological maps.

Usually, the application of satellite images is the first step in different geological missions in the developing countries. The imagery can be applied for identification and mapping of geological features such as lithological complexes, geomorphic units, tectonic boundaries, alteration zones etc. They could be also very useful for planning field reconnaissance, places for detailed studies, sampling etc. In many cases they are also very important as substitute for topographic maps.

Specialists of the Polish Geological Institute several times have applied satellite images for such projects abroad, among them — for detailed mapping of the ophiolitic massifs Sierra de Nipe and Sierra de Cristal and tectonic structures in Cuba, as well as — for regional geological mapping in the Abu Simbel–Tushka region in Egypt (Graniczny et al., 2000; Graniczny, 2002).

Presently, the analysis of Landsat ETM+ of El Salvador has been performed. El Salvador, located on the Pacific Ocean side of Central America, is crossed from west to east by a chain of Quaternary volcanoes, the result of plate subduction process. Two types of earthquakes can be characterized in the region; the ones occurring within the volcanic range, which are crustal earthquakes (Plafker & Ward, 1992). This type of earthquakes despite having magnitude not larger than approximately 6.5 have been historically responsible for the largest loss of life and damage in El Salvador. They have been mostly produced by right-lateral faults running parallel to the volcanic range as a result of the oblique convergence of the Cocos plate relative to the Caribbean plate. The earthquakes of the second type are the subduction earthquakes occurring in the shear zone of the subducting Cocos plate and also within the plates. The aim of the analysis of satellite images was to map tectonic features on the basis of lineament's interpretation. The interpreted area covered vicinity of the El Salvador city and Ilopango Lake (Fig. 5).

Nowadays, it is practically unimaginable to perform geological mapping without application of remote sensing data and analysis. Development of new technologies is very fast and new techniques are becoming available, like permanent scatter interferometry, laser scanning, etc. However, we should always remember, that they are only very useful tools to help geologists in their field mapping art and practice.

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