Lineaments interpreted at the radar images and the digital elevation model within the Palaeozoic rocks of the Holy Cross Mts.

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A b s t r a c t . Lineaments, visible in radar images and detected with the digital elevation model, and occurring within the Palaeozoic of the Holy Cross Mts., were analysed using computer processing of the tectonic data. The fault network in the Palaeozoic Holy Cross Mts., up to now studied mostly with surface cartography methods, is rather weakly expressed in linear structures, discernible in aerial, satellite and radar imagery. A detailed analysis allowed to determine main directions of the lineaments of tectonic origin and to arrive at cinematic characteristics of large dislocations present, important for reconstructing the tectogenesis of the area.

Key words: *radar images, Holy Cross Mts, cartography, tectonics, dislocations, DEM*

The studies of fault network in the Palaeozoic Holy Cross Mts in Central Poland (Fig. 1), have been mostly qualitative, and only in selected fragments of the area, local quantitative research were attempted. Published papers and archive materials included only some, mostly the largest, faults mapped during surface cartographic surveys. Various authors employed different methodology, and the results of field measurements were not correlated with analysis of aerial photographs or satellite images (or *vice versa*), and with the land relief.

Recently, major discrepancy has been noted between the results of interpretation of radar images, very useful in tracing discontinuous deformations, and the pattern of fault network obtained from surface charting. New photogrammetric and remote sensing methods, combined with structural analysis, allow also to establish the origin and kinematics of faults, both longitudinal and transverse ones, whose interpretation still rise controversies.

Radar images were interpreted, the digital elevation model was studied, and the detected lineaments were analysed statistically using computer software to process the digitized lineaments.

Historical overview of previous tectonic research on the Palaeozoic of the Holy Cross Mts.

Discontinuous deformations were known in the Palaeozoic core of the Holy Cross Mts. since the second half of the 19th century (see Michalski, 1983, 1988).

Many faults, both longitudinal and transverse to the major tectonic structures of the Holy Cross Mts., were discovered and described by Czarnocki (1919, 1927, 1928a, 1928b, 1936, 1937, 1938, 1939, 1947, 1950, 1957) and Samsonowicz (1922, 1923, 1924, 1925, 1926, 1928, 1934a, b, c).

An important stage in surveying the discontinuous tectonics of the Palaeozoic of the Holy Cross Mts. coincided with the work on the Detailed Geological Map of Poland (Filonowicz, 1962, 1963, 1968, 1969, 1971, 1973; Walczowski, 1964, 1968; Dowgiałło, 1974 a, b). Discontinuous deformations received also much attention from Kowalczewski (1963, 1970, 1975) and his co-authors (Kowalczewski et al., 1976; Kowalczewski & Rubinowski, 1968), while the discontinuous deformations in the Cambrian of the Pepper Mountains (Góry Pieprzowe) were studied by Żak (1962). The discontinuous tectonics of the Holy Cross Mts area was also elucidated by Jaroszewski (1972, 1973), who presented the relationships between the Palaeozoic and its Permian-Mesozoic envelope in the northern part of the Holy Cross Mts. and provided an interpretation of tectonic movements along the Holy Cross Mts. Dislocation.

Besides, the discontinuous tectonics of various fragments of the Holy Cross Mts. area was commented upon by authors of numerous papers on local geological structure (e.g., Szczepanik et al., 2004; Mardal, 1988, 1993; Dembowska, 2004). The nature and position of the Holy Cross Mountains Dislocation was discussed by Stupnicka (1988), Tomczyk (1988), and Znosko (1988). Discontinuous deformations were the subject of many papers by Mizerski alone (Mizerski, 1979a, b, 1981a, b, 1982, 1988, 1991, 1995, 1998) or with co-authors (Mizerski & Ozimkowski, 1978; Mastella & Mizerski, 1981, 2002; Jurewicz & Mizerski, 1987, 1990; Mizerski et al., 1986; Mizerski & Skurek-Skurczyńska, 1999).

Another line of research trying to locate discontinuous deformations within the Palaeozoic core of the Holy Cross Mts. was analysis of aerial, satellite and radar images of the whole country (Bażyński et al., 1984; Bażyński & Graniczny, 1987; Doktór & Graniczny, 1993; Doktór et al., 1988; Piątkowska, 2003), or just of the Holy Cross Mts. area (Wilczyński et al., 1981; 1981; Konon et al., 2004; Piątkowska, 2003), or its fragments (Mizerski & Ozimkowski, 1978; Mastella & Mizerski, 2002).

It should be noted that fault deformations of the Holy Cross Mts area were shown in various ways in different geological maps of Poland (e.g., Pożaryski et al., 1992; Znosko, 1998).

All these studies allowed to locate the fault structures. However, the course of particular structures with the Palaeozoic, largely covered by younger strata, was traced differently in the maps. In some maps, transverse and longitudinal dislocations predominated, while others showed fairly numerous diagonal faults.

Various readability of the discontinuous structures led to the near complete lack of major and uncontroversial dislocations in maps based on interpretations of satellite, aerial or radar images, which is due to the geological situation in particular parts of the Holy Cross Mts. area.

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Major dislocations within the Palaeozoic of the Holy Cross Mts. discovered with cartographic methods

Extensive cartographic survey of the Holy Cross Mts. Palaeozoic core (see references cited above) discerned numerous dislocations, longitudinal and transverse to major tectonic structures. Those dislocations (Fig. 1) are widely known, but their exact course differs among geological maps. This is mostly due to poor exposition of the bedrocks and few shallow boreholes penetrating the older basement under locally thick Pleistocene and Holocene sedimentary cover.

However, regardless of their authors and dates, the maps generally show major dislocations as either perpendicular or parallel to the axial geological structures.

Longitudinal dislocations form a small percentage of the total number of dislocations shown in the geological maps. Besides the Holy Cross Dislocation — the major longitudinal dislocation in the Holy Cross Mts (Guterch et al., 1976), there are also other prominent longitudinal dislocations both within the Łysogóry Block (Świślina River Dislocation), and the Kielce Block (e.g., the dislocations bordering the Dyminy Anticline from the north and from the south). Besides, there are several smaller longitudinal dislocations, of limited extent.

Unfortunately, the longitudinal faults are poorly manifested in the field. Their presence can be confirmed, but tracing their precise course is difficult because of the thick Pleistocene and Holocene cover. Only in few areas shallow geophysical research were conducted, that helped to pinpoint some segments of longitudinal dislocations.

Mastella & Mizerski (2002), judging from analysis of radar images, suggested that yet unknown longitudinal dislocations may be present and that many transverse faults in the Holy Cross Mts. Palaeozoic core may run differently than previously assumed.

There are different views concerning the type and origin of the longitudinal dislocations in the Palaeozoic of the Holy Cross Mts. This can be best exemplified with the case of the Holy Cross Mts. Dislocation; there are three hypotheses about he movements along this structure:

❏ According to geophysical research by Guterch et al. (1976 and other), the Holy Cross Mts. Dislocation ca be regarded as a surface manifestation of a deep fracture reaching down the Moho surface, and dividing the periphery of the East European Craton into blocks. The dislocation is steep, generally subvertical (Mizerski, 1988, 1995);

❏ Traditionally, since 1920s (after Czarnocki, 1919), the Holy Cross Mts Dislocation has been viewed as an overthrust, more or less inclined to the north. Stupnicka (1988) even directly supposed that the overthrust resulted from Variscan subduction directed northward;

❏ The Holy Cross Mts Dislocation can be also treated as one of longitudinal dislocations, probably active during Alpine orogeny (Mastella & Mizerski, 2002). According to such interpretation, the Holy Cross Mts Dislocation might be a dextral strike-slip fault.

It should be noted, however, that the transpressive movements could have been (and probably were) secondary to older vertical (normal or reverse) movements along that dislocation.

The transpressive nature of the Holy Cross Mts. Dislocation has been supported, among others, by cartographic evidence from the Klonówka area. New evidence will be presented below.

Regardless of interpretation of nature and movements along the Holy Cross Mts. Dislocation, four kinds of longitudinal dislocations have been supposed at least by some authors to occur within the Palaeozoic core.

1. The oldest, related to the Late Cadomian or Early Caledonian tectonic movements (Mizerski, 1995, 1997), are near E-W-oriented thrust surfaces indicating northward movement, found within the Chęciny-Klimontów Anticlinorium.

Also pre-Ordovician, thus associated with Late Cadomian or Early Caledonian movements, are the near E-W-oriented thrust surfaces in the southern wing of the Wygiełzów Syncline (Orłowski & Mizerski, 1995).

2. During the Variscan activity, longitudinal discontinuities formed, inclined to the north, along which tectonic transport occurred to towards the south. Numerous such structures, are visible as steep thrust surfaces within the Bodzentyn Syncline, consisting of Devonian strata.

Czarnocki (1919) and Stupnicka (1988) suggested a similar nature for the Holy Cross Mts Dislocation.

3. Longitudinal reverse faults, with both northern or southern footwalls, are associated with the Variscan stage of activity, partly with the folding stage and partly with the uplifting stage. However, only some of these longitudinal faults are reliably dated, because many were reactivated during Laramide or later movements (see Stupnicka, 1972).

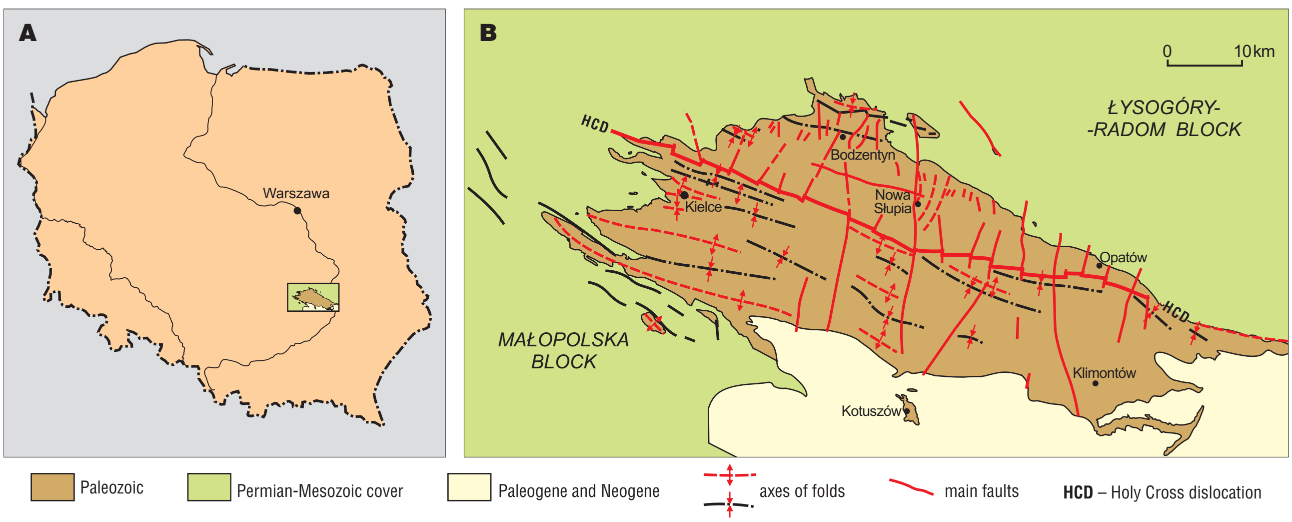

Fig. 1. Location (A) and tectonic sketch map of the Palaeozoic core of the Holy Cross Mts (B)

4. Longitudinal strike-slip faults, related with the Alpine activity sensu lato, has to be regarded as the youngest ones (Mastella & Mizerski, 2002), presumably associated with Late Cenozoic phase of transpression.

Particular major transverse faults were described in many papers. Among others, Jaroszewski (1973) analyzed in detail the main transverse fault — the Łysogóry Fault, interpreting it as a strike-slip fault. This view was criticized by Mizerski (1979) who believed that the Łysogóry Fault, like other major transverse faults within the Łysogóry Block, was a normal fault or oblique-slip fault.

It should be, however, reminded that it is very difficult or even impossible to analyze the transverse faults during field survey because of sparse outcrops in the fault zones and generally poorly exposed bedrock. The poor exposure hampers attempts to chart the course of faults and outcrops of adjacent strata of particular age, important for characterizing the movements along particular dislocations.

The cartographic pattern of the Bodzentyn Syncline indicates that the transverse faults are also mainly normal or oblique-slip faults. Some of them are pivotal or hinge faults. The cartographic pattern precludes a transpressive interpretation of these dislocations.

Normal or oblique-slip nature of major faults within the Łysogóry Block of the Holy Cross Mts., and the fact that these faults cut through both Lower and Upper Palaeozoic strata, and disappear (mostly) at the contact with the Permian-Mesozoic envelope suggest that the faults should be regarded as associated with the Variscan tectonic activity of the area — probably with the post-folding uplift stage. Nevertheless, some of them, continuing through the rocks of the Permian-Mesozoic envelope, must have been reactivated during later (Laramide or younger) uplifts, and then the direction and thrust of walls along them might have been different that during the Variscan movements.

Transverse faults present within the Łysogóry Block, often continue into the Palaeozoic rocks of the Kielce Block, where additional major transverse faults abound. A detailed characteristic is available for major transverse faults within the Klimontów Anticlinorium (Mizerski & Orłowski, 1993).

The cartographic pattern of the faults leave no doubts that the movements were mostly vertical there (Fig. 8), and the direction of thrust indicates successive uplifting of Palaeozoic toward the east. Major transverse faults are accompanied with lesser faults, also predominantly normal.

Lineaments

Discontinuities, both longitudinal and transverse ones, should be reflected in lineaments visible in various photographs. Lineaments within the Holy Cross Mts. area were mostly located during interpretation of images covering whole Poland. Interestingly, the map of principal lineaments of Poland and adjacent areas shows basically only lineaments oriented NW–SE and ENE–WSW (Graniczny & Mizerski, 2003), i.e., those virtually absent in geological maps (with an important exception of the Mójcza Fault directed NW–SE).

Aerial, satellite or radar images covering only the Holy Cross Mts. were seldom analysed. Undoubtedly, the most extensive such project was the photogeological radar map of the Holy Cross Mts. by Studencki & Wilczyński (1981).

Mizerski & Ozimkowski (1978) used various photographs to analyze the fault network of the Łysogóry Unit.

Comparison of the lineaments detected in satellite and aerial photographs with maps of the surface relief revealed differences between all three kinds of images. It remains to be shown what are the reasons for these discrepancies. Are they due to the thick Pleistocene and Holocene sedimentary cover? Certainly it is not the only reason, as demonstrated by the substantial differences between the maps of photolineaments based upon landscape relief and upon aerial photographs. Thus the causes of the discrepancies must lie deeper.

New ways of tracing transverse and longitudinal dislocations was necessary. Analysis of radar images could provide a solution.

The applicability of radar images to interpretation of tectonic discontinuities was hinted at by the interpretation of surface relief map, revealing some features common with geological maps.

In 2002, Mastella & Mizerski presented new conclusions regarding discontinuous tectonics deduced from radar images:

Possible presence of a longitudinal dislocations, bordering the Łysogóry Unit from the north;

Observation, that transverse faults, so numerous in geological maps, are not manifested in radar images, except for the Łysogóry Fault. Clearly visible are instead NW–SE-oriented faults, dividing the Łysogóry Unit into several thrust sheets;

A possibility of transpressive movements along longitudinal dislocations.

Mastella & Mizerski (2002) based their conclusion on geometrical analysis of discontinuities of various magnitude and their relations to each other, as well as on analysis of geological map of the Radostowa area and Krajny Wall. It was a novel interpretation, contrasting with the previously assumed ones.

Notably, research on the Wiśniówka area by Szczepanik et al. (2004) not only confirm the oblique (NW–SE) orientation of the Wiśniówka Fault, but also (though not noticed by those authors due to stratigraphic nature of their work) the possibility of near N-S-oriented movements, as suggested by Mastella & Mizerski (2002).

All the above facts led the authors to reanalyse the radar images of Palaeozoic core of the Holy Cross Mts. and to perform statistical analysis of lineaments located in the images that could correspond to dislocations.

Analysis of radar images

The images (Fig. 2) performed by Russian company in 1978, used for our interpretation were made by side-looking airborne radar (SLAR) at 26 mm wavelength. The radar signal was emitted and received subhorizontally. The interpreted images were made during flights oblique and parallel to the axis of regional structures. The images in 1 : 200,000 and 1 : 100,000 scales had resolution up to 30 m.

The analysis demonstrated presence of numerous lineaments (Fig. 3), probably reflecting discontinuities, and some of them are identical with previously recognized faults.

Noteworthy, prominently visible in the image is the Łysogóry Fault, the main transverse fault in the Holy Cross Mts. area, while the principal longitudinal dislocation — Holy Cross Mts. Dislocation — is barely noticeable. The latter phenomenon can be due to the thick Pleistocene and Holocene sedimentary cover, impenetrable to the radar beam.

Other transverse faults, known from the Holy Cross Mts. are less evident. Their cartographically determined course only locally coincides with lineaments detected in radar images. So the question remains, whether the faults are real or were they just hypothetically placed in the geological maps?

It should be also noted that a previously unnoticed distinct transverse fracture zone is present across the Łysica–Łysa Góra Massif, as well as many NW–SE-oriented lineaments.

It should be stressed that our analysis confirmed the presence of structures oblique to the Łysogóry Unit, previously noticed by Mastella & Mizerski (2002), as well as the presence of a distinct zone of longitudinal lineaments stretching at the foothills of the Main Range of the Holy Cross Mts. Interestingly, this zone of longitudinal lineaments continues westward also within the rocks of the Permian-Mesozoic envelope, that can be important for interpreting the age of tectonic movements responsible for the origin of these dislocations.

Generally, in the resulting map of lineaments the predominant directions are: WNW–ESE, NW–SE and NE–SW. N–S orientation is subordinate.

To obtain a clearer pattern of main directions of lineaments, they have been plotted in directional diagrams. To avoid overinterpretation, the new lineament map was first superimposed onto that assembled by Wilczyński and Studencki (1980). The combined image (Fig. 4) is equivocal. Some lineaments, traced by the various authors coincide with one another, and with segments of dislocations shown

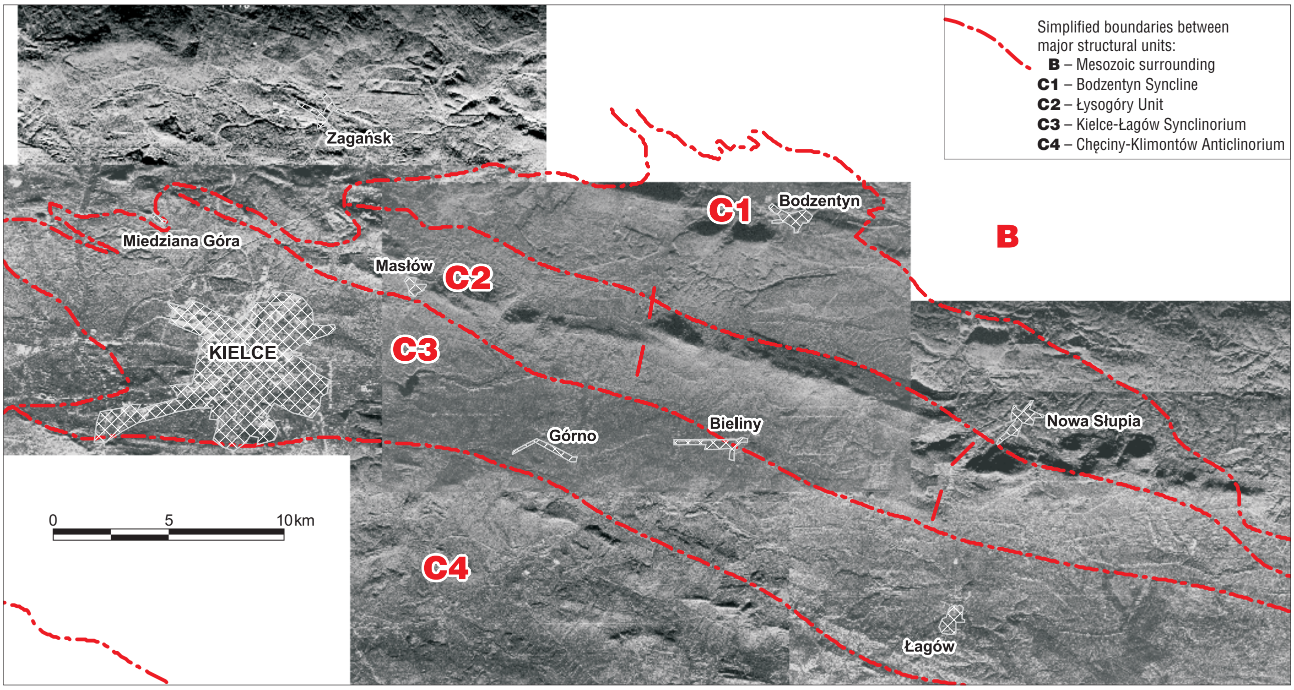

Fig. 2. Radar image of the Holy Cross Mts. area with superimposed major tectonic units of the region, B — Mesozoic margin of the Palaeozoic core of the Holy Cross Mts; C1 — Bronkowice–Wydryszów Anticline and Bodzentyn Syncline; C2 — Łysogóry Unit; C3 — Kielce–Łagów Synclinorium; C4 — Chęciny–Klimontów Anticlinorium

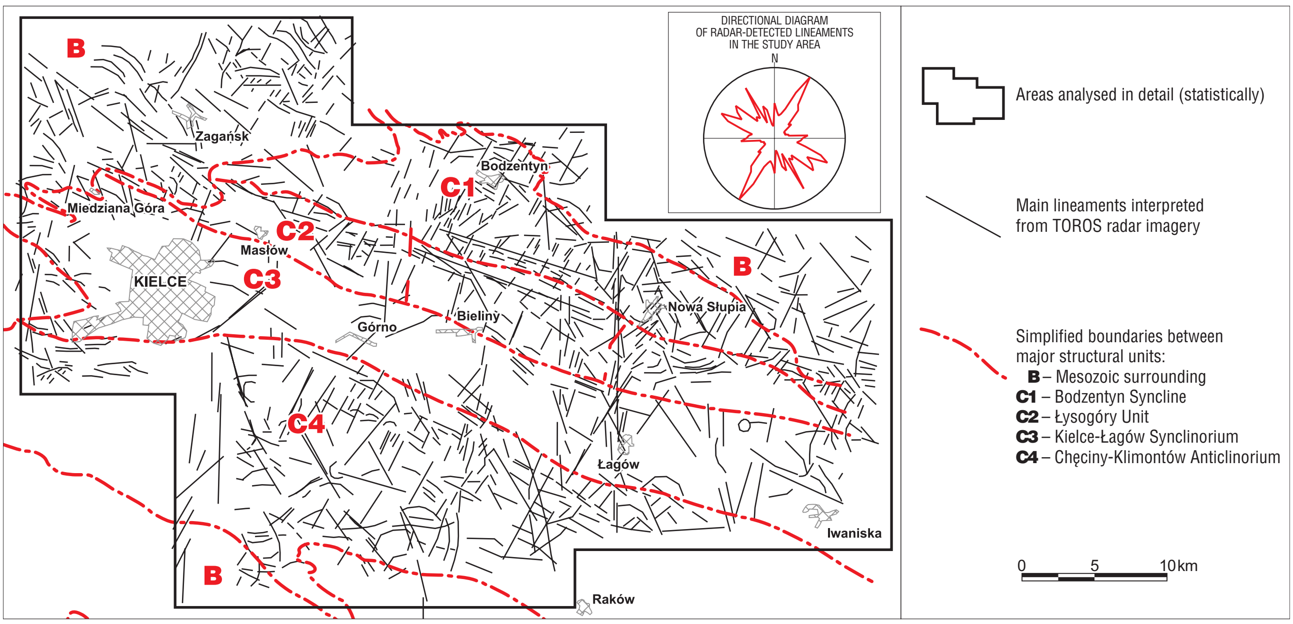

Fig. 3. Lineaments interpreted by the authors and by Wilczyński & Studencki (1981) in radar images of the Holy Cross Mts. area and diagram of directions this lineaments

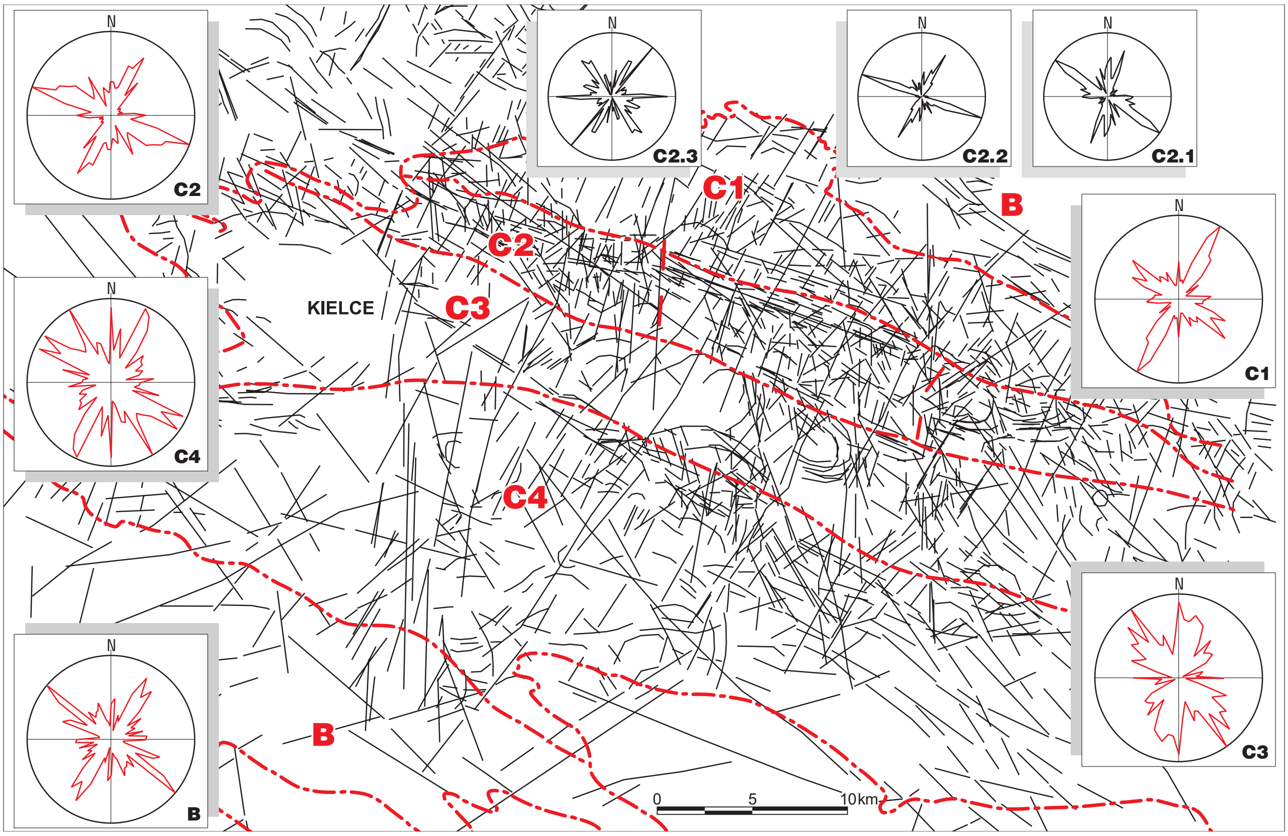

Fig. 4. Map of lineaments within the Holy Cross Mts. area discerned by present authors and by Wilczyński & Studencki (1981), with lineament direction diagrams in the different units of the Holy Cross Mts.

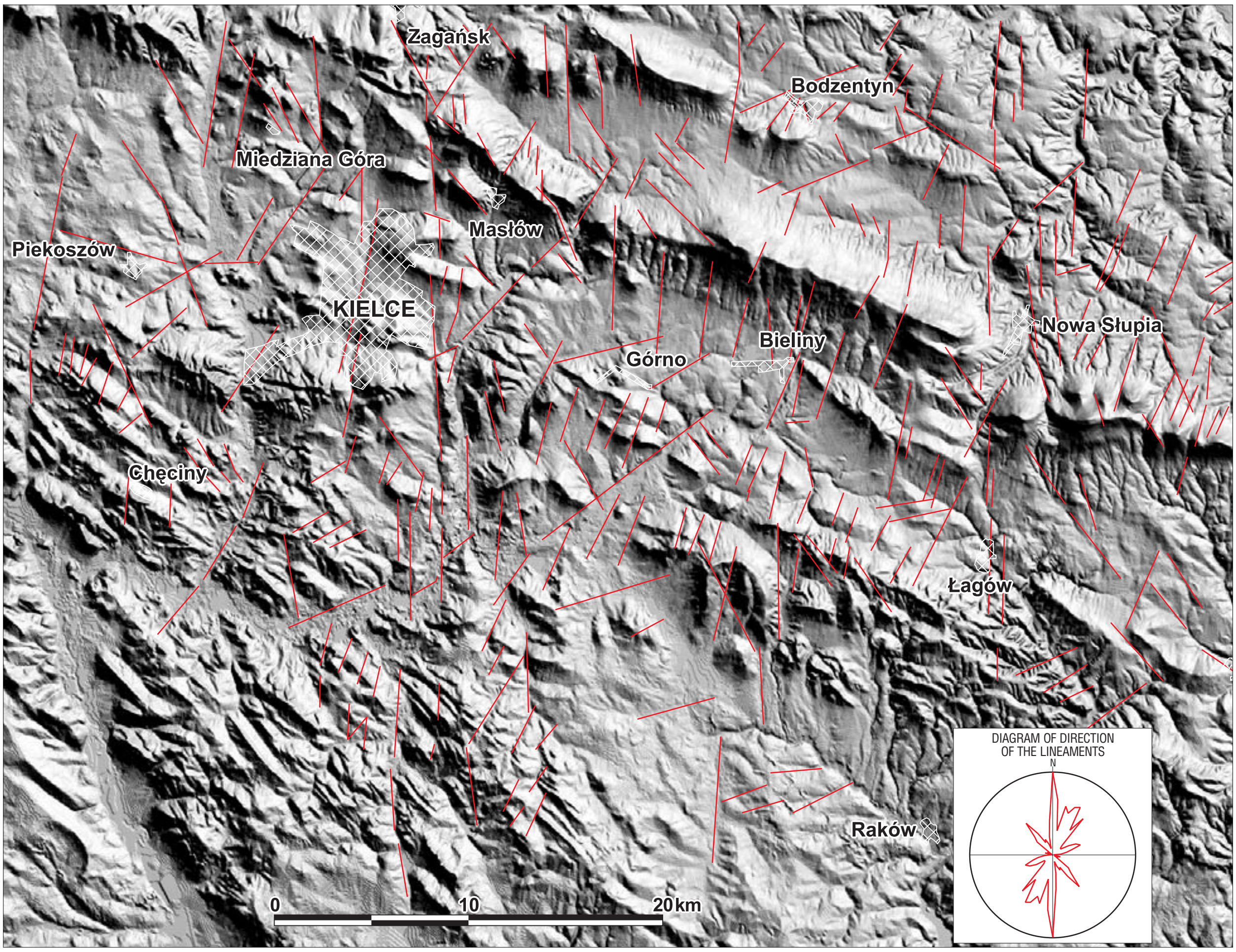

Fig. 5. Digital elevation model and the lineaments traced using it; on the right-side —diagram of direction of the lineaments

in detailed geological maps. However, a wide variety of directions is noticeable all over the area.

A clearer pattern is obtained only after statistical processing of the lineaments and plotting them as rosette diagrams. The diagrams are based on a composite sketch of radar lineaments (Fig. 4), made without discerning those more and less prominent. The circular diagrams show the main directional trends among the lineaments. A composite diagram of all the lineaments was made, as well as diagrams for particular units of the Palaeozoic core and for the Permian-Mesozoic envelope of the Holy Cross Mts.

The composite diagram of radar lineaments of the whole study area reveals two predominant directions: I — WNW–NW–SE–ESE; II — NNE–SSW. Among much rarer directions are: I — W–E; II — N–S; III — NNW–SSE.

Comparing the composite diagram with diagrams for particular units of the Palaeozoic core of the Holy Cross Mts. indicates that the Palaeozoic units of the Holy Cross Mts. differ in the predominant lineament directions (Fig. 4).

A more detailed analysis of lineaments, performed only for the Łysogóry Unit (Fig. 4) allows to discern substantial differences in lineament orientation between various parts of the unit.

In the northern part of the Łysogóry Unit, the predominant directions are: I — WNW–NW–SE–ESE; II — NNE–SSW; III — N–S. In the central, tectonically most uniform part, two directions predominate: I — WNW–ESE; II — NNE–SSW. In the eastern part, the diagram shows a completely different pattern, with three major maxima: I — W–E; II — NW–SE; III — NNE–SSW; IV — NE–SW.

While the pattern of radar photolineaments throughout the whole Palaeozoic core of the Holy Cross Mts. might seem chaotic, individual units and subunits do show regularities. Thus, the radar images of the Holy Cross Mts. Palaeozoic should be analysed separately for smaller domains: particular tectonic units or their parts.

Noteworthy is the large number of longitudinal lineaments in the central segment of the Łysogóry Unit. Their origin can be tectonic, but a major role can be also attributed to lithological features of the rocks outcropping along the axis of the unit. On the other hand, lithologically similar rocks occur also in other parts of the unit, where longitudinal lineaments are common. This suggests that the longitudinal lineaments are of tectonic origin, like the transverse lineaments.

What the radar lineaments really show is still debatable. There is, nevertheless, no doubt that at least some of them reflect actual discontinuities in the Palaeozoic core of the Holy Cross Mts. This problem shall be investigated further.

Digital elevation model

Besides the statistical processing of lineaments discerned in radar images, a similar procedure was applied to the digital elevation model.

In the digital elevation model (Fig. 5), we traced lineaments, equivalent to linear segments of surface relief and thus can be of tectonic origin.

The digital elevation model shows the same part of the Holy Cross Mts. area as the radar images. Thus the patterns of lineaments obtained by analysis of the digital elevation model and radar images can be easily compared.

The lineaments are shown both in the digital elevation model in various scales, and in a sketch map (Fig. 5). A distribution diagram of lineament directions was also made.

The digital elevation model clearly favours three directions: I — N–S; II — NNE–SSW; III — NW–SE.

The longitudinal discontinuities, so characteristic for radar images, are almost entirely missing. This is most probably caused by poor readability of longitudinal discontinuities in landscape morphology, due to locally thick Pleistocene and Holocene sedimentary cover. Transverse lineaments, on the other hand, are well visible, because they transect morphological elevations, where the cover of younger sediments is thin.

Noteworthy is the presence of a NW–SE peak (even though less prominent that the other two maxima). Thus, lineaments of this orientation in the Palaeozoic of the Holy Cross Mts. may reflect existence of discontinuities formed during Laramide movements.

The digital elevation model reveals also, especially in the Łysogóry Unit, lineaments directed WNN–ESE, locally coinciding with faults of such orientation, discerned by previous authors. They may support the hypothesis of dextral rotation suggested by Mastella & Mizerski (2002), perhaps due to the Late Alpine activity (see Mastella & Konon, 2002).

Conclusions

The analysis of the radar images and digital elevation model, and comparison with previous cartographic studies, allowed to discern following major trends among lineaments within the Palaeozoic of the Holy Cross Mts.: NW–SE, NE–SW, WNW–ESE, NNE–SSW, NNW–SSE, W–E and N–S.

All the above lineament directions vary in frequency both in various types of images and in various geological units or their parts.

The analysis confirmed the possibility of dextral rotation within the Palaeozoic of the Holy Cross Mts., as previously suuggested basing on low-angle discontinuities oblique to principal longitudinal discontinuities and main structural units of the Palaeozoic strata in the Holy Cross Mts.

So numerous directions of discontinuities in the Palaeozoic of the Holy Cross Mts. suggests their formation in multiple phases. By analogy with various discontinuities found previously during fieldwork, it can be supposed that the NW–SE discontinuities may be related to the Laramide activisation, those WNW–ESE-oriented with the Late Alpine activisation. Other lineaments are probably associated with various stages of Palaeozoic tectonic activisation, mainly Variscan.

The analytical researches need continuation, especially to clarify the status of various forms noted during field studies.

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