Evaluation of Cartographic Resources in Researching Landforms in High Mountains

Case Study of Double Ridges in the Polish Part of the Tatra Mountains

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Abstract

Cartography has traditionally played an important role in advancing research in physical sciences. This has been even more pronounced in recent years due to the increased availability of high resolution and high definition cartographic resources, such as aerial photography, satellite imagery, large scale topographic and thematic maps and databases. These resources enable researchers to locate and identify ever finer landforms in difficult terrain, such as high mountains.

This paper examines the availability of cartographic resources and systematically evaluates their suitability for researching high mountain landforms in the Polish part of the Tatra Mountains. In particular, it considers methods for identifying and locating double ridges, relatively small longitudinal depressions along mountain ridge tops. The paper suggests that, although the available resources are not yet sufficient for comprehensive geomorphological studies, existing approaches are adequate for detecting larger depressions. It recommends the investigation and evaluation of other cartographic resources currently not available for the Tatra Mountains for more detailed analysis of high mountain landforms.

1. Introduction

Cartography has traditionally played a significant role in supporting physical sciences research, from providing base maps and thematic databases for analysis to representing the results in spatial context. An important part of this support has been facilitated by cartographic products, both hard copy and digital, that deal with mountain environments. Researching geomorphological processes and landforms in difficult terrain can be a very demanding and challenging endeavour. Application of appropriate cartographic resources, reinforced by their systematic evaluation, could form a valuable aid in such studies. In particular, these resources could be used to identify and locate various landforms in high mountains.

Over the last decade, the mountain cartography research efforts have primarily focussed on representation and modelling of mountainous terrain, including issues of design, tools, databases and visualisations (e.g. Haeberling, 2004; Heuberger and Kriz, 2006; Hurni et al., 2001; Kriz, 1999). Other areas of active research include high mountain hazard mapping, monitoring of snow cover and glacier dynamics, as well as cognitive aspects in mountain cartography (e.g. Kaufmann et al., 2006; Kriz, 2001; Trau and Hurni, 2007; Wood et al., 2005). Considerably less attention has been devoted to a systematic evaluation of cartographic resources that could be useful for identifying and locating landforms in high mountains.

An application of a detailed digital elevation model (DEM) to represent the Hellenic Volcanic Arc was described by Vassilopoulou and Hurni (2001). The model was thoroughly evaluated with regard to its positional accuracy and was found suitable as a basic tool for tectonic and geomorphological analysis. However, no examples were given to illustrate the performance of this model in identifying or locating landforms. A process for updating the rock and scree representation on Swiss topographic maps at the scale of 1:25,000 was illustrated by Gilgen (2006). A wide range of cartographic resources including existing maps, photogrammetric plots, and aerial photographs in colour and

Fig. 1: Double ridge at Starorobociańska Przełęcz (no 30, see Fig. 5 for explanation) with Starorobociański Wierch (2176 m) in the background. Photography: Justyna Żyszkowska

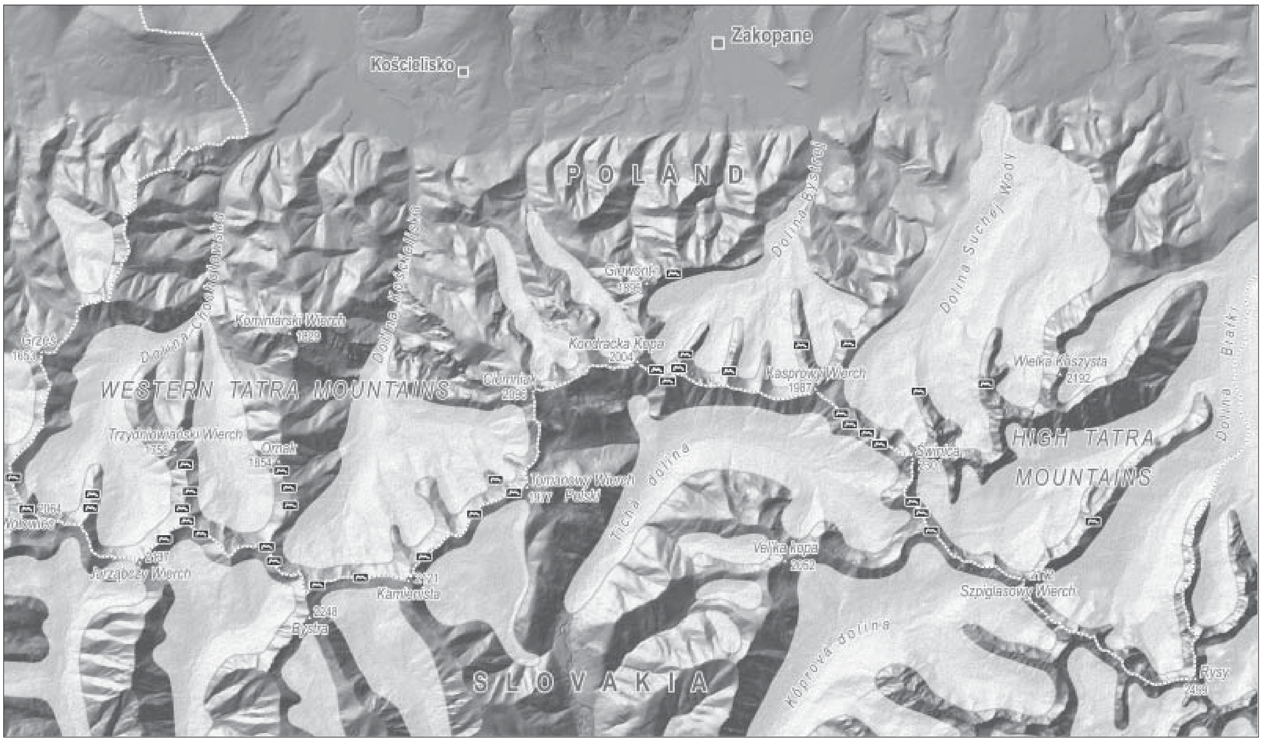

Fig. 2: The Tatra Mountains during Würm (Vistulian) glacial episode (~20,000 years BP) (adapted from Nemčok, 1993) and the current distribution of double ridges. Glaciers are represented by semi-transparent white polygons, while double ridges by solid black-filled symbols. Note the relationship between the locations of double ridges and heavily glaciated neighbouring valleys.

greyscale were used to perform this task. Gilgen (2006) reported that accurate distinction between landforms in mountainous terrain is sometimes difficult to make even for an experienced cartographer. The research did not perform any evaluation of the cartographic resources used in the updating process.

This paper aims to contribute to mountain cartography research by examining the available cartographic resources and systematically evaluating their suitability for identifying and locating high mountain landforms. In particular, it considers methods for detecting double ridges in the Polish part of the Tatra Mountains.

2. Double Ridges

Double ridges are relatively small longitudinal and often asymmetric depressions along mountain ridge tops (Jaroszewski et al., 1985) (Fig. 1). They are formed by a process called sackung which involves gravitational spreading of a mountain ridge and eventually a collapse of large blocks along structural rock fractures and faults. This process leads to the formation of trenches or double-crested ridges at the tops and in some cases a bulging of lower slopes (Barrett, 1997). It is often attributed to the glacial oversteepening of the neighbouring valley walls and removal of lateral support during deglaciation (Barrett, 1997; Żyszkowska, 2005). In some cases, seismic activity can be responsible for the formation of double ridges in high mountains (Jaroszewski et al., 1985).

Double ridges occur mostly in mountain ranges of the Alpine orogenic cycle, especially those built of igneous or metamorphic rocks which were recently or are currently glaciated (Żyszkowska, 2005). The Tatra Mountains are an example of a recently glaciated mountain range where these landforms can be found throughout (Fig. 2).

The term double ridge is not well recognised in English geomorphological literature, despite being very fitting to describe this particular landform. Attempts in popularising this term (e.g. Rubín et al., 1986) were unsuccessful and the name double ridge remains rarely used today. It seems that for many years these landforms were subject of intensive scientific research in a non-English speaking countries where the term double ridge (or alternatively ridge top depression), in local languages of course, has been established and accepted among the scientific community. Examples include zdvojený hřbet (Czech), crête doublée (French), doppelgraten (German), podwójna grań (Polish) and zdvojený hreben (Slovak). The alternative term of ridge top depression has its equivalent in sdružený hřeben (Czech), rów grzbietowy (Polish) and zdruśený hreben (Slovak).

Double ridges are a common landform in high mountains on all continents. Apart from the Tatra Mountains, they have been found and documented on Svalbard and Greenland (Jahn, 1947, 1958), the Alps (Nemčok, 1982), Altay Mountains, Caucasus Mountains (Nemčok, 1982), the Southern Alps (Barrett, 1997), the Japanese Alps, the Andes and the Rocky Mountains (Barrett, 1997; Carson et al., 1997; Nemčok, 1982). They can also be found in the Low Tatra Mountains, Lesser Fatra Mountains (both in Slovakia), Fogaras Mountains (Romania), the Ural Mountains (Russia), the Pyrenees and Himalayas (Żyszkowska, 2005).

The size of double ridges in the Tatra Mountains varies and can be classified into three broad groups based on their morphometric characteristics. Small landforms are up to 2 m deep and up to 80 m long, while the medium size ones are 2–10 m deep and 80–300 m long. The large double ridges can be up to 30 m deep, 10–70 m wide and up to 830 m long. In other parts of the world even larger landforms can be found. For example, Żyszkowska (2005) provides an account of a very large, 100 m deep double ridge located in the Southern Alps of New Zealand near Manapouri (Fig. 3).

3. Polish Part of the Tatra Mountains: Study Area

The Tatra Mountains form the highest part of the 1,300 km long Carpathian Mountains. They cover an area of 785 km^2 and are located on the border between Poland and Slovakia in Central Europe. They are the only mountain range having an alpine landscape between the Alps and the Caucasus Mountains. The highest peak is Gerlachovský štít in Slovakia at 2655 m. Due to the geological composition, and consequently landscape and land relief characteristics, the Tatra Mountains consist of (west to east) the Western Tatra Mountains with the highest peak of Bystra at 2248 m, the High Tatra Mountains and the Belianske Tatra Mountains with the highest peak of Havran at 2152 m.

Fig. 3: A very large double ridge (below the left peak) in the Southern Alps near Manapouri. Photography: Jacek Drecki

The Polish part of the Tatra Mountains occupies only 175 km^2, less than 25% of the entire mountain range and does not include any part of the Belianske Tatra Mountains. The highest peak is Rysy at 2499 m located in the High Tatra Mountains on the border with Slovakia. The highest peak of the Polish part of the Western Tatra Mountains is Starorobociański Wierch (Klin in Slovak) at 2176 m.

Although the occurrence of double ridges is common around the world (e.g. Nemčok, 1982; Barrett, 1997; Żyszkowska, 2005), the Tatra Mountains are an ideal study site due to their great accessibility for undertaking field surveys combined with availability of wide range of cartographic resources. In this research, field survey was limited to the Polish part of the Tatra Mountains covering about 30% of the area and including almost entire main ridge and numerous side ridges (see Fig. 4). The eastern and central part of the High Tatra Mountains, where geological structure of rocks was not favourable for the formation of double ridges, was excluded from the survey. Also the area of Kominiarski Wierch (1829 m) in the Western Tatra Mountains was excluded, as this region was already surveyed by the Tatra National Park rangers and no double ridges were found there.

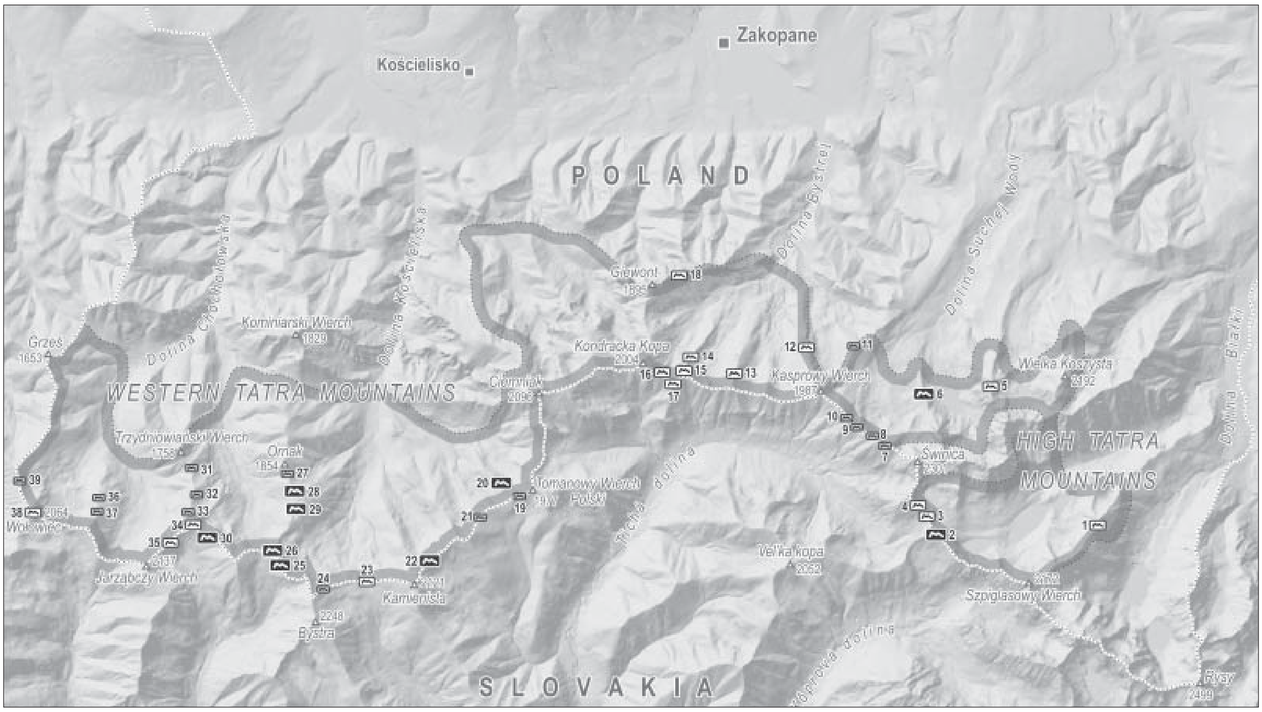

Fig. 4: Distribution of double ridges in the Polish part of the Tatra Mountains and their relative sizes. Consecutive numbers, next to double ridge symbols, correspond to the listing in Fig. 5. Study area is shown by a grey, dotted line and a semi-transparent band on the inside.

No	Name	Size
	Wierch, Turnia – a *Peak,* Przełęcz – a *Saddle,* Grzbiet – a *Ridge*	
1	Opalone *(next to Opalony Wierch)*	M
2	Gładki Wierch	**L**
3	Between Gładka Przełęcz and Walentkowy Wierch	M
4	Next to Walentkowy Wierch	M
5	Żółta Turnia	M
6	Mały Kościelec	**L**
7	Behind Skrajna Turnia - Pits	S
8	Behind Przełęcz Liliowe *(towards the first eastern peak)*	S
9	Przełęcz Liliowe	S
10	Between Przełęcz Liliowe and Beskid	S
11	Uchrocie Kasprowe	S
12	Kasprowy Wierch, Suchy Upłaz *(a ridge between Dolina Goryczkowa and Dolina Sucha Kasprowa)*	M
13	Kondratowy Wierch	M
14	Łopata	M
15	Suchy Wierch Kondracki	M
16	Przełęcz pod Kopą Kondracką	M
17	Przełęcz pod Kopą Kondracką *(in the direction of Suchy Wierch Kondracki)*	M
18	Next to Długi Giewont	M
19	Between Tomanowy Wierch Polski and the arm of Zadni Smreczyński Grzbiet	S
20	Zadni Smreczyński Grzbiet	**L**
21	Between Smreczyńska Przełęcz and Smreczyński Wierch	S
22	Hlińska Przełęcz	**L**
23	Pyszniańska Przełęcz	M
24	Between Pyszniańska Przełęcz and Błyszcz	S
25	Baniste	**L**
26	Siwy Zwornik	**L**
27	Ornak	S
28	Ornak – Siwe Skały	**L**
29	Ornak – Kotły	**L**
30	Starorobociańska Przełęcz	**L**
31	Trzydniowiański Wierch	S
32	Czubik	S
33	Between Czubik and Kończysty Wierch	S
34	Kończysty Wierch	M
35	Jarząbcza Przełęcz	M
36	Czerwony Wierch	S
37	Czerwony Wierch II	S
38	Wołowiec	M
39	Between a saddle next to Wołowiec and Rakoń	S

Fig. 5: Summary of double ridge systems in the Polish part of the Tatra Mountains. The first column (No) refers to the number on Fig. 4 and the third column (Size) to a size of a particular landform, i.e. large (L), medium (M) or small (S).

Fig. 5 (above) lists all double ridges that were identified and located during the survey. There are a total of 39 double ridge systems, including 9 large, 15 medium and 15 small ones. They became a benchmark in evaluating the suitability of cartographic resources for researching double ridges in this study.

4. Cartographic and Non-cartographic Resources

The Tatra Mountains are very well covered by a multitude of cartographic and non-cartographic resources for undertaking research in physical sciences. They include topographical maps, geological maps, specialised geomorphological maps, aerial photography, satellite imagery, digital spatial databases and a wide range of scientific articles and reports. Their suitability for identifying and locating double ridges varies greatly. Discussed below are only those cartographic materials that are relevant in researching double ridges in the Polish part of the Tatra Mountains. They provide a full coverage of the study area at their respective scales and were reasonably easy to access, either from the Warsaw University Library or the Tatra National Park headquarters in Zakopane.

4.1. Topographical Maps

An excellent source of topographic information for the purpose of identifying and locating double ridges is the Polish Tatra Mountains map series (Zarząd Topograficzny Sztabu Generalnego WP, 1984, 1991) at the scale of 1:10,000 (14 sheets). Two editions of these maps were examined, i.e. Edition 1 from 1984 and Edition 3 from 1991. Apart from their currency, the significant difference between these editions is that the 1991 edition shows contour and rock drawing details for entire sheets, while the 1984 one shows these features only up to the national border with Slovakia. Since significant number of double ridges is located on the main mountain ridge along the national border, only the 1991 maps were used in this study because they show topographic information consistently on both sides of the national border.

1:10,000 Polish Tatra Mountains, Edition 3 1991 (labelled TOPO in Fig. 7)

This set of maps provides the most detailed topographical information available for the Polish part of the Tatra Mountains (Fig. 6a). The contour interval is 5 m except the rock drawings and cliffs where 50 m interval is used. Double ridges are represented by either contour lines, or a configuration of rock drawing symbols, or a combination of both. Some landforms are very hard to interpret and require cartographic and geomorphological expertise, often coupled with *a priori* knowledge to be successfully identified on these maps.

4.2. Geological Maps

There are two geological maps that were found suitable for this research. They include the Geological Maps of Polish Tatra Mountains (Guzik and Sokołowski (eds), 1958) at the scale of 1:10,000 (14 sheets) and the Geological Map of Polish Tatra Mountains at the scale of 1:75,000 included in the Polish Tatra Mountains. Geological guide for tourists (Bac-Moszaszwili and Gąsienica-Szostak, 1989).

1:10,000 Geological Maps of Polish Tatra Mountains (GEOL 1)

These maps provide a detailed account of the complex geology of the area. Double ridges are represented by a series of black lines with ticks facing the inside of the landform (Fig. 6b). This symbol can be easily identified on the map by any reader.

1:75,000 Geological Map of Polish Tatra Mountains (GEOL 2)

The map represents generalised geology of the Polish part of Tatra Mountains. A separate symbol, consisting of two black, roughly parallel lines with ticks facing the inside, is used for representing double ridges (Fig. 6c). This symbol can be easily identified on the map by any reader.

4.3. Atlas of Tatra National Park

The Atlas of Tatra National Park (TPN and PTPNoZ, 1985) contains 32 thematic maps including 12 dedicated to physical sciences. Of particular interest for this study is Plate 9 Geomorphology - Western and High Tatra Mountains printed on two facing pages (Klimaszewski, 1985).

1:30,000 Geomorphology - Western and High Tatra Mountains (ATLS)

The map provides a detailed account of various types of landforms present in the Tatra Mountains including fluvial, erosional, glacial, periglacial, karst as well as those shaped by anthropogenic processes (Fig. 6d). Double ridges are represented by a dedicated symbol of two parallel dashed lines in dark blue colour. Their identification on the map is very easy for any reader.

4.4. Aerial Photography and Orthophotomap

There are two image-based cartographic resources available for the Polish part of the Tatra Mountains. They include aerial photography at the scale of approximately 1:29,000 (CODGiK, 1999) and the Tourist Photomap of Polish Tatra Mountains, an ortophotomap at the scale of 1:20,000 (Drachal, 2002). Since the above orthophotomap was digitally compiled using the above aerial photographs, and the necessary orthorectification process introduced some radial displacements of land features (Drachal, 2004), it was decided that there is no real advantage of using this cartographic resource. Therefore, only the aerial photographs were used in this study.

1:29,000 Aerial Photographs of Tatra Mountains (PHTO)

A set of cloud-free aerial images for the Tatra Mountains was taken on 15 September 1999 (Fig. 6e). Because of the flight occurring in mid autumn, the images are subject to long cast shadows and only limited image enhancement procedures were possible to improve their legibility. However, identification of double ridges was possible, although good photo-interpretation skills were required in some instances.

4.5. Other Cartographic Resources

Other cartographic resources considered for this research included the Topographical Map of Slovakia (VKU, 2002, 2007) at the scale of 1:25,000 and the Slovak Orthophotomap of the High Tatra Mountains at the scale of 1:20,000 (VKU, 2003).

The Topographical Map of Slovakia was deemed not suitable for identification of double ridges, mainly due to its scale. A thorough examination revealed that none of the landforms were represented on this map, even the largest 830 m long and 51 m wide double ridge on Hlińska Przełęcz (Hlińska

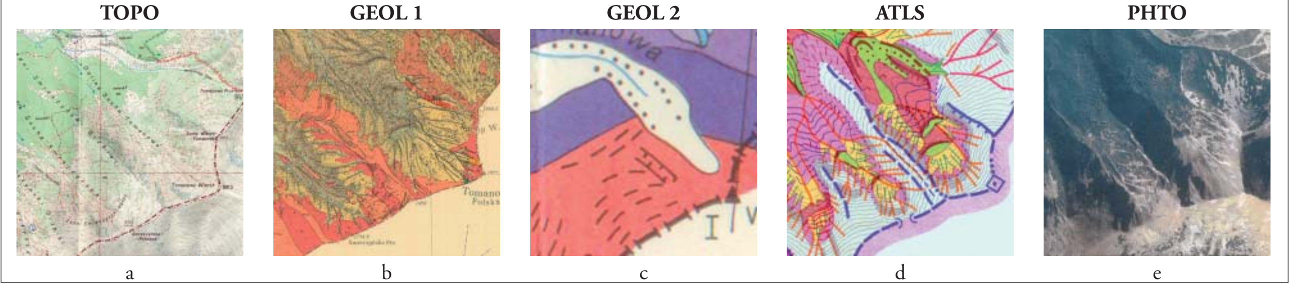
TOPO GEOL 1 GEOL 2 ATLS PHTO

Fig. 6: A series of small samples of cartographic resources used in this study. Their scale is ~1:50,000 and they cover approximately 2.25 km^2 (1.5 x 1.5 km). The area shown spans between Tomanowy Wierch Polski and Zadni Smreczyński Grzbiet. Please note that the Fig. 6e (PHTO) shows the relief in reverse due to the south-eastern sun illumination.

Saddle) in the Western Tatra Mountains (double ridge no 22 on Fig. 4).

The Slovak Orthophotomap of the High Tatra Mountains was also found not suitable as none of the double ridges were shown. It is rather surprising, as both the scale of the orthophotomap and the image-based nature of this resource should allow at least the largest forms (no 2, 4 or 6 on Fig. 4) to be identifiable.

4.6. Non-cartographic Resources

A geomorphological textbook (Klimaszewski, 1988) was referenced in this study as an example of a non-cartographic resource (labelled KLIM in Figure 7). It contains a table (p. 97) of 31 double ridge systems found in the Polish part of the Tatra Mountains. Only general textual descriptions are given without any map (or illustration) that is showing their locations. The table was also included in the evaluation process described below.

5. Evaluation

An evaluation process can take two possible general approaches. The first approach involves establishing a solid benchmark based on a detailed field survey and then evaluating cartographic resources against it. The other approach involves identifying and locating landforms using the available resources and then undertaking a detailed field survey for evaluation purposes. In this research, the first approach was adopted due to an existence of a suitable benchmark.

The *Genesis of Ridge Top Depressions in Polish Tatra Mountains* (Żyszkowska, 2005) is the most comprehensive study of double ridges in the Polish part of the Tatra Mountains available to date. The research was undertaken between 2002 and 2004, and included an extensive field survey of the study area (see Fig. 4). The work contains a detailed description of each of the existing 39 double ridge systems, including their geology, morphometric characteristics and detailed cross-sections. Most of the cartographic resources described above were not significantly used for identifying or locating double ridges. Exceptions include the 1:10,000 topographical maps (TOPO) employed for field survey logistics and for marking all double ridges within the study area, the 1:75,000 Geological Map (GEOL 2) for identifying and locating a double ridge next to Opalony Wierch in the High Tatra Mountains (no 1 on Fig. 4), and the 1:29,000 aerial photographs (PHTO) for illustrating the distribution of all landforms (as an Appendix).

Żyszkowska's (2005) study was found appropriate and fitting to serve as a benchmark for evaluating the suitability of all cartographic and non-cartographic resources described above. The systematic evaluation process involved an assessment of these resources in terms of their performance against data quality components described in the Spatial Data Transfer Standard (SDTS) (NIST, 1992) and in more recent research (e.g. Thomson et al., 2005; Drecki and Maciejewska, 2005; Drecki, 2007). In this study, completeness, accuracy (both spatial and attribute), and logical consistency were particularly relevant. Other data quality components are also briefly discussed below.

5.1. Completeness

Completeness deals with issues of missing information. In this research it is applied to measure the number of double ridges marked on the cartographic resources against the benchmark, i.e. the 39 landforms identified by Żyszkowska (2005). Fig. 7 gives a summary of findings.

Topographical maps (TOPO) were found to be the best cartographic resource with 51.3% of all double ridge systems identified on these maps. Aerial photographs (PHTO) and generalised geological map (GEOL 2) showed just above 25% of all landforms, while geomorphological map (ATLS) just 8 double ridges. On the detailed geological map (GEOL 1) only eight landforms were found, a rather disappointing result considering its scale. One explanation could be that majority of double ridges are located along the main ridge which forms part of the national border. Since the map design forced the authors to show the data only up to the border with Slovakia, they decided against marking only one side of the landform on the map and not the other. The geomorphological textbook (KLIM) was the most complete resource with 64.1% of all landforms listed.

5.2. Positional Accuracy

Positional accuracy is a measure of discrepancy between geographical location of on object and its location on a map. In this research it describes the discrepancy of double ridge locations on all cartographic resources (taking to account their scale) and their true locations in the field. Topographical maps (TOPO) were superior to all other resources with regards to representing double ridges with accuracies of ± 0.5 m in x and y, and ± 0.7 m in z direction. These results were more than satisfactory for describing landforms of this size. Other resources, despite being less accurate, were found at least satisfactory considering their scale. The non-cartographic resource of KLIM was not evaluated for obvious reasons.

5.3. Attribute Accuracy

Attribute accuracy refers to the degree of conformity between graphic description of an object on a map and the attribute of a corresponding object in the field. Considering its pure definition, only TOPO maps were subject to this evaluation. The contour lines were most helpful in identifying double ridges, with 12 landforms interpreted purely from their graphical configuration. Rock drawing was useful in 4 instances, while 4 double ridges were identified using both contour lines and rock drawings.

Furthermore, attribute accuracy was used to check whether double ridges identified on a particular resource had their equivalent in the field. From all identified landforms, only two resources posed some problems. On GEOL 2, two separate double ridges identified by Żyszkowska (2005) (no 30 and 34) were shown as one landform, while KLIM describes

No	TOPO	GEOL 1	GEOL 2	ATLS	PHTO	KLIM	# matched
1			Y(es)				1
2					Y	*Y*	2
3	Y c						1
4					Y	*Y*	2
5							-
6							-
7							-
8						*Y*	1
9						*Y*	1
10	Y c						-
11							-
12		Y				*Y*	2
13						*Y*	1
14	Y c			Y			2
15	Y c	Y		Y	Y	*Y*	5
16	Y c			Y	Y	*Y*	4
17	Y c					*Y***	2
18							-
19							-
20	Y c	Y	Y	Y	Y	*Y*	6
21	Y c					*Y*	2
22	Y c		Y	Y	Y	*Y*	5
23	Y c				Y	*Y*	3
24						*Y*	1
25	Y s		Y		Y	*Y*	3
26	Y c				Y		2
27							-
28	Y cs	Y				*Y*	3
29	Y cs	Y	Y			*Y*	4
30	Y cs		Y*	Y	Y	*Y*	5
31	Y s	Y				*Y*	3
32						*Y*	1
33	Y s	Y		Y			3
34	Y cs	Y	Y*		Y	*Y*	5
35	Y c			Y		*Y*	3
36	Y s		Y			*Y*	3
37			Y			*Y*	2
38			Y			*Y*	2
39							-
Σ	20	8	10	8	11	25	
%	51.3	20.5	25.6	20.5	28.2	64.1	

Fig. 7: A summary of matches between double ridges marked on evaluated resources and the benchmark (Żyszkowska, 2005). Light grey column indicates a non-cartographic resource, i.e. a geomorphological textbook (KLIM). ***c:*** *interpreted from the contour lines;* ***s:*** *interpreted from rock drawing;* ***Y*:*** *double ridges no* ***30*** *and* ***34*** *are shown as one landform;* ***Y**:*** *double ridge no* ***17*** *is described as two separate landforms.*

Size	bnchmk	TOPO	GEOL 1	GEOL 2	ATLS	PHTO	KLIM
L	9	7	3	5	3	6	7
M	15	8	3	3	4	5	10
S	15	5	2	2	1	-	8
Σ	**39**	**20**	**8**	**10**	**8**	**11**	**25**

Fig. 8: A relationship between landform sizes and their appearance on the evaluated resources. None of the resources show all large forms, i.e. over 300 m in length and over 10m in width (Żyszkowska, 2005). Light grey is used to indicate a non-cartographic resource, i.e. a geomorphological textbook (KLIM).

# of resources	Large	Medium	Small	Σ
0	1	2	5	**8**
1 (KLIM only)	-	1	4	**5**
1	-	2	1	**3**
2	2	5	2	**9**
3	1	2	3	**6**
4	2	1	-	**3**
5	2	2	-	**4**
6	1	-	-	**1**
Σ	**9**	**15**	**15**	**39**

Fig. 9: A summary of matches between the size of double ridge systems, i.e. large, medium and small and the number of resources that identify them.

two double ridges at Przełęcz pod Kopą Kondracką, while in the field only one was identified. Also, KLIM lists further five double ridges which were not found in the field during the survey.

5.4. Logical Consistency

In general terms, logical consistency assures that there are no contradictory relationships between a map and field survey data. Since double ridges were classified into three broad classes based on their size, it was expected that all large landforms should be represented first, before medium and small ones. Logical consistency was employed to check whether this is the case.

The results of this exercise are rather surprising. TOPO is missing two large forms (no 2 and 6), but shows several small ones (e.g. no 10, 21, 31, 33 and 36). GEOL 2 misses four large double ridges (no 2, 6, 26 and 28), but shows two small landforms at the same time (no 36 and 37). The most consistent resource was PHTO which shows only large and medium size landforms in a consistent proportion. Fig. 8 summarises the results for all resources.

Fig. 10 gives an overview of a relationship between the position and size of double ridges and the number of resources that identified them. A total of eight landforms are not identified on any of the resources including one large (no 6!), two medium (no 5 and 18) and five small ones. There are five more double ridges, including one medium and four small ones, which are identified only on the non-cartographic resource (KLIM).

There is only one double ridge system that is identified on all six evaluated resources, i.e. Zadni Smreczyński Grzbiet (no 20). Four further landforms, two large (no 22 and 30) and two medium (no 15 and 34) ones are mentioned by five separate resources. All results including four and less matches are given in Fig. 9.

5.5. Other Data Quality Components

Lineage information (NIST, 1992) had little relevance in evaluation process, although it helped to determine which edition of the topographical map (TOPO) to use (see discussion above). Currency (Drecki, 2007) was not evaluated as double ridges have not changed enough in the last 50 years to create difference in their representation on any of the evaluated resources. Credibility, subjectivity, interrelatedness and even precision (Thomson et al., 2005) were not considered. Regrettably, there was not enough information to perform a systematic and thorough evaluation based on these data quality components.

6. Conclusions

This research focused on examining the availability of cartographic resources and evaluating their suitability for researching landforms in high mountains. In particular, it considered methods for identifying and locating double ridges in the Polish part of the Tatra Mountains.

There are several cartographic resources currently available for the Tatra Mountains to assist research in physical sciences. The most useful in this study were topographical (TOPO) and geological maps (GEOL 1 and GEOL 2),

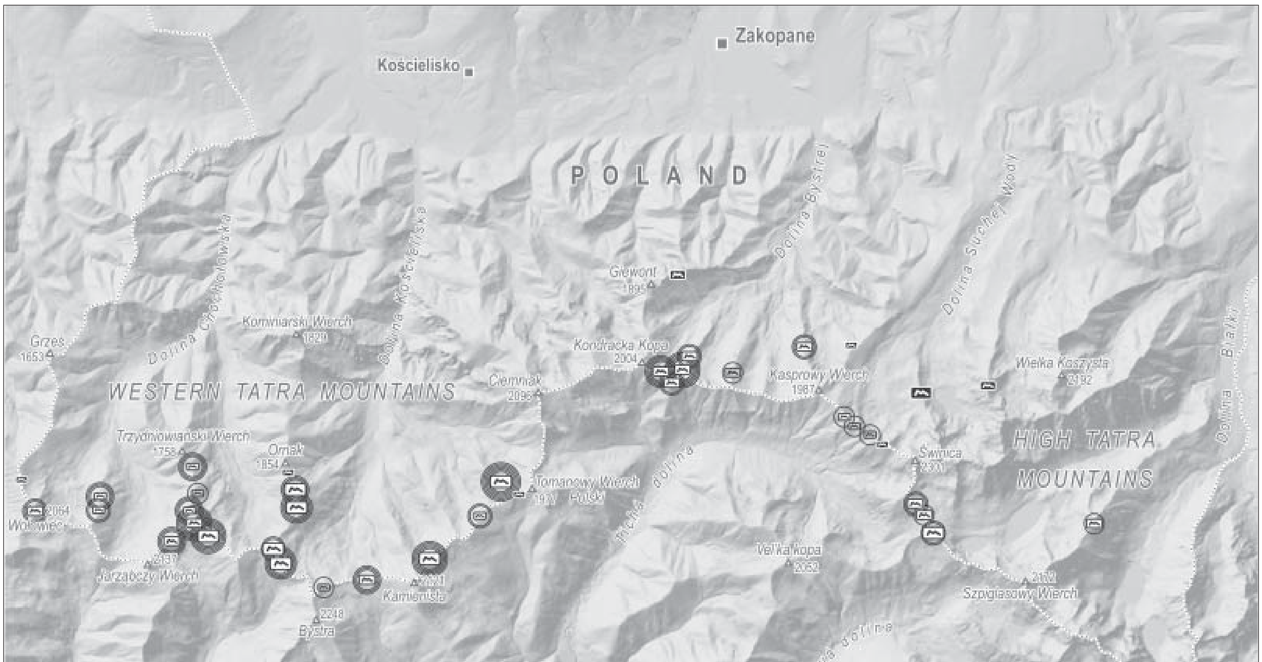

Fig. 10: A relationship between the position and size of double ridges and the number of resources, marked as concentric circles centred on a double ridge symbol, that identify them. Double ridges that are marked by a solid black-filled symbol are not identified by any of the evaluated resources, those marked by a grey-filled symbol are only identified by a non-cartographic resource (KLIM), and those marked by a white-filled symbol are shown on at least one cartographic resource.

a geomorphological map (ATLS) and aerial photographs (PHTO). Accessing these resources was reasonably easy, either at better libraries or at the Tatra National Park headquarters in Zakopane. Their coverage was complete for the entire study area.

A systematic evaluation of cartographic resources used in this study involved the assessment of their performance against data quality components described in SDTS (NIST, 1992), with completeness, accuracy (both spatial and attribute), and logical consistency being particularly relevant. The TOPO scored well against all categories, although some landforms required substantial cartographic experience and *a priori* knowledge to be identified. The PHTO performed well with regards to logical consistency where many large and several medium double ridges were identifiable. A poor performer in the completeness category included GEOL 1 with only 8 out of 39 landforms shown. The geomorphological textbook (KLIM) scored very poorly with regards to attribute accuracy, with several identification mismatches against the benchmark. Unfortunately, it was rather difficult or even impossible to use other data quality categories for evaluation purposes due to the lack of appropriate metadata.

This research demonstrates that many current cartographic resources are not yet sufficient for comprehensive studies of relatively small landforms in high mountains. Ideally more detailed resources from both scale and resolution perspective are required to support such studies. Examples might include high resolution satellite imagery or aerial photography, an optical remote sensing technology such as LIDAR, or large scale topographical or geomorphological maps. Their systematic evaluation, based on the procedure proposed above, is critical in assessing their suitability for researching double ridges or other similar landforms in high mountains. However, it is strongly believed that even high quality resources and rigid evaluation processes would not completely remove a need for a comprehensive field survey.

The adopted approach for studying double ridges was satisfactory in detecting large and medium size depressions. This could potentially help in reducing the time needed for field surveys and in targeting specific areas for logistical planning and field investigation. The key is to use multiple cartographic resources as well as to cross-reference them against relevant literature.

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