ACTA UNIVERSITATIS CAROLINAE
2004 GEOGRAPHICA, No. 1, PAG. 47–58

Morphotectonic effects in fault zones

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Abstract

The work was done from 1989 to 2001 in the territories of Bohemian Massif (Czech Republic) and the Andes of Peru mainly. The approach includes methodical considerations, monitoring and interpretations. For the direct monitoring of present tectonic movements in Bohemian Massif was used the special geodynamic polygon and for the investigation in the fault zone of Cordillera Blanca (Peru) the crack gauge TM-71. Direct morphological manifestation of neotectonic movements consist in a set of disturbed landforms, like dissected moraines, alluvial fans or fault steps in slopes. River capture, reflection of seismic activity and development of fault slopes are other signs of tectonic activity. Indirect morphological signs like increased river erosion, steps in longitudinal valley profiles or valley asymmetry have to be proofed for other possible origin. All of these signs aren't studied individually but are considered to be components of landscape evolution. Comparing the regions under study we conclude that fault zones are characteristic of processes which tend to hazardous situations or create suitable conditions of such situations.

Key words: active tectonics, geomorphology, monitoring, morphostructural analysis

1. Introduction

Publications from different parts of the world describe various effects of neotectonics. Publications oriented to morphostructural effects of young tectonics are less frequent (e.g. Ollier, 1981; Vita-Finzi, 1986; Summerfield, 1997; Burbank and Anderson, 2001; Petro et al., 2004). The problems that concern recent tectonic activity of the Bohemian Massif were approached in a broader scope and the neotectonic research is under extension step by step to more active parts of Europe. In Bohemia it was notably the fault zone of Krušné Hory Mts. (Vilímek, 1995 and Vilímek, Stemberk, 1994). Other investigations concern the marginal zone of Rhine Fault in Germany (Stemberk, Vilímek, 1993), then the contact of the Pamirs with the Tian-Shan Mts., the Vakhsh River zone (Stemberk, Vilímek, 1992), and notably the fault zone that borders the Cordillera Blanca Mts. in Peru (Vilímek, Zapata, 1998). Another work concerns the archaeological locality Machu Picchu in Peru (Vilímek, Zvelebil, 2002), where slope movements are of primary importance, yet their neotectonic predisposition is evident.

We are going to deal with the methods that identify morphotectonic effects, and with their real manifestations in relief. Uneven geological-morphotectonical conditions, reached levels of general examination, technical conditions for instrumentation, and even, not the least, an access to the locality in the terrain, resulted in local differentiation of the work character and applied methods. However, the aim was the same and variations in the type of locality allow comparison of morphotectonic effects in fault zones of an uneven activity. Research in active orogenous areas is useful when studying neotectonic effects and phenomena in relatively more stable Bohemian Massif. Our concern was mainly disjunctive tectonics, nevertheless, in particular cases, there is an importance even of the conjunctive deformations which provide conditions for increasing activity of exogenous processes.

Regarding the geological past, the work concentrates to the neotectonic movements because it was just these movements that produced dominant features of the present relief. The definition of the movement and an overview of our approach were given by Stemberk (1991). Regarding the fact that the most recent geological history has the best covering, available historical data, and the chance for monitoring, it is just the phenomena described usually as present or recent tectonic movements which play an important role in the examination of neotectonic movements (Stemberk, 1991).

Processes of disjunctive tectonics are closely connected with the development of the fault zone relief. These are areas where direct products of vertical and horizontal displacements, as well as combined movements can be found. Disjunctive time-character of these movements can be also observed during seismic events. This is why studies in seismic zones provide important data for geomorphology, and vice versa, geomorphologic methods are beneficial in finding paleoseismic data.

2. Research methods

Different methods were used regarding specific geological and geomorphologic conditions. In the Krušné Hory Mts. a special geodynamical polygon with precise levelling was organized (Kalvoda et al., 1993, 1994). Later on, an evaluation of geodetic survey was done (Vilímek, 1996).

In Peru, the Cordillera Blanca, it was the crack gauge TM-71 that was installed in a selected fault zone (Vilímek, Zapata, 1996), (Photo 1). Results in terms of displacements are evaluated continuously (Košťák et al., 2002). Monitoring with the use of rod dilatometers was applied at Machu Picchu to determine slope movements. Nevertheless, the paleogeographical development of the locality cannot exclude registration of even tectonic movements (Vilímek, Zvelebil, 2002).

The zone of the Krušné Hory Mts. Fault in the NW section of Bohemian Massif was found as a very useful area for studying morphotectonic fault zone effects because, due to a long period of coal mining, the area is well examined from the point of view of geology and geomorphology. Moreover, it is well instrumented for monitoring (e.g. Košťák, 1998; Vilímek, 1999a; Košťák et. al., 2001). As for morphotectonic effects, it is the tectonically more active area like the fault zone at the toe of the Cordillera Blanca Mts. in Peru where our investigations took place, that is of higher importance. Nevertheless, when trying to introduce monitoring, the Andes of Peru is a difficult area to reach the level of examination that exists in the Krušné Hory Mts.

Looking for areas with optimum conditions we may come to the Mediterranean with its activity of young tectonic movements which are relatively intensive. More-

Photo 1 The result of the youngest faulting is a step in the slope covered by glacial sediments. Across this step was the trench excavated and crack gauge TM-71 installed (Photo by V. Vilímek)

over, research can be supported with the most effective technical methods for paleodating and monitoring. One can present an example of the research being introduced on the Gargano Peninsula and the Central Apennines in Italy, which fulfils the condition of a well balanced geological, and geomorphologic methodical approach (Piccardi, 1998).

Vilímek (1997) and Vilímek (1999b) described research methods of Quaternary tectonic movements generally. The optimum research into most recent tectonic movements can proceed in the following steps (not necessarily in the given order):

- Analysis of topographic maps and aerial or satellite pictures (e.g. search for: lineaments, stream and block pattern character of the relief).
- Use of geological maps (geological structure, character of fault tectonics, etc.).
- Preliminary field investigations (recognition of relief type and processes).
- Analysis of borehole documentation, description of outcrops and exploration pits.
- Construction of cross and longitudinal profiles of selected valleys or streams using topographic maps of suitable scale and detail (identification of steps in the gradient and asymmetry of valleys, etc.).
- Geomorphological survey and mapping (documentation, maps and analysis of relief forms).
- Transfer of other geoscience data and their consequent processing into a model of the relief development (e.g. studies of engineering-geological, geophysical and geodetic documentation).

- Selection of zones, places or areas of anomalies in the relief development that could indicate present or Quaternary activity of tectonic processes. Consequently, their detailed investigation including mapping.
- Designing actual exploratory actions, like geophysical or engineering-geological, to verify dynamics of tectonic processes in selected localities.
- Synthesis of all investigations to define development of the relief, its recent changes, and production of a special geodynamical map.

The results should be correlated with all other geoscience data. Suggested combination of geomorphologic, geological, geophysical and geodetic data should be balanced, and then methodically developed and tested in selected areas.

3. Monitoring of present tectonic movements

Monitoring in the Krušné Hory Mts. employed precise levelling and registered mean uplifts that reached about 1 mm per year in the area adjacent to the castle of Jezeří (Košťák et al., 2001). One should stress, of course, that the sensitivity of levelling was lower than that of the measurement done with the use of the crack gauge TM-71. Also, the quality of stabilization of Pitec measurement is higher, and the measurement is arranged across the fault plane which was unambiguously identified. A special geodynamical levelling traverse with individual geodetic points that were stabilized in zones subject to different types of deformation processes provided serious variation of anomalous increments in positions of the points. This has shown that different geological structures react to unloading due to excavations in the basin, as well as to seismic impulses unevenly (Kalvoda et al., 1994).

In the Krušné Hory Mts., anomalies of movement trends appropriate to six individual geological points were registered from the fall of 1988 to the spring of 1989. The anomalies can be explained most probably with a reference to the earthquake near Bad Salzungen in Germany, dated 13. 3. 1989 (Kalvoda et al., 1994). Most intensive uplifts between 1984 and 1992 were registered on geodetic lines Z_2b 11, Z_2b 12 a Z_2b 3 at geodetic points lying in the superficial part of the Krušné Hory Mts. fault slope. This was found including a point with deep stabilization (Vilímek, 1996).

Direct measurements performed currently with TM-71 at the Pitec locality, the Cordillera Blanca, where documentation indicated an older movement of 6.5 m, provided following data. The most significant single movement was registered due to the earthquake of 15. 8. 1997 (M 3.8; focal depth 100 km; epicentre on the opposite eastern side of the ridge). The indicated movement was vertical, reading 0.55 mm (Fig. 1). (Coordinate x indicated slow opening and coordinate z vertical displacement in the investigated fault plain.) Other movements were relatively lower. With the exception of one single step, one can evaluate the five-year measurement period as relatively calm, leaving time to increase stresses. Besides, the Pitec gauging with TM-71 indicated continuing opening of the fault trench, indicated also by outwash of soil into the open crack. A tendency of angular deviations (gama xz) seems to indicate pressure growth in the depth (Košťák et al., 2002).

Mean rates of movements were estimated in Cordillera Blanca as follows: Yonekura et al. (1979) 2 to 3 mm; Schwartz (1983) 0.86 to 1.1 mm; Bonnot (1984) 0.7 mm per year. Peruvian experience with TM-71 shows that when good stabilization secured, the

gauge can be installed even into sediments without the danger of disqualification of measurements by exogene effects (Vilímek, Zapata, 1996). Variations of precipitation and temperature are to be considered inevitable always, similarly to geodetic measurements.

The interpretation of such direct measurements must respect paleogeography with its evaluation of long-term development of the relief. Although useful in quantification of present relief processes, the measurements increase their value considerably only when correlated with other findings (e.g. stress in the massif). According to B. Košťák (private communication) findings regarding movement trends and reactions to different events in the massif will be more valuable than absolute measured values. One should consider the fact that neotectonic movements may result not only in long-term slow creep displacements but also in sudden shifts due to earthquakes. Both will produce shifts of Earth Crust blocks which after a time would be manifested by abnormal erosion or accumulation processes.

Results of monitoring could be depreciated or even covered by exogene effects. Geodetic results have to be interpreted with regard to the period in which the measurement has been done, since spring provides uplifts due to water saturation of the massif or of the individual superficial deposits (Kalvoda, Zeman, 1982).

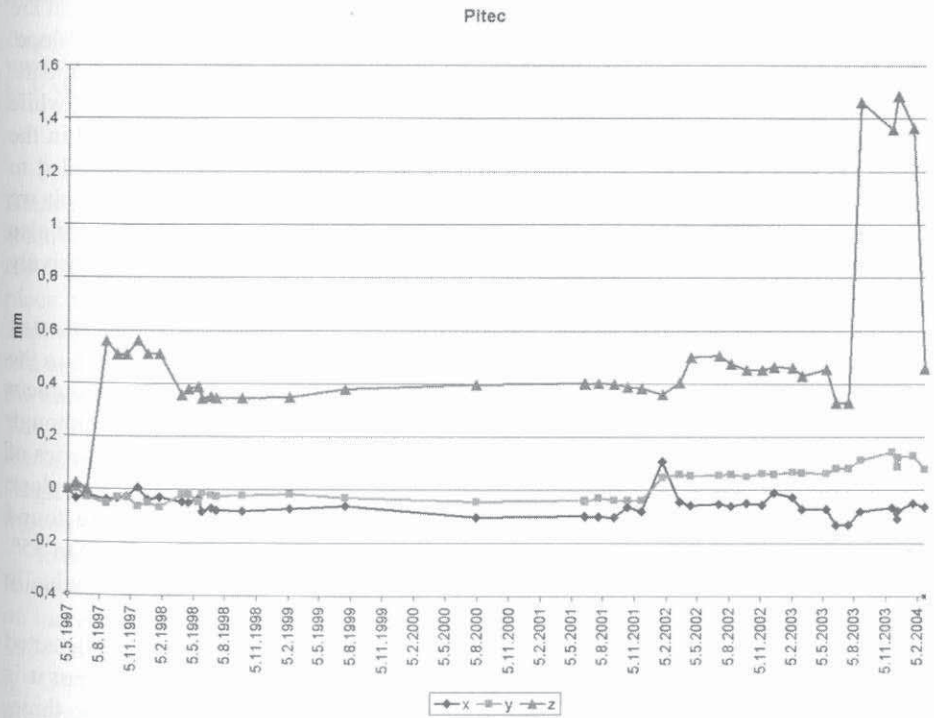

Fig. 1 Direct measurement of movements at the fault in Pitec under Cordillera Blanca (Peru). Displacements: **x** – horizontal component across the scarp, **y** – horizontal component along the scarp, **z** – vertical component

Fault slopes of the Krušné Hory Mts. and the Cordillera Blanca are of a different character appropriate to different age and dynamics of the relief processes, and partially also due to different type of the processes. The slope of the Krušné Hory Mts. is presently in the stage of a more advanced denudation, and the original tectonic forms are more difficult to be identified. Nevertheless, even here neotectonics was more efficient in the formation of the relief than climatic alterations.

Uplifts of the Krušné Hory Mts. appeared even before Quaternary as testified by the granular character of accumulations at the slope toe. Increase of difference in altitude between the mountains and the basin, that took place in Quaternary, can be attributed more likely to the uplifts in the mountainous block rather than to a subsidence in the basin. An intensive uplift of the investigated part of the mountains in the period of Middle Pleistocene – beginning with Riss, can be documented with the volume and age of sediments at the toe. Holocene, as well as present movements are likely to be less intensive. However, the uplift was uneven in the individual parts (Vilímek, 1995).

The origin and development of the Krušné Hory Mts. fault slope impressed the original character of the drainage system in the area. It is evidenced by the contrast between flat, moderately undulated denudation platforms with shallow valleys that are found on the flat top of the Krušné Hory Mts., and the deep valley cuts in the fault slope. The surface itself flattened originally was also dissected by neotectonic movements. Individual sectors are tectonically limited and apparently separated in elevations, while internal altitude variations are lower. Quite a different character was indicated in the so-called slope valleys even regarding longitudinal profiles. The flows responded to the intensive uplift of the mountains which was uneven in plain, and as a result we can compare different altitudes of the heads of erosion phases. The uplift caused also entrapment of the lower sections of some flows by younger and more intensively evolving slope flows.

The outcrop of fault plain found near Osek Town bears evident signs of weathering (Photo 2). Similar localities are unique in the Krušné Hory Mts. Contrary to that, in the zone of Cordillera Blanca fault on such outcrops of fault plain was possible to document the striations. The same was found in the archaeological site of Machu Picchu, although no morphologically clear and continuous fault slope was indicated there. The series of measurements earlier mentioned provided a chance to construct a model of fault slope development in the Cordillera Blanca. Gradients of partial fault planes were found between 50 to 70°, while the general inclination of the fault slope, was only 30 to 35°. Primary the slope was formed by a series of partial tectonic movements and gradually exogenous processes degraded the slope gradient by 20°.

The youngest fault step well identified from aerial photos, and even directly detected in the relief at the toe of the Cordillera Blanca, has no linear course in fact but it is moderately undulated. Moreover, it was found split into two, exceptionally into three, at places. Its course is modified sometimes with slope movements. In the trench where the crack gauge TM71 was installed (Vilímek, Zapata, 1996) the fault plane gradient reads 70°, while the superficial form (fault step) now reads 45° only.

Photo 2 The outcrop of fault plain in Krušné Hory Mts. (NW Bohemian Massif) is rather intensively weathered. Similar outcrops on the fault slope of Cordillera Blanca were accompanied by striations (Photo by V. Vilímek)

Partial movements in individual segments of the main toe fault of the Cordillera Blanca was registered by individual authors as follows: Lliboutry et al. (1977) 10 m; Read (1979) 6 m; Schwartz (1983) 2.5 m; Bonnot (1984) remarks "rarely to 10 m". Such results were confirmed by fieldwork at different sectors of the fault belt, since only one place was found (at the head of Valley Ishinca), where the value reached 10 m (Vilímek, Zapata, 1998). Observations at other localities came to lower values. Nevertheless, one can assume even here different levels of movement activity in individual segments of the normal fault bisected by crossfaults, similarly to the Krušné Hory Mts. observation. There is an unanswered question, however, what is the contribution of slow long-term tectonic movements to the formation of the fault slope, and what is that of sudden, single movements during seismic events. This is why direct measurements of tectonic movements become so urgent.

Investigating the period of last 210 years in the Krušné Hory Mts. and in its forefield, section between the towns of Kadaň and Chomutov, there were 4 periods of increased seismicity identified, notably 1784–1785, 1860–1866, 1896–1914 and 1977–1980 (Vilímek, Stemberk, 1994). The intensity was usually in the limits $I_0 = 3° – 4°$ MSK-64 with only two exceptions $I_0 = 5°$ MSK-64. Nikonov (private communication) forwarded an assumption that in the period of the latest 1000 years the intensity I_0 might have reached 7.5° MSK-64. At the locality Salesius Hill near the town of Osek investigations discovered cases of individual quartzite rock plates shifted against the action of gravitation (Vilímek et al., 2002).

We had a chance to observe interesting manifestations of tectonic activity in the region of Vakhsh nappe in the Pamirs. There are described cases of phenomena there like inclined buried soil horizons, landslides triggered by seismic events, chaotically mixed horizons of loess (Stemberk, Vilímek, 1992), overfault of Cretaceous rocks sitting on Quaternary sediments (Nikonov, 1981). Observations of the SW margin of the Rhine Fault after the earthquake of April 13, 1992 provided data showing that the positioning of the most intensive superficial effects did not coincide with the epicentre. The largest macroseismic effects appeared at places where the active fault reached the surface (Stemberk, Vilímek, 1993).

5. Indirect morphological signs of neotectonic movements

Indirect morphological signs of neotectonic movements are notably needed in regions of lower tectonic activity, These are e.g. increased level of erosion or accumulation, valley asymmetry, steps in valley bottom in the longitudinal profile, etc (Photo 3). However, all these signs may be of another origin, like increased precipitation in the drainage area, different lithological conditions. This is why all indirect morphological signs of neotectonic movements should be seen in the context with the set of other forms, and in regard of present and preceding morphological processes. Spatial analysis of recent geodynamic movements in the middle course area of the Ohře River (NW Bohemia) provided a result that they show a tendency to concentrate to specific places in relation to conditioning factors (Vilímek, Stemberk, 1994). Time analysis shows a similar tendency – phase development.

Photo 3 Due to the neotectonic uplift is the river erosion and following accumulation in the zone of Vakhsh nappe (Pamirs) very intensive (Photo by V. Vilímek)

Current erosion–denudation process in the Bohemian Massif precludes often discernment whether given superficial forms resulted from old tectonic movements or represent only a sign of passive morphostructure (Balatka et al., 1999). However, morphostructural research made possible to discern morphostructural units of relatively independent evolution, as exemplified by the research in the drainage area of the Jihlava River in the SE of Bohemian Massif (Balatka et al., 2000).

6. Conclusions

The role of geomorphology in the research of young active tectonics, is identification of such periods and zones, which exhibit the specific disproportion between tectonic failure and potential dynamic balance. Comparison of neotectonically active regions (selected regions of the Peruvian Andes and Bohemian Massif) identified similar, as well as dissimilar signs that follow different intensity of tectonic movements, and of the dynamics of present formative processes in the relief. The intensity of exogene factors can be well studied on the Cordillera Blanca fault slope, where the general slope gradient was in average by 20° lower than the gradient of partial fault planes.

The fault slopes in the two selected regions are of different character. Nevertheless, even in the region of Bohemian Massif one can conclude that neotectonic effects are predominant over the climatic ones in the landscape evolution. Besides, it was possible to localize sections of the fault slope with more intensive uplifts and identify the effect of young tectonic movements to the development of the drainage system (e.g. entrapment).

Both the regions have shown chances to identify seismic events in the fault zones. On the other hand, relatively fast action of exogene factors brings about a situation that young fault steps and visual defects of superficial forms (e.g. dejection cones, moraines), as well as striations on exposed fault plains are preserved only in the case of younger and more intensive tectonic movements of the Peruvian Andes.

A more close recognition of fault movements and of their character (slow, intensive, continual, and episodic) is possible with the use of the crack gauge TM-71, as exemplified on the locality of Pitec, Peru. We have identified the minimum intensity of the movement (6.5 m in total) from the position of correlate sediments, and monitoring of the movements is under way at the place. The series of Pitec measurements provided a chance to construct the present stage model of the particular fault slope development in the Cordillera Blanca. Results must be interpreted with a particular regard to morphostructural nature of the relief. This is to be remembered mainly when a transfer of local data to major units is made. One cannot define uplift or subsidence of a mountainous range having only one locality data. Moreover, one must see that the intensity of tectonic movements will be variable in time.

Active fault zones monitoring may help to solve two basic questions: what is the contribution of slow long-term tectonic movements to the formation of the particular fault slope, and what is that of sudden, single movements during seismic and other episodical events. Morphostructural analysis and indirect signs of neotectonic movements may help to discern morphostructural units of relatively independent evolution. Even in areas, where it is impossible to identify signs of active tectonics regarding the lapse of time since the last movements, and high intensity of exogenic processes, as exemplified in the drainage area of the Jihlava River (SE of Bohemian Massif).

Impulses of fast changes in the relief and countryside, like earthquakes, global warming, intensive precipitation accompanying in Peru the effect of El Niño, and also those of anthropogenous activity are extremely effective in specifically sensitive places. The zones that exhibit such specifically increased sensitivity are just the tectonically active zones.

Acknowledgements

This work was supported by the project MSM 00216 20831 and by INGO, LA 157 from the Czech Ministry of Education, Youth and Physical Culture.

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MORFOTEKTONICKÉ PROJEVY NA ZLOMOVÝCH ZÓNÁCH

Résumé

V rámci výzkumu geomorfologických projevů recentní tektoniky byly porovnávány regiony s různou mírou intenzity neotektonických pohybů. Srovnání bylo provedeno zejména mezi územím Krušných hor a některými oblastmi s vyšší mírou recentní tektoniky, jako pohoří Cordillera Blanca v Peru či zóna Vachšského násunu (mezi Pamírem a Ťan Šanem). Při srovnání bylo využito jak metod přímého monitoringu, tak též interpretace nepřímých projevů neotektoniky, a to odezvy oxogenních procesů na tento typ endogenních pochodů.

Mezi oblastmi s různou intenzitou neotektonických pochodů byly nalezeny jak shodné, tak i rozdílné rysy. Např. exogenní přemodelování původního zlomového svahu v Krušných horách se nachází v nepoměrně pokročilejším stádiu vývoje ve srovnání se zlomovými svahy pohoří Cordillera Blanca, nicméně i v Krušných horách lze doložit převažující vliv neotektoniky na vývoji tzv. svahových údolí nad vlivy klimatickými.

Seismická aktivita je identifikovatelná ve všech studovaných regionech, i když s různou intenzitou. Mladými pohyby porušené formy reliéfu (dejekční kužely, morény apod.) lze ze studovaných regionů popsat pouze z oblasti Peruánských And či Vachšského násunu. I v částech Českého masívu, kde jsou stopy neotektonických pohybů již setřeny, lze pomocí morfostrukturní analýzy identifikovat oblasti (zóny) relativně odlišného neotektonického vývoje.

Zlomové zóny jsou více náchylné ke změnám v reliéfu a v krajině, jako jsou např. globální oteplování, extrémní srážky doprovázející efekt El Niño či antropogenní zásahy do přírodního prostředí.