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FAULT NETWORK IN RIO COLCA VALLEY BETWEEN MACA AND PINCHOLLO, CENTRAL ANDES, SOUTHERN PERU

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Abstract: The network of faults and joints within the Mesozoic, Miocene and Pleistocene–Holocene formations was studied in the Rio Colca valley, in the Pinchollo–Lari–Maca area (Central Andes, southern Peru). A complex, multi-phase development of these structures was revealed. The results show that the structural framework of the Rio Colca valley consists of WNW–ESE and NE–SW faults, and a few W–E faults. The strike of the most common fault sets is approximately parallel (longitudinal) or perpendicular (transverse) to the W–E oriented strike of stratification surfaces in the Mesozoic sedimentary series and the W–E fold macro-structures, developed in these strata. Diagonal faults and joints are less common, although at some localities they are numerous. The recurrence of major fault systems throughout the Mesozoic and Miocene series and the Pleistocene–Holocene (mainly colluvial) deposits is proof of recent, tectonic activity in the study area. The recent faulting has led to the development of a system of distinct, primary fault scarps, tectonic grabens and horsts, as well as open fissures, which are well marked in the surface morphology, and in many cases have not yet been eroded.

Key words: tectonics, structural geology, fault activity, Rio Colca valley, Andes, southern Peru.

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INTRODUCTION

The structural setting of the Rio Colca Canyon and the Valley of Volcanoes was investigated during the 2006, 2008 and 2010 field seasons. Such research had not been carried out previously in the area. The areas, studied during these expeditions, included (Fig. 1): the Colca Canyon in the areas of Huambo-Canco (1), Cabanaconde-Paradiso-Llahuar-Soro, Cabanaconde-Choco (2), the valley of the Rio Colca (above the Canyon) in the section from Chivay to Pinchollo (3), and the Valley of Volcanoes in the areas of Ayo, Chachas and Orcopampa (4). The main objective of the studies was to investigate the structural setting of the Colca Canyon and also to determine the relationship between tectonic activity and volcanic processes, as well as the geohazards, resulting from them in the area (volcanic eruptions, displacement and ground deformation), associated with fault activity, earthquakes, landslides and mudslides (e.g., Sébrier *et al.*, 1985; Sébrier and Soler, 1991; Dorbath *et al.*, 1991; Huamán-Rodrigo *et al.*, 1993; Żaba and Małolepszy, 2008a; Żaba *et al.*, 2009).

This paper presents the results of structural investigations, conducted in the valley of the Rio Colca in the section from Chivay through Madrigal, Lari and Maca to Pinchollo (see area 3 on Fig. 1). The studies were focused on an attempt to determine the orientation, nature and relative sequence in the fault network, which was regarded as important from scientific, as well as practical points of view. Faulting, associated with volcanic processes, is still very active in the area, initiating earthquakes and mass movement, which threaten both inhabited and agricultural areas. For instance, the earthquake of 1991, 5.6 on the Richter scale, initiated a massive landslide in the vicinity of Maca village, completely destroying it. These shocks had a close connection to the activity of the nearby volcano, Sabancaya, located to the south of the site (see Guillande and Salas, 1995; Bulmer *et al.*, 1999; Antayhua *et al.*, 2001, 2002). Included among the structures studied were tectonic horsts and grabens in the Holocene deposits, with scarps reaching up to several metres. These are clearly expressed in surface morphology, which was generated during the seismic event (and later earthquakes in 1992, 1998). The study provided a unique opportunity to compare the different characteristics of these newly formed faults and the older structures, occurring in the Mesozoic strata.

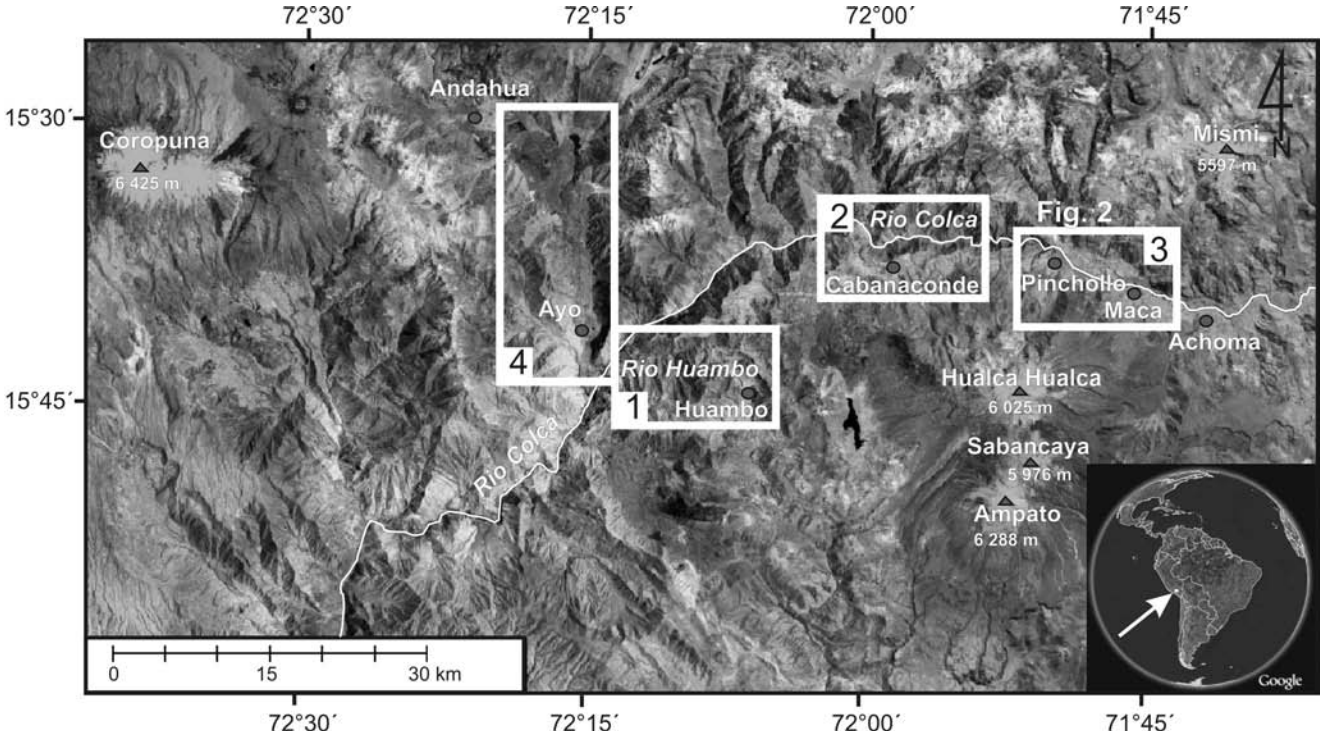


Fig. 1. Location map for study area of the Polish Scientific Expeditions, Peru 2006, 2008 and 2010 (studied areas in rectangles) in vicinity of Colca Canyon, Central Andes, Southern Peru (LANDSAT 7)

THE AREA OF STUDY

The middle section of the Rio Colca valley between Pinchollo and Maca was chosen for detailed structural investigation (Fig. 1). The area is located in Arequipa Province, in the Central Andes (Cordillera Central) of southern Peru (Garayar, 2004; Fig. 1). It is situated between two large and powerful, Neogene volcanic massifs, represented primarily by the stratovolcanoes: Sepregina (5,597 m a.s.l.) – Mismi (5,597 m a.s.l.) in the north and Hualca Hualca (6,025 m a.s.l.) – Sabancaya (5,976 m a.s.l.) – Ampato (6,288 m a.s.l.) in the south (Fig. 1). The bottom of the Rio Colca valley in this area is located at an altitude of 3,030–3,220 m a.s.l. The river runs mainly in an ESE–WNW direction, whereas a latitudinal orientation (W–E) of the valley occurs only in the eastern part, near the villages of Lari and Maca. Downcutting of the Rio Colca to the present valley floor was more or less completed between 9 and 3.8 Ma, but was followed by filling, due to pyroclastic flows, until 1.36 Ma and finally re-incision (Thouret *et al.*, 2007). The lack of correlation between channel slope and bedrock lithology, as well as the extreme V-shaped morphology of the valley (especially in the middle section) suggest that the incision of the Rio Colca was controlled by external parameters, namely runoff (climate) and/or tectonic activity (Gonzales and Pfiffner, 2012).

The study area is located above the active subduction zone of the Nazca Plate beneath the South American Plate, with a rate of convergence of about 9 cm/yr (Romanyuk, 2009; Heflin, 2012), which plays a most important role in the tectonic evolution of all of the rock formations, occurring there. Earthquakes, with magnitudes reaching 9.5, have been recorded along the Benioff seismo-focal zone, traced down to a depth of 670 km (Romanyuk, 2009).

The oldest rocks are the Late Jurassic – Early Cretaceous dark grey quartzites, quartz sandstones and siltstones and shales of the Yura Group (Fig. 2; Klinck and Palacios, 1985; Paulo, 2008), which contain abundant plant detritus, mainly in the Late Jurassic series, in the vicinity of Maca and Lari. They are exposed in only a few places in the riverbed of the Rio Colca (mainly between Madrigal and Lari; Figs 2 and 3A) on the modern land surface, as well as on the southern slopes of the valley, NW of Madrigal (Fig. 2). The contact between the Mesozoic sedimentary series and the younger Neogene white tuffs above (Fig. 3B) can be observed in the central part of the study area. The thickness of the exposed Neogene deposits is up to 200 m. However, Pleistocene–Holocene colluvial sediments, overlapping the alluvial ones, are the most common deposits within the study area (Fig. 2). They form an extensive, colluvial cover, with a thickness of up to several dozens of meters, and locally even exceeding 100 m. In particular, they occupy a large area in the eastern part of the area, near the village of Maca (Fig. 2). Fragments of volcanic rocks, formed in the Neogene, as a result of the surrounding volcanoes activity, occur as the main residual material on the slopes and floor of the valley.

METHODOLOGY

The study area was divided into twelve domains, which were delineated mainly on the basis of GPS readings. The outcrops, studied within the first six domains, are composed of Mesozoic clastic rocks, represented mainly by Late Jurassic and locally Early Cretaceous quartz sandstones, quartzites and siltstones and shales (Fig. 2; domains 1–6), whereas those of the remaining domains comprise Holocene and Pleistocene colluvial deposits (Fig. 2; domains from 7 to 12). Five domains were located in the central part of the study area, between Madrigal (3,291 m a.s.l.) and Maca (3,270 m a.s.l.), mainly at the bottom of the Rio Colca valley and on northern slopes, at altitudes ranging mostly from 3,000–3,300 m a.s.l. (Fig. 2). The sixth domain was situated in the westernmost part of the area, south-west of Madrigal. It included outcrops of the Early Cretaceous strata and Neogene tuffs (Fig. 2). The Pleistocene–Holocene outcrops studied (domains 7–12) were situated in the eastern part of the study area, in the vicinity of Maca (Fig. 2).

Structural studies within the selected domains of the Rio Colca valley, were carried out on the basis of a detailed structural analysis (e.g., Ramsay, 1967; Whitten, 1969; Hills, 1972; Ragan, 1973; Hobbs *et al.*, 1976; Ramsay and Huber, 1983, 1987; Price and Cosgrove, 1988; Ramsay and Lisle, 2000; Fossen, 2010). The tectonic structures present are mainly folds (usually within the Mesozoic series), fractures (with accompanying joint structures) and faults (with accompanying striations on the fault surfaces).

A detailed, structural analysis was applied to the tectonic structures, in order to recognize their geometry and kinematics. The analysis included the morphological characteristics and spatial orientation of all the observed, tectonic structures, their age relationships (superposition), the direction and sense of relative displacement, the direction of shortening and of extension, as well as the regime of deformation. The major parts of the geometrical and kinematic analysis were done during the fieldwork. The analysis was supported by over 1,200 photographs and 150 documentation sketches during the three field-sessions in 2006, 2008 and 2010.

The study was based mainly on analysis of the orientation of the various minor deformation structures. The resulting data were summarized in the form of charts and graphs, mostly statistical. Rose diagrams – presenting the strike directions of the structures – were most commonly used to facilitate the comparison of the fault or joint networks of the selected, structural domains. The stratification surfaces of the Mesozoic series and part of the faults are also presented on structural diagrams, as equal-area Lambert-Schmidt projections for the upper hemisphere. In a few cases, the analysis of the superposition of structures permitted determination of the relative sequence of formation for groups of faults and hence the recognition of stages in their evolution.

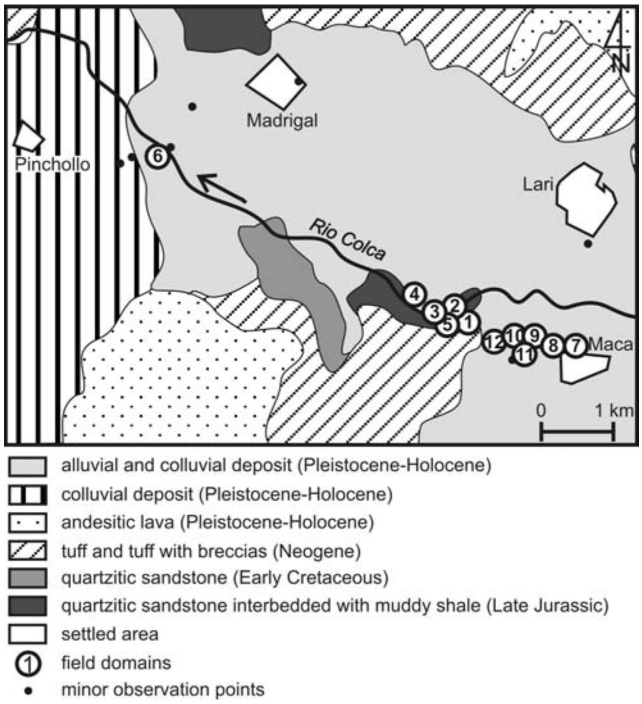


Fig. 2. Geological sketch map of study area (modified after Klinck and Palacios, 1985; see Fig. 1); map projection UTM zone-19, Southern Hemisphere

FAULTS IN THE MESOZOIC SEDIMENTARY COMPLEXES

A detailed structural analysis of the faults and the joints, occurring with them in the Mesozoic series, was carried out in the six domains, located in the central and the western part of the study area (Figs 2, 4 and 5), near the villages of Maca (domains no. 1, 3 and 5), Lari (domains no. 2 and 4) and Pinchollo (domain no. 6). The analysis was concentrated mainly on the Jurassic strata (domains no. 1–5), although the Cretaceous deposits were also included (domain no. 6).

The Mesozoic series are gently folded in the study area (Fig. 3C). Their stratification surfaces are slightly inclined in different directions (Fig. 3E), but mostly (over 20% of measurements) dip towards the NNW at an angle of about 30° (maximum of poles to stratification: 160/30). The projection points of the bedding are distributed in the form of a clear girdle, indicating a latitudinal fold macro-structure (Fig. 3E), with a sub-horizontal fold axis, plunging towards the east at an angle of about 10° (95/10; see Żaba and Małolepszy, 2008b). These fold structures were developed in a compressional regime (N–S shortening direction), closely related to sublatitudinal thrusts (see Fig. 3F).

A very complex and multi-phase fault network with various strikes and kinematics occurs in the Mesozoic sedimentary series (Fig. 3F), probably for the most part younger (with the exception of the sublatitudinal thrusts and reverse faults) than the fold structures.

Three principal, well marked fault sets (Fig. 6A) were recognised in **domain 1**, located near the eastern opening of the road tunnel in the vicinity of Maca (Figs 2, 4 and 5). Strike-slip faults, striking ENE–WSW (N60°–70°E), parallel to the fold axis, predominate there. In agreement with that direction, two phases of strike-slip displacements were distinguished; the younger were sinistral, but the sense of the older ones was not determined. Normal faults of NW–SE (N40°–50°W) orientation are also numerous. They displaced both the Mesozoic strata and the Miocene volcanic deposits, represented by tuffs. The north-eastern fault wall, recognized as the foot wall, was relatively elevated. Lo-

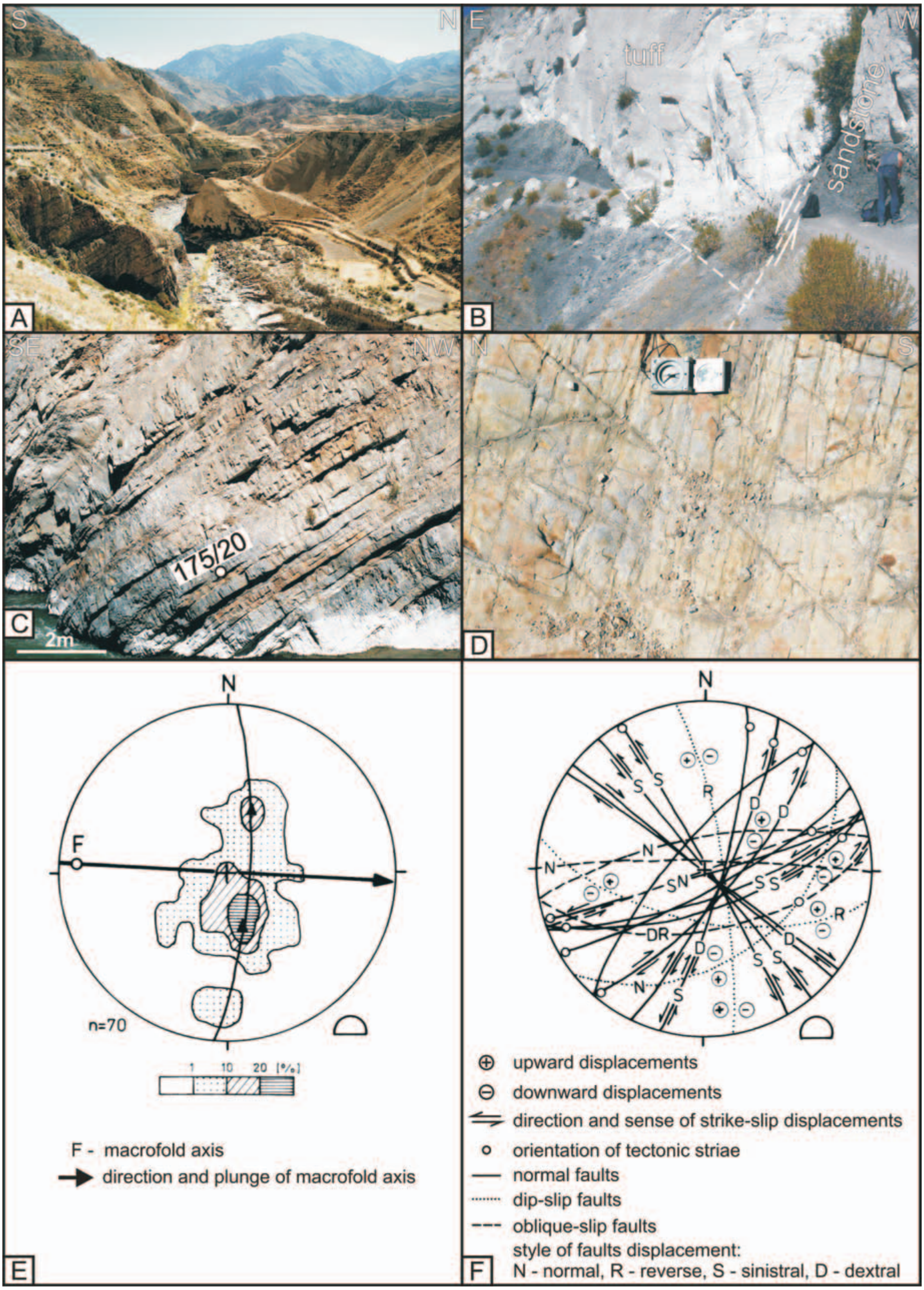


Fig. 3. Bedding and fractures in Mesozoic sedimentary formation cut by Rio Colca. **A** – Rio Colca valley in Maca-Lari area, view to West. Jurassic quartzitic sandstone outcrops in bottom of valley; **B** – contact of Neogene tuff (white) with Jurassic quartzitic sandstone and silty shale (dark) at road tunnel in Maca; **C** – gently dipping Cretaceous strata at bottom of Rio Colca valley in Pinchollo area (domain no. 6;, **D** – joint network (rhomboidal system), observed on top surface of Upper Jurassic succession at bottom of Rio Colca valley in Lari area (domain no. 4); **E** – poles to stratification surfaces within Mesozoic succession in Pinchollo-Lari-Maca area; **F** – kinematic interpretation of faults in Mesozoic succession in Pinchollo-Maca-Lari area; photograph by J. Żaba and Z. Małolepszy (modified after Żaba and Małolepszy, 2008b)

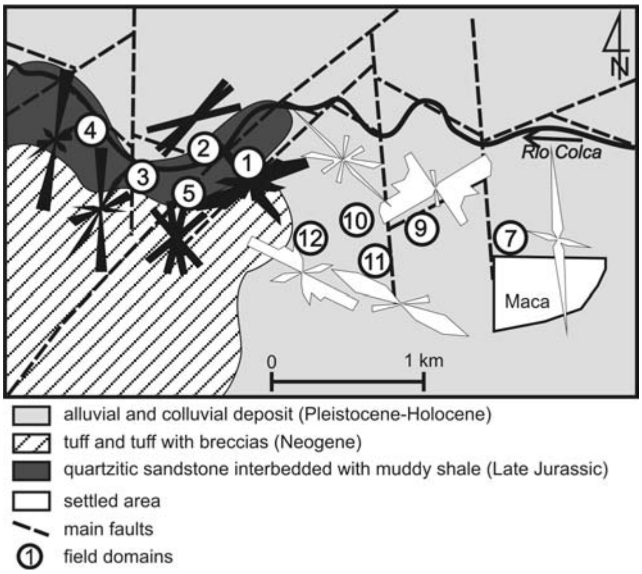


Fig. 4. Lateral variability of fault orientation in Pleistocene–Holocene colluvial deposits and Late Jurassic strata in Maca-Lari area

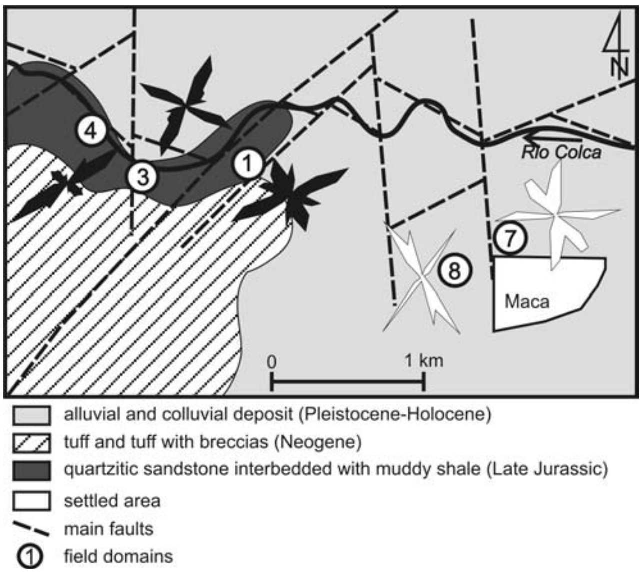


Fig. 5. Lateral variability of joint orientation in Pleistocene–Holocene colluvial deposits and Late Jurassic strata in Maca-Lari area

cally, strike-slip tectonic striae (sinistral displacements) also were observed on these fault planes. Rarer observed faults, bearing W–E (N85°W), were characterized by oblique-slip displacements, older, normal-sinistral and younger, reverse-strike-slip. Other fault sets were observed much less frequently. They were characterized by sinistral and dextral strike-slip displacements (NE–SW faults, N30°–40°E), as well as oblique-slip movements with a reverse sense of the dip-slip component (ENE–WSW faults, N80°E). The rose diagram of joints in the domain replicates the main orientation of the faults (Fig. 6A). The predominating, longitudinal and transverse joints are oriented ENE–WSW (N75–80°E) and NNW–SSE (N25°W), respectively. Their bearing is in agreement with the orientation of the folds, forming together an orthogonal system.

Domain 2 is located on the northern, steep slopes of the Rio Colca valley, in the vicinity of Lari (Figs 2 and 4). The faults pattern recognized in the area is very simple (Fig. 6B). Two main fault sets were found there (Fig. 6B): dip-slip normal faults with a NE–SW orientation, with the north-western fault wall as the footwall, and dip-slip reverse faults, oriented ENE–WSW, with the southern fault wall as the footwall.

In contrast to the domains described above, four distinct fault sets, oriented: N–S, NE–SW, ENE–WSW and W–E were recognized (Fig. 6C) in **domain 3**, located on the southern slope of the Rio Colca valley, in the vicinity of Maca (Figs 2, 4 and 5). They were mainly vertical or very steep, normal dip-slip faults, developed in an extensional regime. The faults striking N–S (N0°) and NE–SW (N35°E), transverse in relation to the fold macro-structures, were the most numerous in the domain. They form perfectly marked, tectonic scarps, as well as grabens and horsts in the morphology of the area. The joint pattern follows the main fault directions only in a small percentage of cases (Fig. 6C). Two joint sets, forming an orthogonal system, are dominant there, namely NNE–SSW (N25°E; transverse) and WNW–ESE (N65°W; longitudinal to the fold structures in the Late Jurassic strata). Extensional joints, oriented ENE–WSW (N75°E), recognised during the field study, form the only set that is complementary to the vertical and very steep, normal dip-slip faults of the same orientation, described above.

The faults network, observed in the Late Jurassic series of **domain 4** (Fig. 6D), located on the Rio Colca valley floor in the Lari area (Figs 2, 4 and 5), was similar to the one in domain no. 3, described above (see Fig. 6C). It consists of four fault sets: (1) two generations of dextral strike-slip faults, oriented NW–SE (about N50°W), (2) W–E ones, folw slip faults, with a sinistral sense of strike-slip (NE–SW; N65°E), and (4) oblique-slip faults, with a normal sense of dip-slip displacements ENE–WSW (N80°E) and NNE–SSW (N10°E), transverse in relation to the fold structures. In that area, the Rio Colca valley parallels the first set of faults (NW–SE). The faults frequently intersected each other, which resulted in well marked and clear superposition criteria (Fig. 7). The joint network roughly follows the orientation of the faults (Fig. 6D). The NE–SW joints (N55°E), which were activated by oblique, normal-sinistral displacements, dominate (24% of measurements) there. A diagonal joint set (N60°W), parallel to which dextral strike-slip multi-phase displacements occurred, is subordinate.

A network of numerous, normal dip-slip faults, oriented: NE–SW (N50°E), NNE–SSW (N15°E) and NW–SE (N40°W), was identified in **domain 5** (Fig. 6E), located on the northern slope of the Rio Colca valley, in the vicinity of Maca (Figs 2 and 4). They showed similarities to the pattern of the regional fault network. In addition to the Late Jurassic series, the faults also cross-cut and displace the overlying Miocene volcanic deposits, represented by tuffs. The eastern fault walls are down-thrown.

Domain 6, located at the bottom of the Rio Colca valley, in the vicinity of Pinchollo (Fig. 2), was the only one

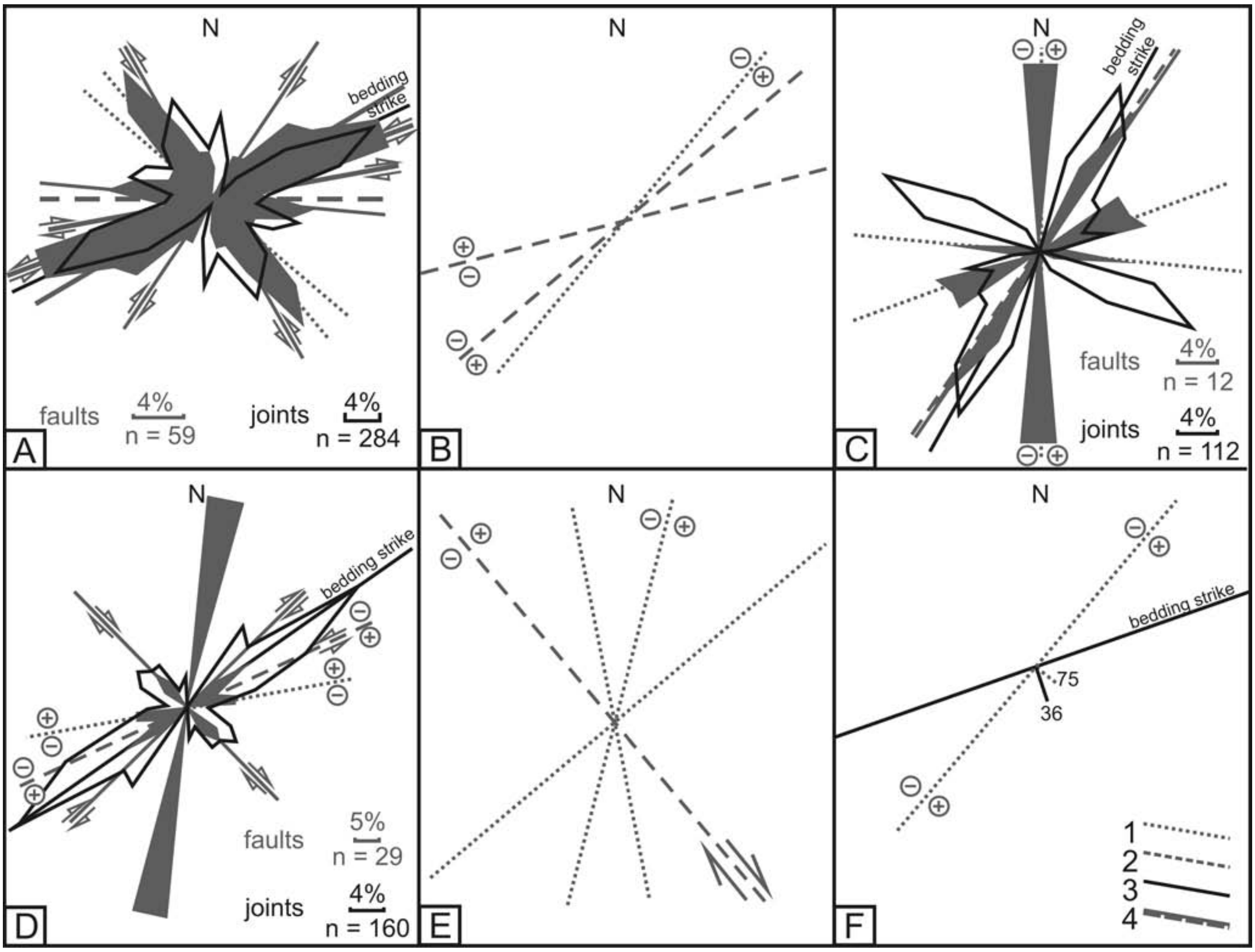
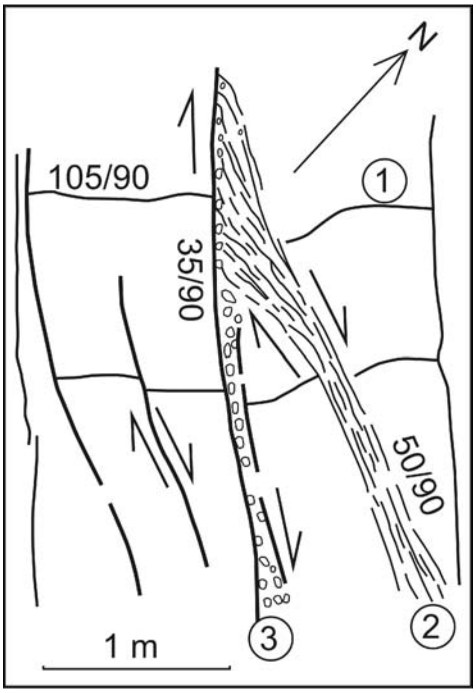


Fig. 6. Fault and joint orientation in Mesozoic Yura Group (modified after Żaba and Małolepszy, 2008b). **A** – faults and joints in area of Maca (domain no. 1); **B** – major faults in Lari area (domain no. 2); **C** – faults and joints in Maca area (domain no. 3); **D** – faults and joints in Lari area (domain no. 4); **E** – major faults in Maca area (domain no. 5); **F** – major faults at bottom of Rio Colca valley in Pinchollo area (domain no. 6): *1* – dip-slip fault, *2* – oblique-slip fault, *3* – strike-slip fault, *4* – tectonic graben



that includes outcrops of the Cretaceous sedimentary series. Only one distinct set of faults, oriented NE–SW (about N40°E; Fig. 6F), was recognised at that location. They were very steep, even sub-vertical dip-slip faults with a reverse sense of movement (the western wall is the footwall).

FAULTS IN THE PLEISTOCENE–HOLOCENE DEPOSITS

A detailed structural analysis of faults and accompanying joints, occurring in the Pleistocene–Holocene colluvial deposits, was carried out within the six structural domains (Figs 2, 4 and 5), in the eastern part of the study area near Maca village.

Fig. 7. Mesofault superposition in Late Jurassic succession at bottom of Rio Colca valley in Lari area (domain no. 4; modified after Żaba and Małolepszy, 2008b); 1 – oldest fault, 3 – youngest fault

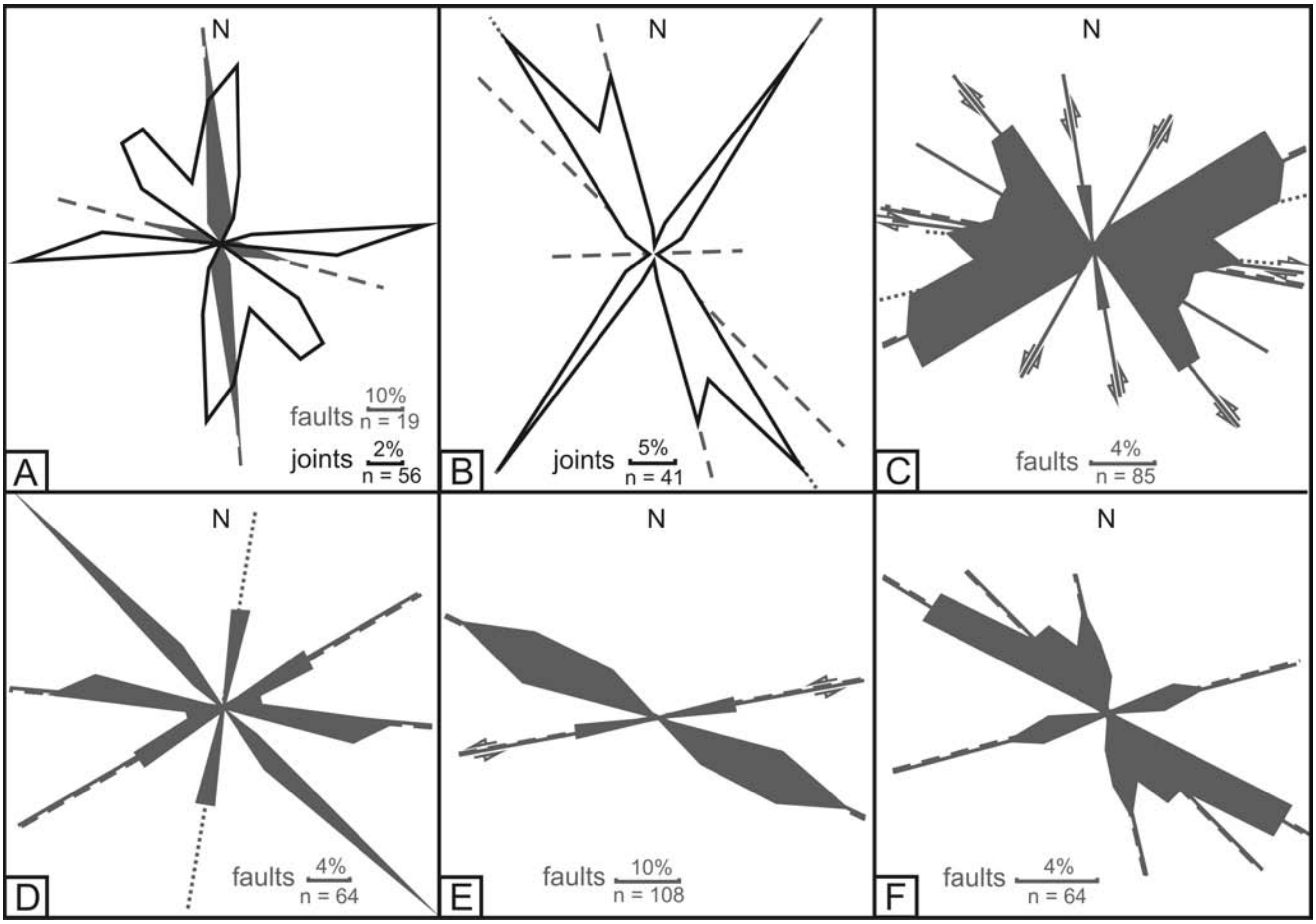


Fig. 8. Fault and joint orientation in Pleistocene–Holocene deposits (modified after Żaba and Małolepszy, 2008b). **A** – faults and joints in Maca area (domain no. 7); **B** – joints in Maca area (domain no. 8); **C** – faults in Maca area (domain no. 9); **D** – faults in Lari area (domain no. 10); **E** – faults in Maca area (domain no. 11); **F** – faults in Maca area (domain no. 12). For explanation see Fig. 6

The vast majority of the faults (over 50% of measurements), were of N–S orientation (N05°W; Fig. 8A) in **domain 7**. They were, without exception, steep, normal faults. In the morphology of the area, they form well marked primary, fault scarps. The axes of tectonic grabens, also clearly visible in the morphology, are very frequently parallel to the strike of these faults (Fig. 9). Normal faults, striking WNW–ESE (N75°W) and forming sharp and steep scarps, very distinct in the morphology, are much less numerous than the N–S oriented faults (about 17% of measurements). The cross-cutting relationships of these faults show that the formation of the WNW–ESE faults preceded development of the sub-meridional, tectonic grabens, which presumably evolved under a sinistral, transtensional regime (Fig. 9). Left-lateral displacements were accompanied by the development of extensional strike-slip duplexes, and sinistral, low-angle Riedel shears, oriented NW–SE (N40°W). The orientation of those shears, which in many places initiated

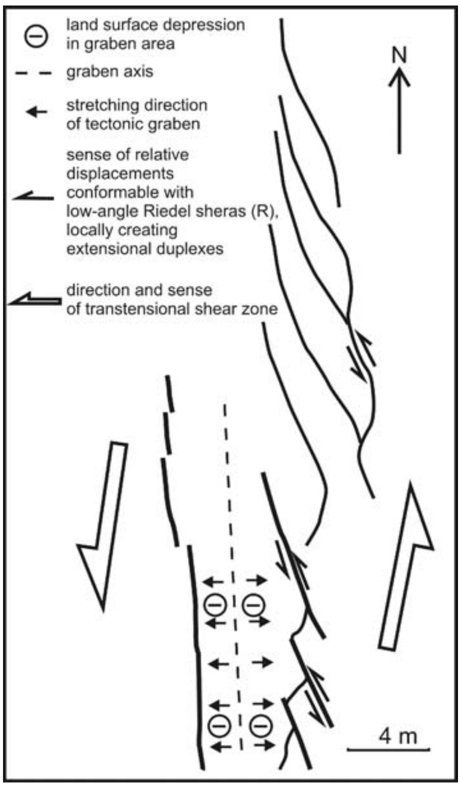


Fig. 9. Development of modern, tectonic grabens (sinistral transtension regime) in Pleistocene–Holocene colluvial deposits of Maca area (domain no. 7; modified after Żaba and Małolepszy, 2008b)

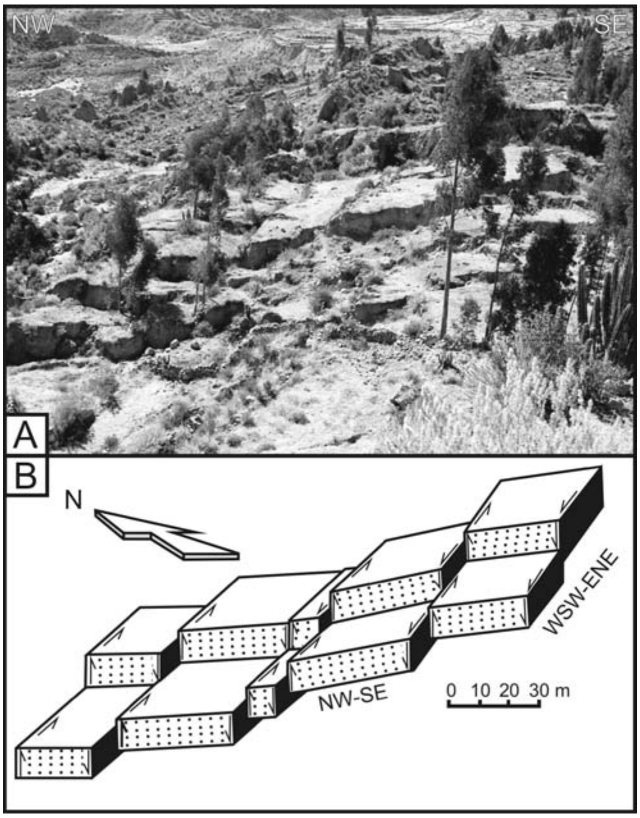


Fig. 10. Superposition of two fault sets in Pleistocene–Holocene colluvial deposits in Maca area (domain no. 11). **A** – photograph (after Żaba and Małolepszy, 2008a) and **B** – schematic sketch. Both sets were initiated as sinistral strike-slip faults formed under sinistral shear conditions. NW–SE fault set preceded WSW–ENE set. They might be interpreted as D shears and slightly younger – R shears, respectively (Riedel, 1929; Skempton, 1966; Ramsay and Huber, 1983; Price and Cosgrove, 1988; Katz *et al.*, 2004; Yakovlev, 2010). Subsequently, transformed into dip-slip faults with normal sense of relative displacement

the formation of extensional duplexes, is a perfect duplication of the statistical pattern of joint strike in the area (Fig. 8A). They form a distinct maximum of 11% measurements concentration. The orientation of the other joint directions indicates that either they follow the direction of sub-meridional tectonic grabens (azimuth 0°, 14% of measurements) or they are transverse to those structures (N90°W – 16% of measurements). Both of these sets form an orthogonal joint system.

The analysis of the brittle deformation structures in **domain 8** was based only on predominating shears. They are steeply dipping shears, developed under a sub-horizontal extension regime. Most of them created a system of two conjugate shear sets of normal meso-scale faults, as evidenced by both the asymmetry of the minor structures, observed on fault planes, and sigmoidal, extensional fissures. The structures were formed in an extensional regime, with a presumably almost vertical, maximum, principal stress axis.

Three main joint directions, with bearings: N35°W, N15°W and N35°E, and a much less common one with a N85°E bearing, can be distinguished on the rose diagram of domain no. 8 (Fig. 8B). It is characteristic of this domain that all of the joint sets recognized there were formed under an extensional regime. The faults scarps, parallel to the joints of N35°W bearing, are very clearly visible in the morphology of the area.

A complex, multi-phase developed network of very steep or even vertical faults was observed in **domain 9**. Many of those faults are visible in the morphology as extremely impressive fault scarps, with heights of up to several meters, mostly with a NE–SW orientation (N65°E, see Fig. 8C). They are related to the activity of normal faults (the NW fault walls are footwalls), often forming multi-steps structures in the morphology. Tectonic grabens were commonly developed between these faults and they are also distinctly visible in the morphology of the area. Tectonic grabens, oriented WNW–ESE (N60°W), are probably of the same age. These grabens belong to the oldest group of structures within the study area, since they are cut and displaced by several generations of younger faults. The second generation of faults is characterised by almost latitudinal strike (N85°W; Fig. 8C). They are strike-slip faults with a dextral sense of movement. In the morphology of the area, they also form well marked fault scarps. Faults of the third generation, oriented NW–SE (N40°W), are sinistral strike-slip faults and in many localities cut and displace older fault scarps. The youngest generation of faults is also characterised by a sinistral strike-slip movement along fault planes, striking NNE–SSW (N30°E). The sinistral strike-slip faults, oriented NNW–SSE (N10°W), probably formed synchronously with them. Even though they are definitely less common than the previously mentioned fault sets, their superposition in relation to the faults of the first, second and third generations is very clear.

The fault network in **domain 10** shows many similarities to that of the previously described domain 9 (Fig. 8D). The faults are grouped into four distinct sets, with bearings: N10°E, N60°E, N85°W and N45°W. The first direction is represented by the oldest, normal dip-slip faults, which are cut and displaced by all the other faults. The tectonic grabens commonly were created by the fault sets distinguished. All fault sets observed in that domain, with the exception of the oldest one, are also represented in domain 9 (see Fig. 8C).

A very clear and simple fault pattern was distinguished in **domain 11** (Fig. 8E). Two normal dip-slip fault sets, intersecting at an acute angle, are recognised; the younger faults are oblique-slip, with a very small proportion of sinistral component (Fig. 10 and 11A). The younger faults strike WSW–ENE (N80°E) and intersect and overprint the older faults, which are oriented WNW–ESE (N65°W). Tectonic grabens, very distinct in morphology, are developed along those two faults trends (Fig. 11B). The older, tectonic grabens, oriented WNW–ESE, are much more abundant, occurring more than three times more frequently than the younger ones (Fig. 8E).

The fault network in **domain 12** (Fig. 8F) shows a striking resemblance to the pattern in domain 11 (see Fig. 8E). As well, two sets of normal dip-slip faults occur, clearly distinguished in the surface morphology by fault scarps (Fig. 11C and 12) and frequently forming tectonic grabens (Fig. 11D). The older faults are oriented WNW–ESE (N60°W), the younger faults WSW–ENE (N75°E). The tectonic gra-

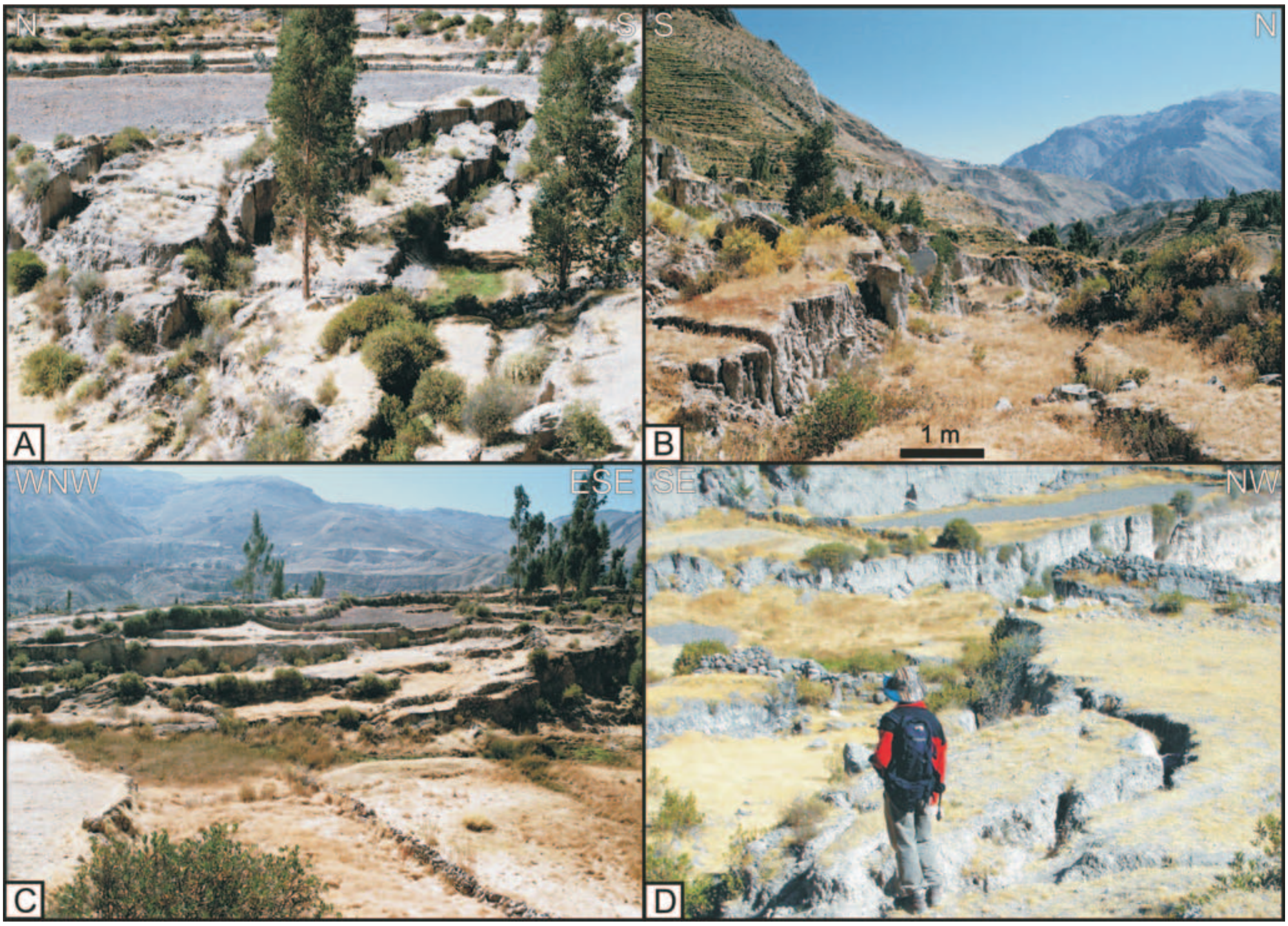


Fig. 11. Very distinctive and clearly visible fault scarps (**A** & **C**) and tectonic grabens (**B** & **D**), developed in Pleistocene–Holocene colluvial deposits of Maca area: domain no. 11 (A & B) and 12 (C & D); photograph by J. Żaba (D – modified after Żaba and Małolepszy, 2008b)

bens of the NNW–SSE (N15°W) and NW–SE (N45°W) trends, formed synchronously with the younger fault structures, are much scarcer, but also well marked in terms of morphology. Fault network stated here was developed under a sinistral shear regime (D, R, P and probably X shears were recognized – see Fig. 12; among others: Riedel, 1929; Skempton, 1966; Ramsay and Huber, 1983; Price and Cosgrove, 1988; Katz *et al.*, 2004; Yakovlev, 2010), as a result of NE–SW (ENE–WSW) shortening.

LINEAMENT NETWORK IN THE RIO COLCA VALLEY, BETWEEN MACA AND PINCHOLLO

Morphotectonic studies were conducted on the basis of LANDSAT 7 and Google Earth images, as well as geological maps of the area (Klinck and Palacios, 1985) and data from the literature (Antayhua *et al.*, 2002; Delacour *et al.*, 2002). The pattern of lineaments obtained (Fig. 13) was similar to the results, acquired in the field for meso-scale faults (see Figs 4 and 5). Lineaments, oriented NNE–SSW, transverse in relation to the fold structures in the Mesozoic series, are in the majority, with regard to number and total length. They constitute more than 25% of all the lineaments identified and show a total length of almost 30 km (Fig. 13). Those lineaments occur mainly in the southern part of the study area, where the drainage system (left-bank tributaries of the Rio Colca) developed along these trends. Faults and joints with such an orientation were commonly observed mostly in the Mesozoic domains (see Figs 4 and 5). In the younger Pleistocene–Holocene deposits, they were much rarer.

The lineaments with a WNW–ESE orientation, latitudinal in relation to the fold structures (see Figs 3E and 13) and forming an orthogonal system with the previously described NNE–SSW lineaments, seem to be older. They occur less frequently than the NNE–SSW lineaments, but are longer. The Rio Colca valley has developed along a WNW–ESE direction within the study area. The edges of the valley are cross-cut and displaced by perpendicular NNE–SSW lineaments. This fault trend was one of the most commonly observed within all of the domains (see Figs 4 and 5). During the field study, the WNW–ESE oriented faults also were shown to be older than the faults, striking NNE–SSW. Most of the tectonic grabens or scarps within the Pleistocene–Holocene deposits also followed the same trend (NNE–SSW; i.e. Figs 8C, E, 10 and 11A). The fault displacements not only were responsible for the development of the Rio Colca valley in the area between Maca and Pinchollo, but also

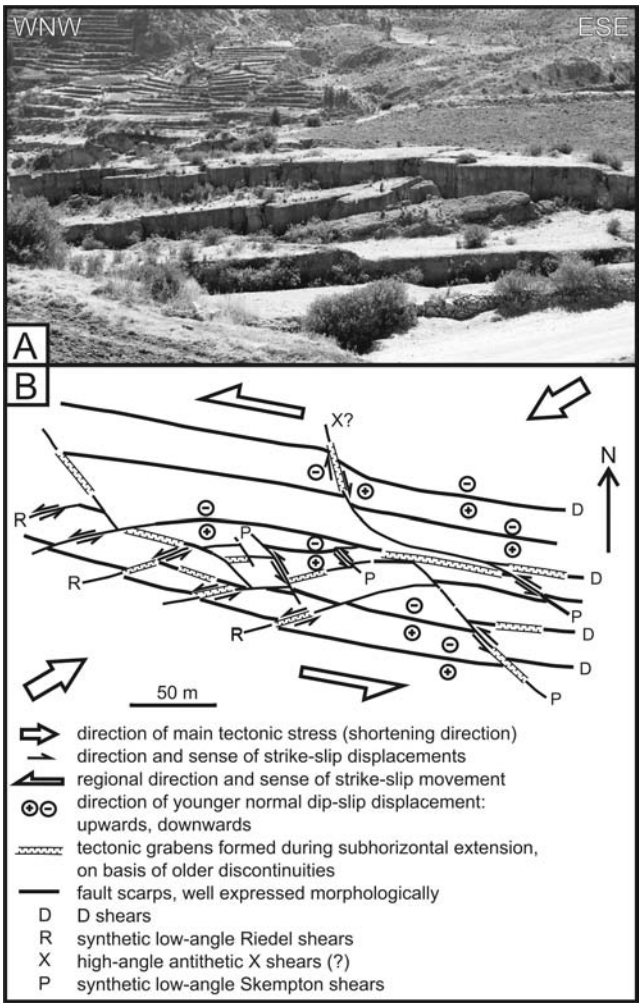


Fig. 12. Fault net for Pleistocene–Holocene colluvial deposits, west of Maca (domain no. 12). **A** – photograph (after Żaba and Małolepszy, 2008a) and **B** – simplified scheme

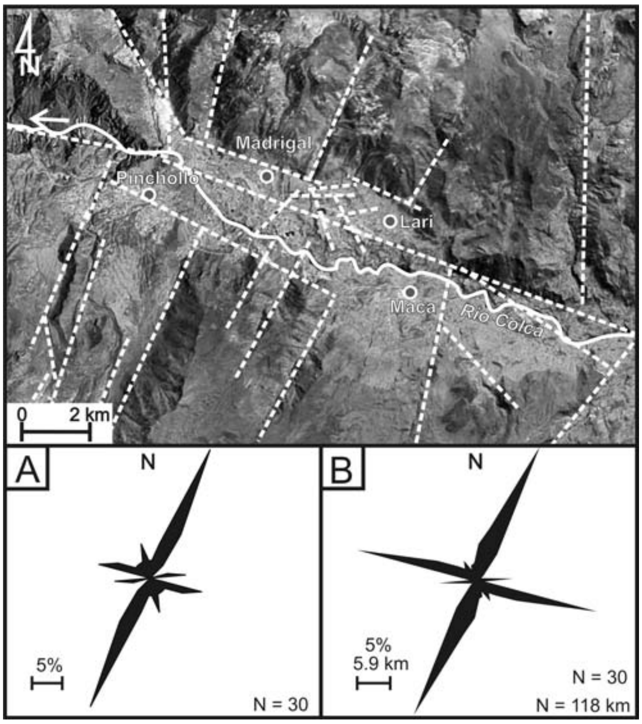


Fig. 13. Photolineament network of section studied in Rio Colca valley. **A** – rose diagram of photolineaments: max. 26.7% (20–30°); **B** – rose diagram of photolineament lengths: max. 25% = 29.5 km (20–30°)

caused uplift of the Precambrian rocks, presently exposed at the surface, below the Colca Canyon (Dalmayrac *et al.*, 1971; Mégard *et al.*, 1971). Moreover fault activity initiated many of the landslides, occurring within the study area (Żaba and Małolepszy, 2008a; Żaba *et al.*, 2009).

DISCUSSION AND CONCLUSIONS

The meso- and macrofold structures within the Mesozoic strata were developed, as the oldest tectonic structures, due to contraction, with a subhorizontal maximum shortening direction, oriented N–S. Probably synchronous or later-formed, normal mesofaults, oriented N–S, were produced, as well as younger strike-slip faults with a NW–SE and NE–SW orientation. The latter were formed, as the result of changes in the tectonic regime from contraction to strike-slip.

After the Miocene, some of those strike-slip faults became normal dip-slip faults, which locally are active until the present day. Almost all of the observed fault structures were formed in a sinistral shear zone (oriented WNW–ESE as the Rio Colca valley), initially under a transpression regime that was gradually evolving into transtension, together with the right rotation of the stress (see Fig. 12). Consequently, the formation of tectonic grabens of at least three generations, (1) NW–SE, (2) WSW–ENE and (3) NNW–SSE, seems to be related to a N–S extensional component of strain, operating under the recent transtensional regime. The inferred, recent strain directions are consistent with the orientation of the maximum, principal stress axis σ_1 (W–E, WSW–ENE), related to the focal mechanism for the latest earthquakes in this area (Antayhua *et al.*, 2001, 2002).

Landslides in the study area show a close relationship with the fault network recognized, especially with the normal faults, striking WNW–ESE (Żaba and Małolepszy, 2008a; Żaba *et al.*, 2009). Fault zones, providing pathways for channelized water flow, could have triggered the mass movements that are evidenced. Primarily, this is true for the later stages of landslide development, so that after an initial slide, combined with rotation, further movement of liquefied rock masses took place in the form of ground and mud flows. The steep inclination of slopes and rapid erosion and undercutting at the toes of slopes (debris fan) by the swift river also had significant influence on landslide development in the Rio Colca valley.

The main outcomes of our study can be summarised in the following points:

1. The study area is characterized by a complex fault network, with a multi-phase history of development. Most of them cross-cut and displace the Mesozoic, Miocene, and Pleistocene–Holocene deposits, giving proof of tectonic activity during this time. The main directions of the faults, occurring in the Mesozoic and Miocene basement series, have

been replicated in the Pleistocene–Holocene colluvial deposits, covering a large part of the area.

2. The normal dip-slip faults, bearing N–S, are the oldest, occurring in the Mesozoic deposits. They also occur in the Pleistocene–Holocene deposits, which proves their long-term activity up to the present, and are expressed as tectonic grabens. The valley of the Rio Colca follows these grabens in some sections.

3. The strike-slip faults with multi-phase development, oriented NE–SW and NW–SE (both dextral and sinistral), belong to the younger generation of structures. After the Miocene, in the final stages of their evolution, they were reactivated as normal dip-slip faults. Both fault sets form distinct and well marked scarps, arranged in step-like structures. Their multi-stage evolution resulted in the exposure of Jurassic rocks in the eastern part of the study area, whereas in the western part, where the Rio Colca cuts much more deeply, Cretaceous rocks occur. In general, the strike-slip faults also are well marked in Pleistocene–Holocene deposits, where they gave rise to primary tectonic scarps, as well as grabens and horsts, which prove their current activity (extensional regime).

4. The reverse faults are relatively rare in the studied section of the Rio Colca valley. They usually are steeply inclined and meridional (thrusting towards the east), NE–SW (thrusting towards the SE) or latitudinal (thrusting in the southern direction) in orientation.

5. The majority of latitudinal faults are of normal dip-slip character, in terms of displacement. Depending on location, the northern or the southern fault walls are downthrown. Some of the faults show multi-phase oblique-slip displacement, with a normal dip-slip component preceding later activity with a reverse sense of dip-slip movement.

6. The Mesozoic sedimentary series are folded slightly into almost horizontal, contractional folds, strictly related to thrusts.

7. The joint network in most cases reflects the fault trends. The joint sets quite commonly form orthogonal systems. Most of the joints are longitudinal joints, developed para-llel to the axes of macro-folds in the Mesozoic complexes.

8. The fault network in the Pleistocene–Holocene colluvial deposits was developed under a sinistral shear regime (D, R, P and probably X shears were recognized – see Fig. 12), as a result of NE–SW (ENE–WSW) shortening. Subsequently, these faults were reactivated as normal dip-slip faults, accompanied by tectonic grabens. The grabens were formed in the following order (from the oldest ones to the youngest): 1 – WNW–ESE, associated with D shears, 2 – WSW–ENE, associated with R shears, 3 – NW–SE, associated with P shears, 4 – NNW–SSE, probably associated with X shears.

9. The present-day fault activity has caused the formation of primary fault scarps, which are very well marked and clearly seen in the morphology of the area. The fault and joint networks are in agreement with the trends of identified lineaments. The most frequently encountered NNE–SSW and WNW–ESE lineaments form an orthogonal system. The Rio Colca valley in the study area follows the WNW–ESE, NE–SW and much scarcer W–E structures, which also caused uplift of the Precambrian rocks, exposed at the surface, below the Colca Canyon (Dalmayrac *et al.*, 1971; Mégard *et al.*, 1971), whereas left-bank tributaries flow in a NNE–SSW direction.

10. The outcomes of the field and remote-sensing studies are consistent with the results of the lineament analysis, based on satellite imagery, for the area, located south of the Rio Colca valley and the Valley of Volcanoes region (cf. Antayhua *et al.*, 2002; Delacour *et al.*, 2002).

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