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Evidence of a plate-wide tectonic pressure pulse provided by extensometric monitoring in the Balkan Mountains (Bulgaria)

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Abstract: The EU-TecNet monitoring network uses customized three-dimensional extensometers to record transient deformations across individual faults. This paper presents the first results from two newly established monitoring points in the Balkan Mountains in Bulgaria. The data from Saeva Dupka, recorded across an EEN-WWS striking fault, show sinistral strike-slip along the fault and subsidence of the southern block. Much of the subsidence occurred around the time of the distal $M_W = 5.6$ Pernik Earthquake. An important transient deformation event, which began in autumn 2012, was reflected by significant compression and following extension, across the monitored fault. The data from Bacho Kiro, recorded across a NE–SW striking fault, show sinistral strike-slip along the fault and subsidence of the north-western block. The same important deformation event was reflected by changes in the strike-slip, dip-slip, and horizontal opening/closing trends. These results have been compared to data from other monitoring points in the Western Carpathians, External Dinarides, and Tian Shan. Many of the sites show evidence of simultaneous displacement anomalies and this observation is interpreted as a reflection of the plate-wide propagation of a tectonic pressure pulse towards the end of 2012.

Key words: Eurasian Plate, Balkan Peninsula, active tectonics research, aseismic transient deformations, slow-slip phenomena, pressure pulse, EU-TecNet.

Introduction

Until the turn of century, the geoscientific community tended to accept the long standing assumption that stress accumulation along faults was released by either continuous aseismic sliding or earthquakes resulting from the instantaneous failure of locked faults (Peng & Gomberg 2010). This assumption came to be challenged around twenty years ago after it was discovered that slow-slip phenomena were far more common in the vicinity of tectonic plate boundary faults than previously thought. Evidence came from a number of distinct regions including southern Japan (Hirose et al. 1999) and Cascadia (Dragert et al. 2001). It has come to fundamentally change our understanding of the ways in which tectonic stresses arising from plate motions are accommodated by slip on faults (Gomberg 2010). Nonetheless, slow-slip phenomena are not unique to the depths of subduction zone plate interfaces. They occur on faults in many settings and appear to span a continuum so that, as a result, it is no longer possible to characterize fault slip modes in aseismic or seismic terms (Peng & Gomberg 2010). These phenomena are manifest as geodetically observed aseismic transient deformations. While geoscientists most commonly use seismic and geodetic monitoring as the basis with which to recognize slow-slip phenomena, less abundant strainmeters and tiltmeters also measure aseismic transient deformations, and with much greater resolution than GPS (Agnew 2009).

The use of extensometers as a means with which to recognize aseismic transient deformations is best exemplified by the fault displacement monitoring network EU-TecNet (Stemberk et al. 2010; Košťák et al. 2011). It was established at the turn of the century in order to accurately quantify the displacements that occur across specific faults over decadal timescales as it is simply not possible to obtain this information from geodetic measurements such as GPS (Košťák et al. 2002; Briestenský et al. 2014a). The network now comprises nearly one hundred and fifty monitoring points spread across mainland Europe along with a smaller number of distal sites in the Arctic, Africa, Asia, North America, and South America. In this paper, the background section outlines a number of its most important findings, while the methods section illustrates both the procedure used to select suitable sites and the technical parameters of the installed extensometers. However, the main aim of the paper is to describe and present the first

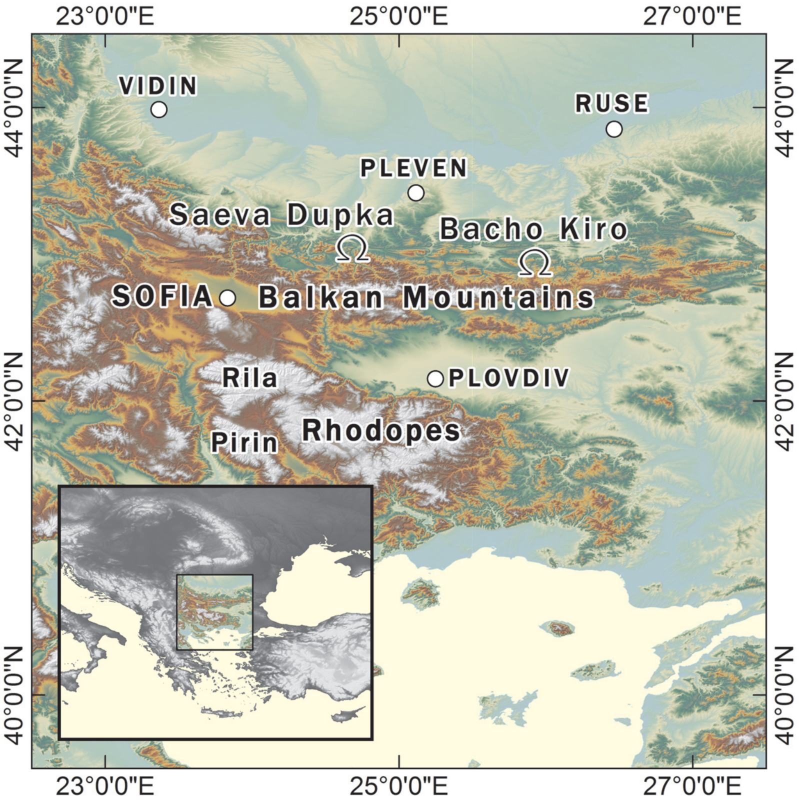


Fig. 1. The location of the recently established fault displacement monitoring points at Saeva Dupka Cave (N 43°2′48.67″, E 24°11′9.17″) and Bacho Kiro Cave (N 42°56′49.80″, E 25°25′47.82″) in the Balkan Mountains of Bulgaria. The cities of Pleven, Plovdiv, Ruse, Sofia and Shumen together with the Balkan, Pirin, Rila, and Rhodope Mountain Ranges are also marked. The inset presents the location of the study area with respect to the rest of the Balkan Peninsula.

two years of results from two of the most recently established monitoring points. These are located in the caves of Saeva Dupka and Bacho Kiro in the Balkan Mountains of Bulgaria (Fig. 1). The presented results are then compared to data obtained over the same period from monitoring points in the Western Carpathians, the External Dinarides, and in the Kyrgyz Ala-Too Range.

Background

The EU-TecNet monitoring network deploys permanently installed extensometers that are able to measure relative fault displacements in three dimensions along with the horizontal and vertical angular rotations of the opposing fault sidewalls (Marti et al. 2013). These extensometers are detailed later but the fact that they are able to record three dimensional displacements is hugely advantageous given that movement between fault planes is generally characterized by horizontal or vertical slip (Košťák 2006). The monitoring points are usually located underground in settings such as mines or caves as this helps to ensure that the recorded slow-slip phenomena are the result of endogenic processes. Monitoring points on the surface are more likely to be influenced by exogenic processes including gravitationally induced slope deformations, extreme rainfall events, prolonged periods of rainfall, or seasonal temperature changes. The area around each new site is mapped to ascertain whether the obtained results could be influenced by deep-seated slope deformations and, if so, the data are then interpreted appropriately (Briestenský et al. 2011a). No evidence, irrespective of whether prolonged periods of rainfall or extreme rainfall events are considered, has ever been found to suggest that precipitation influences the data from underground monitoring points. Furthermore, seasonal temperature changes may influence the opening/closing component across the fault, but this influence diminishes rapidly with depth (Gosar et al. 2009): the seasonal amplitude has been found to decrease from around 1 mm at the surface to less than 0.05 mm at depths of more than 10 m (Briestenský et al. 2010).

The displacements at any given monitoring point are typically characterized by long periods of geodynamic stability during which none of the three displacements move or during which one or more of them is characterized by progressive creep. These periods of stability are then interrupted by shorter periods of anomalous or increased geodynamic activity during which one or more of the displacement components will be affected by, for example, a conspicuous reversal in the progressive creep trend; a sudden enduring displacement; or a series of oscillatory displacements. These shorter periods of geodynamic activity normally last for no more than six months before resumption of the progressive creep. However, in terms of aseismic transient deformations, the most important finding from the network is represented by the recognition of pressure pulses (Stemberk et al. 2010). This is the term given to a period of time in which a number of scattered monitoring points are affected by anomalous or increased geodynamic activity. It is known that slow-slip phenomena are especially sensitive to stress perturbations (Peng & Gomberg 2010). Pressure pulses are therefore particularly significant from a tectonic perspective as they are thought to reflect the widespread redistribution of stress and strain within the shallow crust (Košťák et al. 2007). Furthermore, the changes that characterize the pulse will vary from one monitoring point to the next, depending on the location of the source of the pulse in relation to the fault geometry and orientation of the stress axes.

It is very difficult to constrain the relationship between anomalous or increased geodynamic activity and significant local or regional seismic events while sudden displacements have been noted both before (Košťák et al. 1992; Briestenský et al. 2007) and after earthquakes (Košťák et al. 1998; Dobrev & Košťák 2000). Irrespective of whether the sudden displacements are preseismic or postseismic, they are not thought to be instantaneous mechanical movements generated by a specific earthquake event, and both phenomena are interpreted as reflections of the redistribution of stress and strain in the crust. Furthermore, recent investigations have shown that the progressive creep recorded at a number of sites in Central Europe changed around the same time as the $M_W = 9.3$ Indian Ocean Earthquake on 26 December 2004 (Stemberk et al. 2010) and the $M_W = 9.0$ Tōhoku Earthquake on 11 March 2011 (Briestenský et al. 2014b). The latter study found that these changes also correlated with natural gas concentration anomalies, thereby supporting the results of earlier research (Briestenský et al. 2011b).

Sites

Saeva Dupka

The first study site, Saeva Dupka, 3 km to the south of the village of Brestnitsa in Lovech Province, is situated on the southern slope of the small Brestnitsa Polje. The cave has developed in the massive light Tithonian limestones of the Brestnitsa Formation. This formation has been subjected to intensive karstification and faults in the vicinity of the cave are often expressed morphologically on the surface (Shanov & Kostov 2015). The entrance is found at 510 m a.s.l., its total length is 205 m, and its denivelation is 40 m. Inside the cave, considered to be one of the most beautifully decorated in the country, one large gallery separates five chambers. The inner temperature fluctuates between 7–11 °C and its relative humidity ranges from 90–98 %. This cave is of particular seismotectonic significance as it hosts a number of indicative features such as cave breccia, fallen stalactites, and dislocated or cracked stalactones. The cave breccia has been interpreted as a result of a catastrophic paleo-earthquake while the fallen stalactites have been interpreted as reflections of reactivation of the fault to the south of the cave during the Pleistocene (Shanov & Kostov 2015).

Bacho Kiro

The second site, Bacho Kiro, 5 km to the west of the town of Dryanovo in Gabrovo Province, is situated in the valley of the Andaka River. The cave has developed mainly in the Barremian bioclastic and organogenic limestones of the Emen Formation and the Barremian to Aptian sandstones, marls, siltstones, limestones of the Bulgarene Formation. These formations have again been subjected to intensive karstification, with at least thirty-five caves known in the area around Dryanovo Monastery, the longest of which is Andaka Cave at 5000 m (Suchkov & Sinnyovsky 2010). The entrance to the cave is found at 335 m a.s.l., its total length is 3600 m, and its denivelation is 65 m. Inside the cave, a complex labyrinth of corridors, spread over four levels, connects twelve chambers. The inner temperature is stable at 13 °C and its relative humidity is constant at 95%. It hosts a number of karst features including stalagmites, stalactites, and flowstones. This cave is of particular archeological significance as it has been found to have hosted one of the earliest known Aurignacian burials while further excavations have revealed some of the earliest human remains found in Bulgaria (Beron et al. 2006).

Methods

In 2012, two potential underground observatories for fault displacement monitoring were surveyed in detail, at Saeva Dupka and Bacho Kiro in the central part of the Balkan Mountains. The applied methodology follows that previously outlined by, for example, Briestenský et al. (2014a). Each reconnaissance survey was conducted with the aim of identifying significant tectonic structures which have played, or continue to play, an important role in the development of the specific cave system. These surveys were supplemented by further investigations in the vicinity of the significant tectonic structures, focusing specifically on the analyses of slickensides and damaged speleothems. Damaged speleothems are particularly significant as these commonly reflect recent tectonic movements (Gilli 2005) although, of course, it is important to consider all the mechanisms that may lead to this phenomenon (Becker el al. 2006). Moreover, any evidence of new speleothem growth was also recorded, as tectonic activity helps mineralized water to penetrate along faults prior to the precipitation of its calcium carbonate. Suitable faults for displacement monitoring were identified at both sites, the results of which provide evidence for the active tectonic regime. The selected monitoring point at Saeva Dupka lies across a fault striking EEN-WWS with a 170/80 (dip direction°/dip°) while the selected monitoring point at Bacho Kiro lies across a fault striking NE-SW with a 310/70. In both instances, the strike orientation represents a fundamental control on the development of the specific cave system.

The faults were each instrumented with a precise extensometer called a TM-71 (Košťák 1969). These extensometers have been designed to take advantage of the moiré phenomenon of optical inference as generated by concentric spirals and parallel lines (Nishijima & Oster 1964). Moiré patterns appear when two sets of identical overlapping periodic markings are not perfectly aligned: such misalignment generates a series of macroscopic interference fringes. When two overlapping sets of concentric spirals are poorly aligned, a family of hyperbolic interference fringes is generated, in which the total number of fringes reflects both the distance between the individual rings and the center to center distance between the individual spirals. The common principle axis indicates the

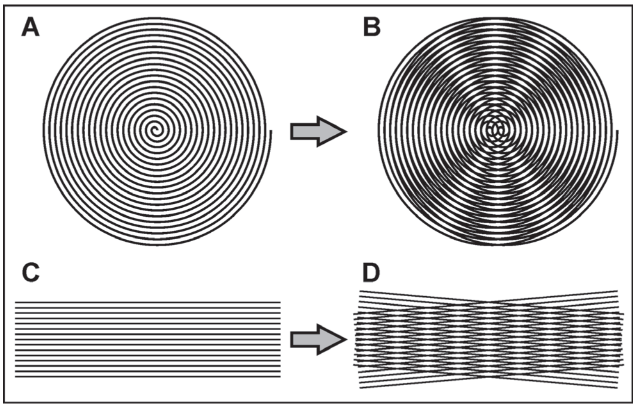


Fig. 2. An illustration of the moiré phenomenon of optical inference as generated by concentric spirals (A and B) and parallel lines (C and D). **A** — Two overlapping concentric spirals aligned precisely on top of one another; **B** — Two overlapping concentric spirals displaced with respect to one another. The displacement generates a family of hyperbolic interference fringes (see text for further details); **C** — Two overlapping sets of parallel lines aligned precisely on top of one another; **D** — Two overlapping sets of parallel lines rotated with respect to one another. The rotation generates a family of parallel interference fringes (see text for further details).

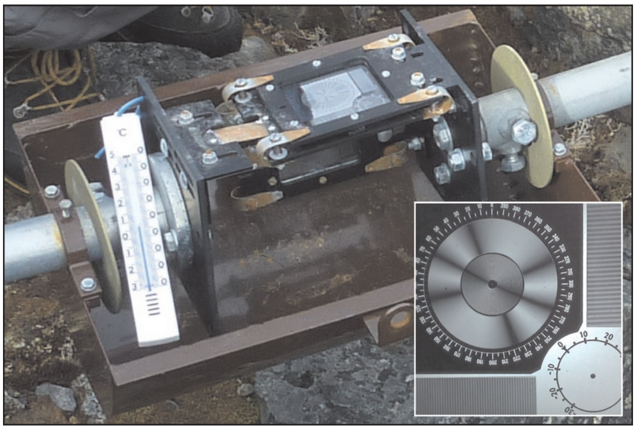


Fig. 3. A permanently installed extensometer used to measure aseismic transient deformations across a fault. These instruments take advantage of the moiré phenomenon to record displacement and rotation in three-dimensions. They comprise two distinct components, one held in place by the left arm and one held in place by the right, which move independently of one another: the number of macroscopic fringes changes as a result of these transient deformations. The inset presents an example of the macroscopic fringes shown on one of the combined indicators (see text for further details).

direction of the displacement (Fig. 2A,B). In contrast, when two overlapping sets of parallel lines are poorly aligned, a family of parallel interference fringes is generated, in which the total number of fringes reflects both the distance between each individual line and the total amount of rotation (Fig. 2C,D). These moiré patterns can be used to measure extremely small movements due to the fact that a comparatively small relative movement between the overlapping periodic markings results in comparatively large changes in the observed moiré patterns: the displacement is magnified (Oster & Nishijima 1963). Therefore, if the number of hyperbolic interference fringes is known, the amount of displacement can be quantified through a simple trigonometric transformation. Likewise, the same is true for angular rotations, if the number of parallel interference fringes is known (Košťák 1991).

The TM-71 uses the deterministic nature of moiré patterns in order to measure movements across a range of different discontinuities (Klimeš et al. 2012). Although the extensometer appears to be a single unit (Fig. 3), this impression is misleading: it actually comprises two distinct constituent components, which are able to move independently, one held in place by the left arm and one held in place by the right arm. Each of these components incorporates two glass plates, one orientated vertically and one orientated horizontally, into which one spiral grid and two sets of parallel lines have been etched. The extensometer superimposes these four glass plates, two on each constituent component, to the extent that when the etched patterns align perfectly the overlapping plates do not generate any moiré patterns. However, if the glass plates move, a series of interference fringes is generated, which can then be used to quantify the amount of movement. Moreover, the use of horizontal and vertical glass plates, combined with the configuration of the spiral grid and two sets of parallel lines, enable us to record these movements in three-dimensions. The precision of the instrument is governed by the number of lines etched into the glass plates: relative displacements can be measured in three Cartesian coordinates (x, y, z) with a precision of better than ± 0.007 mm while horizontal and vertical angular rotations (gxy and gxz) can be measured with a precision of better than ± 0.00016 rad (Marti et al. 2013).

Results

Saeva Dupka

The monitored fault is associated with the majority of speleothem damage recorded in the cave while its strike is mirrored by the orientation of the main passage (Fig. 4). Data from this monitoring point have now been recorded for more than two years and these demonstrate oblique displacement along the fault (Fig. 5). The vertical displacement component shows that the southern block subsided by about

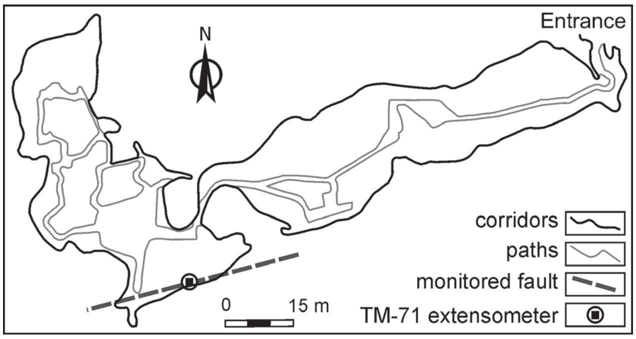


Fig. 4. A plan of the Saeva Dupka study site showing the position of the most significant fault and location of the extensometric monitoring point. The map adapted after Beron et al. 2006.

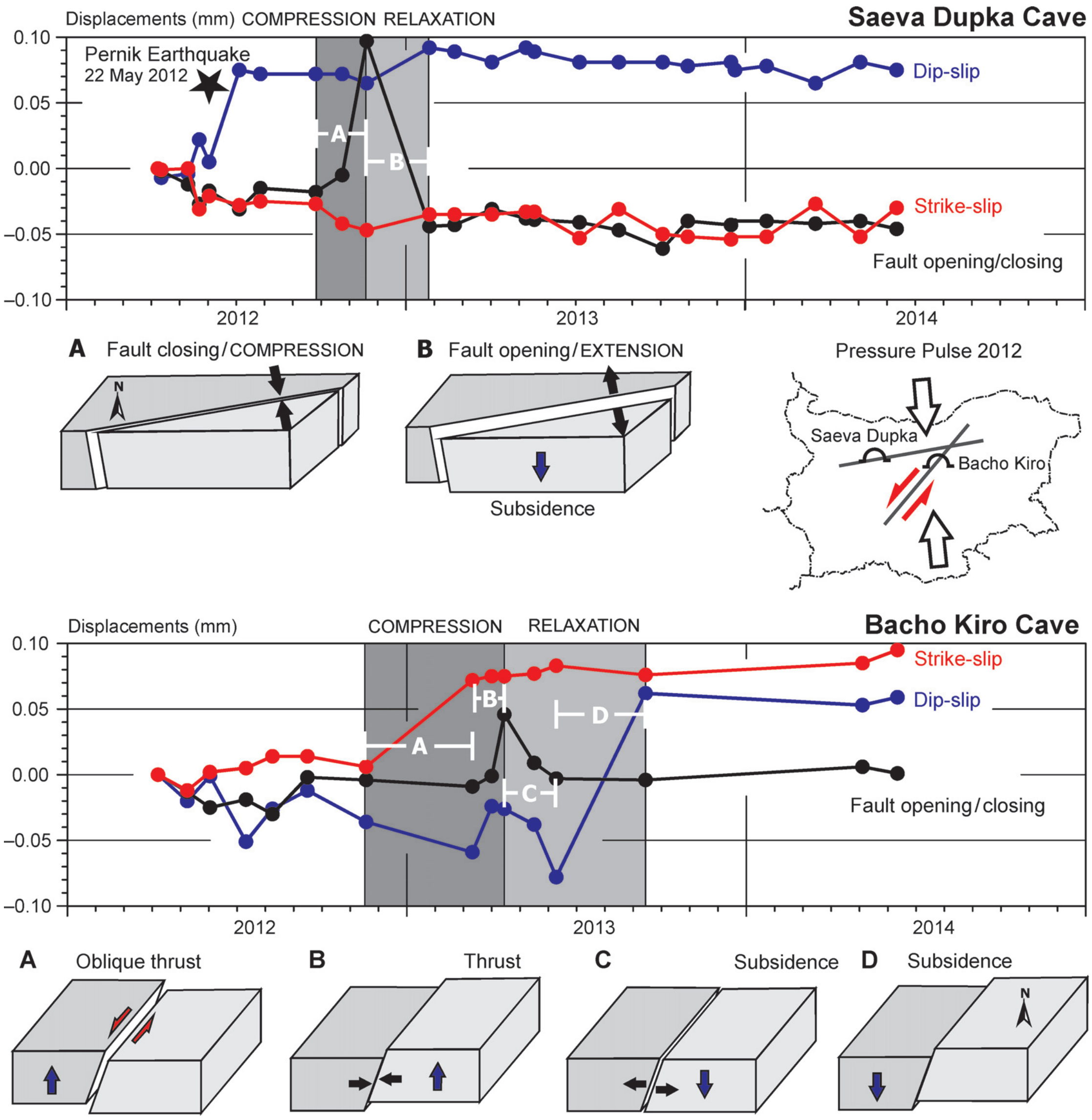


Fig. 5. The displacements registered along the EEN-WWS striking fault in Saeva Dupka and along the NE-SW striking fault in Bacho Kiro. The structural block models characterize the fault displacements that began at both sites towards the end of 2012 and which reflect significant aseismic transient deformations (red arrow — strike-slip, blue arrow — dip slip, black arrow — fault opening/closing). The schematic model in middle right shows that the regional stress-field (white arrows) was orientated approximately N-S during the compressional deformation phase.

0.075 mm with respect to the northern block while the horizontal dextral strike-slip displacement component shows that it has also moved to the east by about 0.05 mm. Much of the vertical displacement occurred around the time of the distal $M_W = 5.6$ Pernik Earthquake. This event, the epicenter of which was located 24 km west of Sofia, took place at 00.00 UTC on 22 May 2012 and was followed by a series of large aftershocks which culminated in a $M_W = 4.6$ event on 14 July 2012. It is not possible to know whether the recorded vertical displacement was preseismic or postseismic due to the monthly monitoring interval, the large number of seismic events, and the considerable length of time over which they occurred. The opening/closing component shows that the fault has an overall tendency to open, indicating extension, in total by about 0.05 mm per year. However, this trend was interrupted towards the end of 2012, when the opening/closing component recorded a sudden pulse of compression and extension prior to resumption of the progressive long-term trend (Fig. 5, Phases A and B). The magnitude of this sudden pulse of compression and extension suggests that the movements were endogenic even though the event was not accompanied by significant strike-slip or dip-slip. The combination of subsidence of the southern block and opening across the fault provides evidence of a generally extensional tectonic regime.

Bacho Kiro

The observed fault is associated with conspicuous speleothem damage while its strike is mirrored by a number of others in the cave, along which many of the passages have devel-

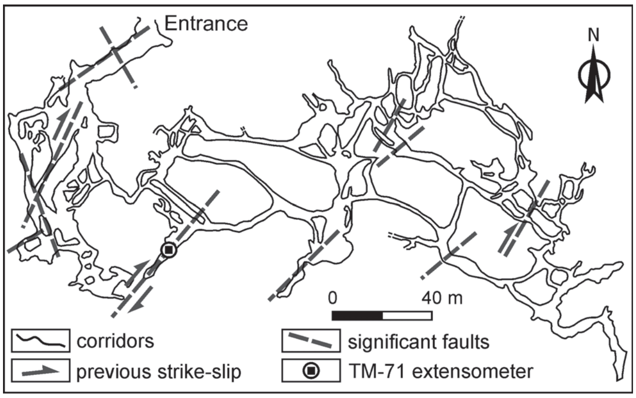


Fig. 6. A plan of the Bacho Kiro study site showing the position of the most significant faults with previous strike-slip displacements and location of the extensometric monitoring point. The map adapted after Beron et al. 2006.

oped, whose slickensides indicate previous dextral strike-slip (Fig. 6). In terms of the general trends, the first two years of data recorded at this monitoring point demonstrate oblique displacement along the fault, with the vertical displacement component showing that the northwestern block has subsided by about 0.05 mm with respect to the south-eastern block and the horizontal sinistral strike-slip displacement component showing that the northwestern block has also moved towards the southwest by about 0.1 mm (Fig. 5). In detail, however, these general trends are more complicated, especially the period from towards the end of 2012 to the middle of 2013. This has been divided into four stages (Fig. 5, Phases A–D): Phase A is characterized by relative uplift of the northwestern block, sinistral strike-slip displacement, and no opening/closing across the fault; Phase B is characterized by relative uplift of the south-eastern block, negligible sinistral strike-slip displacement, and sudden compression (fault closing) across the fault; Phase C is characterized by relative subsidence of the south-eastern block, negligible sinistral strike-slip displacement, and sudden extension (fault opening) across the fault; and Phase D is characterized by relative subsidence of the north-western block, negligible dextral strike-slip movement of the north-western block, and no opening/closing across the fault. The sudden pulse of compression and extension recorded in the middle of 2013 (Fig. 5, Phases B and C) is not typical of the seasonal opening/closing trends recorded at surface monitoring points while the size of the displacements, about 0.05 mm, suggests that they were caused by endogenic processes.

Discussion

The slow-slip phenomena are manifest as aseismic transient deformations which can be identified as a result of seismic and geodetic monitoring or through the use of strainmeters and tiltmeters. An example of the latter is provided by the monitoring network EU-TecNet. This network was established on the basis that faults are sensitive to perturbations in the regional stress field and, therefore, it should be possible to identify aseismic transient deformations using customized extensometers installed across individual fault structures in the shallow crust. In contrast to many other studies made using strainmeters and tiltmeters, this monitoring network is extensive, with nearly one hundred and fifty monitoring points spread across mainland Europe. This enables us to analyse aseismic transient deformations with great precision on the continental scale and it is argued that our method represents the most appropriate approach to characterizing the progressive deformation of the shallow crust. Data from the network have demonstrated that deformation of the shallow crust reflects the process of stress redistribution within the mantle-lithosphere while also showing that it is unusual for conspicuous periods of stress redistribution, here termed tectonic pressure pulses, to be associated with seismic events.

The recorded data indicate that the Bulgarian region was affected by a tectonic pressure pulse towards the end of 2012 and the direction of maximum horizontal stress at that time was orientated orthogonally to the monitored fault. In contrast, at Bacho Kiro, the onset of the compressional phase was marked by a notable acceleration in the sinistral strike-slip trend while closure across the fault only occurred at the end of this compressional phase. Therefore, to account for closing across an EEN-WWS fault at Saeva Dupka and acceleration in the sinistral strike-slip trend across an NE-SW fault at Bacho Kiro, the direction of maximum horizontal stress, 1σ, was orientated approximately SSE–NNW (or, at least, in the NW or SE quadrant). This is an important observation given that the direction of regional extension is generally thought to be N–S in the area of Bulgaria (e.g. Papazachos et al. 1998; Burchfiel et al. 2000; Kotzev et al. 2008). The presented results suggest that the general pattern of N–E extension can be interrupted periodically by short-lived episodes of compression with approximately the same direction.

In order to establish whether the proposed pressure pulse was a regional phenomenon, the data obtained from a number of other fault displacement monitoring sites have been investigated: these sites are located in the Western Carpathians, the External Dinarides, and in the Kyrgyz Ala-Too Range on the northern edge of the Tian Shan. The extensometric network in the Western Carpathians of Slovakia comprises more than forty monitoring points. Of these, thirty-two, at twenty-seven different sites, had been installed across significant faults at the time of the pulse in 2012 (Fig. 7). Seventeen of these points were characterized by anomalous displacements around the time of the proposed tectonic pressure pulse towards the end of 2012. This represents a significant proportion given that, as mentioned previously, the physical characteristics of a specific fault and its orientation in relation to the source of the disturbance provide the fundamental controls as to whether or not it will react to a tectonic event. The anomalies recorded at each monitoring point are summarized in Table 1. All of the seventeen affected monitoring points record changes in at least one of the two slip components while only three record opening/closing across the fault. The different types of identified anomaly include initiation of strike-slip displacements, conspicuous reversals in the progressive creep trend, and oscillatory displacements (Figs. 8, 9, 10). It has not been pos-

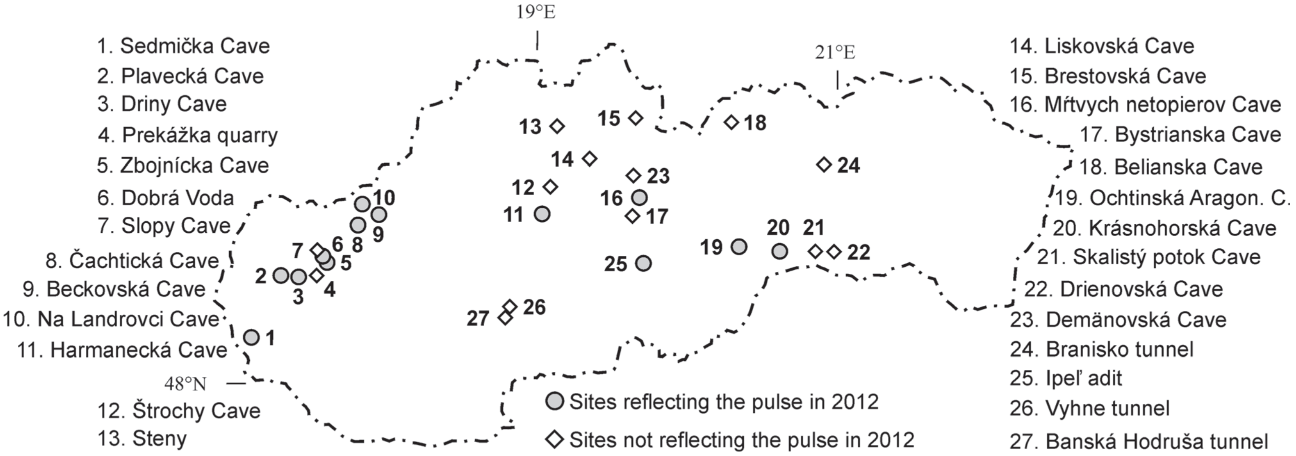


Fig. 7. The EU-TecNet monitoring sites in Slovakia: grey dots represent those monitoring points that offer evidence for the proposed tectonic pressure pulse while the black squares represent those points that do not offer evidence for the proposed pulse.

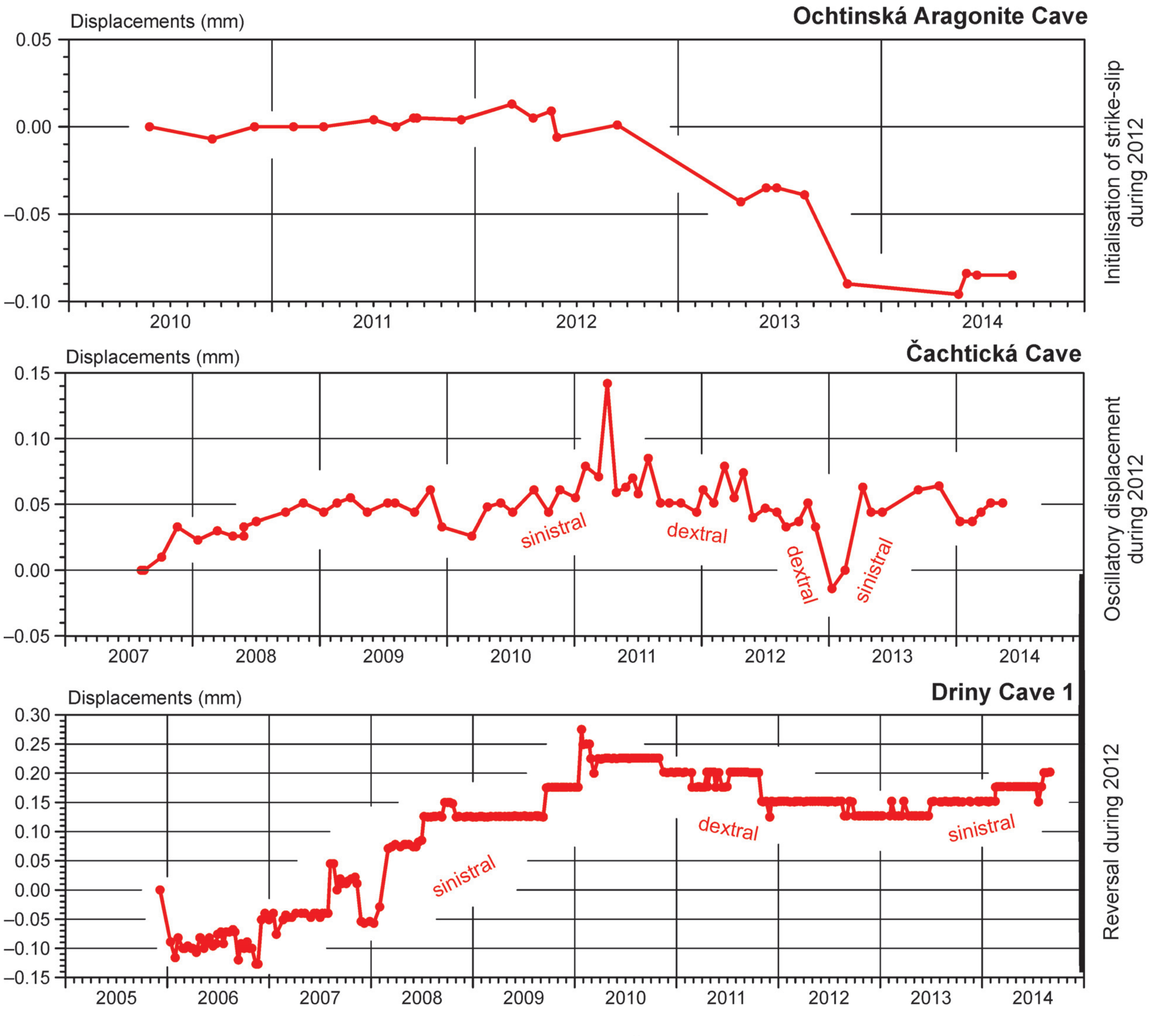
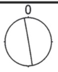
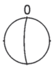
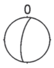
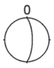


Fig. 8. The strike-slip displacements registered along faults in Driny Cave, Čachtická Cave, and Ochtinská Aragonite Cave in the Western Carpathians of Slovakia. The pressure pulse is expressed as the initialization of displacement at Ochtinská Aragonite Cave, a reversal in the sense of displacement at Driny Cave, and a large oscillatory displacement at Čachtická Cave.

sible to establish a relationship between the characteristics of each fault (i.e. strike, dip, and dip direction) and its reaction to the pressure pulse (i.e. strike-slip, dip-slip, opening/closing).

The subterranean monitoring point of Vrh Svetih Treh Kraljev in Slovenia is located in the Southern Calcareous Alps close to the contact between the Adriatic and Eurasian Plates.

Table 1: The displacement anomalies recorded at each monitoring point across the EU-TecNet network in Slovakia during the tectonic pressure pulse towards the end of 2012.

Site No.	Site name	Monitored fault: dip°→dip direction°	Fault stereoprojection in lower hemisphere	Affected fault displacement components and their character
1.	Sedmička Cave	89°→080°		Fault dilation (initialisation), strike-slip (reversal)
2.	Plavecká Cave	90°→290°		Strike-slip (initialisation)
		65°→240°		Verticals (oscillation), strike-slip (oscillation)
3.	Driny Cave	70°→290°		Verticals (oscillation), strike-slip (reversal)
		70°→110°		Strike-slip (oscillation)
		75°→040°		Verticals (oscillation)
4.	Prekážka quarry	75°→140°		Verticals (oscillation)
5.	Zbojnícka Cave	65°→245°		Verticals (oscillation), strike-slip (oscillation)
6.	Dobrá Voda trench	76°→136°		Strike-slip (oscillation)
7.	Slopy Cave	70°→315°		
8.	Čachtická Cave	80°→270°		Strike-slip (oscillation)
9.	Beckovská Cave	80°→320°		Verticals (reversal), strike-slip (reversal)
10.	Na Landrovci Cave	80°→150°		Verticals (reversal), strike-slip (oscillation)
		80°→150°		
11.	Harmanecká Cave	70°→280°		Strike-slip (reversal), verticals (oscillation), fault dilation (oscillation)
12.	Štrochy Cave	75°→200°		
13.	Steny	88°→120°		
14.	Liskovská Cave	80°→340°		
		85°→220°		
15.	Brestovská Cave	88°→320°		
16.	Mŕtvych netopierov Cave	65°→000°		Verticals (reversal)
17.	Bystrianska Cave	70°→090°		
18.	Belianska Cave	70°→090°		
19.	Ochtinská Aragon. Cave	85°→300°		Strike-slip (initialisation)
20.	Krásnohorská Cave	80°→320°		Strike-slip (oscillation)
21.	Skalistý potok Cave	65°→080°		
22.	Drienovská Cave	80°→190°		
23.	Demänovská Cave	55°→210°		
24.	Branisko tunnel	65°→115°		
25.	Ipeľ adit	80°→322°		Verticals (reversal)
26.	Vyhne tunnel	70°→278°		
27.	Banská Horduša tunnel	73°→130°		

The extensometer is installed across a fault striking E-W with a 354/78. This site presents evidence for the proposed pressure pulse (Fig. 11). The onset of the compressional phase is reflected by both the strike-slip and dip-slip components. During this phase, the southern block was uplifted by about 0.3 mm with respect to the northern block and the horizontal strike-slip displacement component shows about 0.1 mm of sinistral movement, demonstrating oblique thrusting along the fault as a result of significant pressure possibly from the N-S or NNE-SSW direction (SE quadrant) at the time of the pulse in 2012. Such orientation is in good accordance with the general N-S striking maximum horizontal stress axis in Slovenia

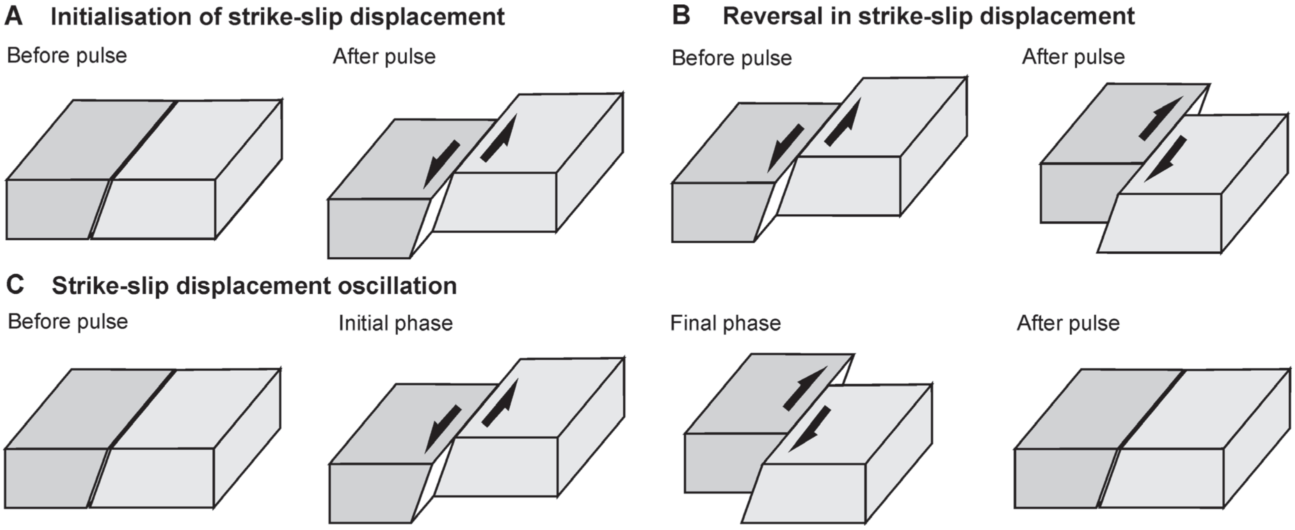


Fig. 9. The structural block models characterize the strike-slip displacement component during the significant tectonic pressure pulse towards the end of 2012. **A** — initiation of strike-slip displacements at sites which were not previously characterized by horizontal slip, **B** — reversal in the sense of displacement that changes the progressive long-term trends, **C** — large oscillatory displacements which do not generally change the progressive long-term trend.

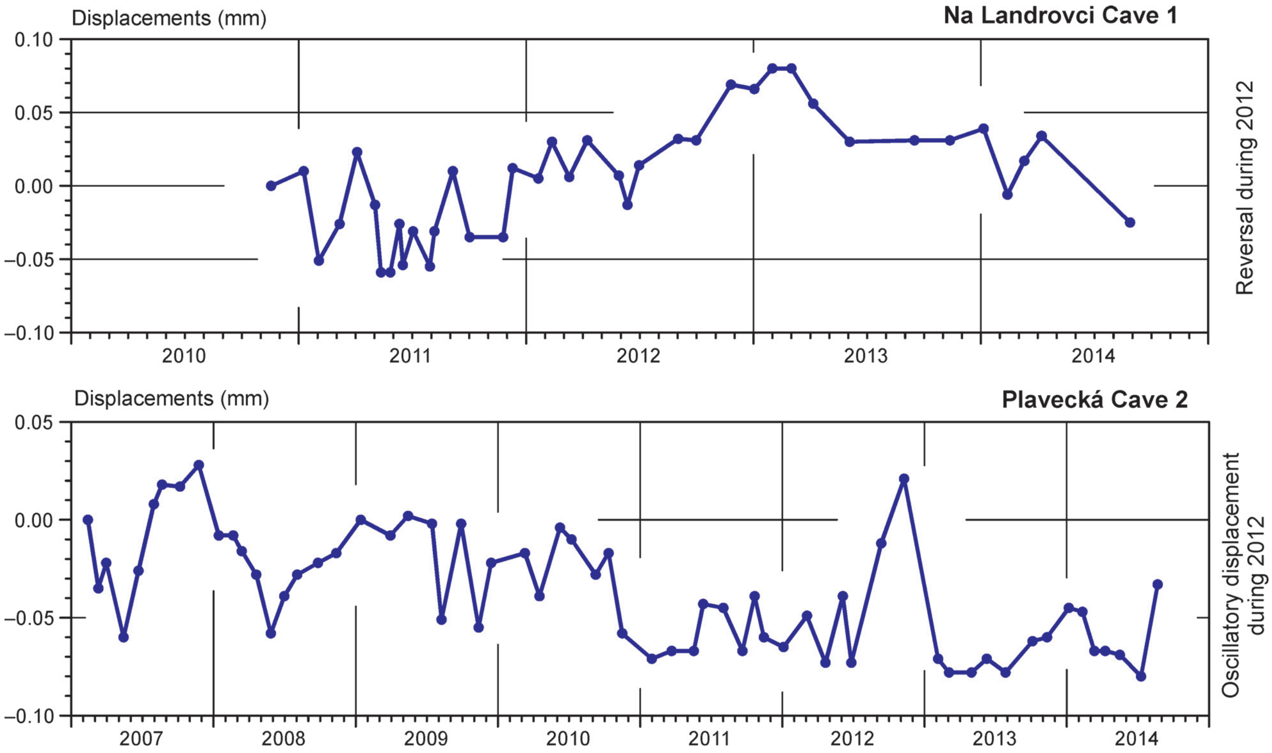


Fig. 10. The dip-slip displacements registered across faults in Na Landrovci Cave and Plavecká Cave in the Western Carpathians of Slovakia. The pressure pulse is expressed as a reversal in the sense of displacement at Na Landrovci Cave and large oscillatory displacement at Plavecká Cave.

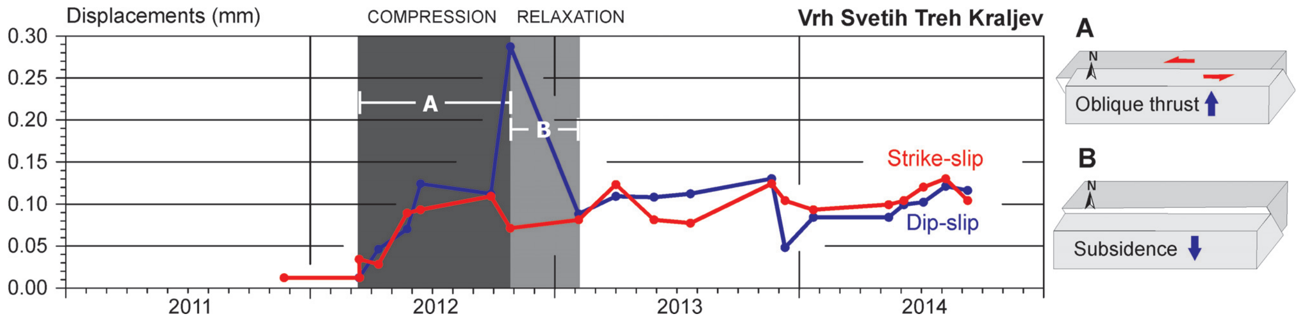


Fig. 11 The displacements registered along an E-W striking fault in Vrh Svetih Treh Kraljev in the Southern Limestone Alps of Slovenia (N 46°0′39.81″, E 14°10′23.11″). The structural block models characterize the fault movements recorded during the compressional and relaxation phases of the significant tectonic pressure pulse (blue arrow — dip slip, red arrow — strike-slip).

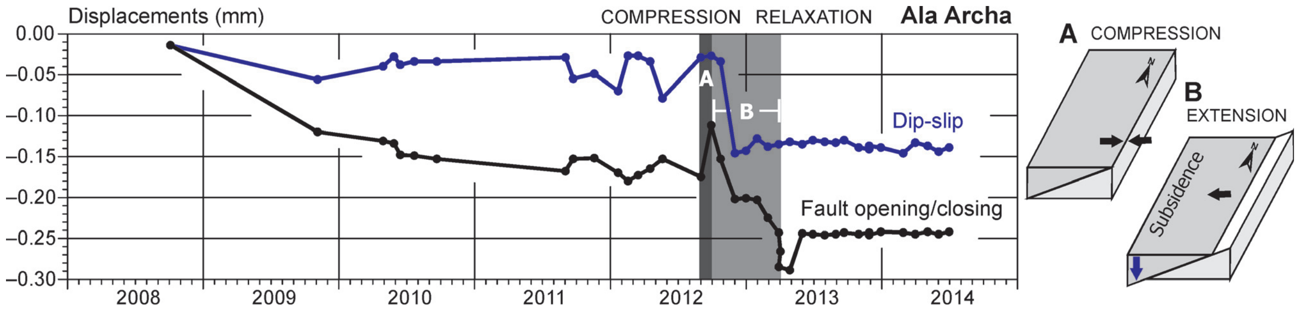


Fig. 12. The displacements registered along a N-S striking fault in Ala Archa in the Kyrgyz Ala-Too Range of Kyrgyzstan (N 42°38′14.87″, E 74°29′41.05″). The structural block models characterize the fault movements recorded during the compressional and relaxation phases of the significant tectonic pressure pulse (A and B) (blue arrow — dip slip, black arrow — fault opening/closing).

(Bada et al. 2007). The onset of the relaxation phase is reflected by the dip-slip component. During this phase, the southern block subsided by about 0.2 mm with respect to the northern block, prior to resumption of the progressive horizontal and vertical trends.

The subterranean monitoring point of Ala Archa in Kyrgyzstan is located in the Kyrgyz Ala-Too Range on the northern edge of the Tian Shan. The extensometer is installed across a fault striking N-S with a 270/20. This distal site also appears to present evidence for the proposed pressure (Fig. 12). The short compressional phase is reflected by about 0.05 mm of closing of the fault while the onset of the relaxation phase is reflected by a significant subsidence and opening across the fault. During this phase, the fault opened by about 0.4 mm while the western block subsided by about 0.1 mm with respect to the eastern block.

Conclusions

The EU-TecNet monitoring network was established on the basis that faults are sensitive to perturbations in the regional stress field and, therefore, it should be possible to identify aseismic transient deformations using customized extensometers installed across individual fault structures in the shallow crust. This paper presents the first results from two newly established monitoring points in the Balkan Mountains in Bulgaria. The data from Saeva Dupka, recorded across an EEN-WWS striking fault, show 0.05 mm of sinistral strike-slip along the fault and 0.075 mm of subsidence of the southern block. Much of the subsidence occurred around the time of the distal $M_W = 5.6$ Pernik Earthquake on 22 May 2012. Furthermore, an important aseismic transient deformation, which began in autumn 2012, is reflected by significant fault closing and opening, or compression and extension, across the monitored fault. The data from Bacho Kiro, recorded across a NE-SW striking fault, show 0.1 mm of sinistral strike-slip along the fault and 0.05 mm of subsidence of the north-western block. The same important transient deformation is reflected by changes in the strike-slip, dip-slip, and opening/closing trends and this event has been divided into four distinct phases on the basis of the recorded data. To account for closing across an EEN-WWS fault at Saeva Dupka and acceleration in the sinistral strike-slip trend across a NE-SW fault at Bacho Kiro, the direction of maximum horizontal stress, 1σ, must have been broadly N-S during the aseismic transient deformation towards the end of 2012. This contrasts markedly the generally accepted picture of N-S extension in this part of the Eurasian Plate (e.g. Kotzev et al. 2008; Olaiz et al. 2009). It suggests that extension can be interrupted periodically by short-lived episodes of crustal stress inversion. These results have been compared to data from monitoring points in the Western Carpathians, External Dinarides, and Tian Shan. The sites all provide evidence of simultaneous displacement anomalies and this observation is interpreted as a reflection of the propagation of a tectonic pressure pulse towards the end of 2012. These results highlight the need for protracted monitoring, across large areas, in order to better understand the aseismic transient deformations that characterize slow-slip phenomena.

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