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ORIGINAL PAPER

BIMODALITY OF P-WAVE TRAVEL TIME RESIDUALS FOUND IN THE CTBTO SEISMOLOGICAL DATA (REB-BULLETINS)

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ABSTRACT

REB-bulletins of CTBTO from the period 2000-2023 were used for simple statistical evaluation of the travel time residuals of P-waves detected at the epicentral distance from 30° to 90° arrived from the seismic events of magnitude 5 or greater, with hypocentre no deeper than 50 km. While histograms of time residuals calculated for individual stations of the International Monitoring System CTBTO show expected unimodal (Gaussian) distribution, curves expressing distribution of the arithmetic means and medians calculated from data of these individual stations are bimodal. This bimodality can be explained by the sum of two Gaussian curves related to groups of "fast" and "slow" stations, with a modus difference of about 0.4 to 0.5 seconds. Although discussed bimodality is best visible on residuals related to phases detected at the epicentral distance 70° to 90°, it is evident that also curves related to the nearest evaluated phases (from 30° to 50°) are the sum of two Gaussian curves. So, the reason for bimodality should be sought in the upper mantle or crust, which is consistent with the assumption of "two kinds" of the continental lithosphere (Poupinet et al., 2003). The distribution of "fast" and "slow" stations on the map corresponds with published results of global seismic tomography studies.

INTRODUCTION

REB-bulletins (Reviewed Event Bulletins) of CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization), compiled in the International Data Centre (IDC) since the year 2000 as a list of seismic events located by the seismic network of the International Monitoring System CTBTO (see Koch, 2012), including information about seismic phases associated with the individual events, represent a unique set of seismological data. Tens of thousands of seismic events are listed in the REB-bulletins of CTBTO every year. These bulletins thus provide useful information not only about individual seismic events or characteristics of global seismicity, but also about other phenomena related to the origination, transmission and detection of seismic waves.

The aim of this article is to inform about an interesting result of a simple statistical evaluation of P-wave travel time residuals, for which the global data contained in the REB-bulletins of CTBTO were used. Travel time residuals of detected seismic phases are affected by lateral inhomogeneities in the Earth's interior, and even simple statistic evaluation of travel time residuals listed in the REB-bulletins can inform us about some interesting effects of these inhomogeneities in a global scale. The most important result of the statistical study, which this article primarily wants to point out, is an illustrative example of bimodality visible in P-wave time residual data (using evaluation of arithmetic means and medians of P-wave time residuals calculated for individual stations). This result is analogous to the bimodality of S-wave vertical travel time delays presented by Poupinet and Shapiro (2009).

DATA SELECTION AND EVALUATION

The data from REB-bulletins of CTBTO from years 2000 to 2023 were statistically evaluated, specifically P-wave travel time residuals related to 11,411 seismic events of magnitude 5 or greater, with hypocentre no deeper than 50 km (Fig. 1), were used. Since the data analysis was focused on the evaluation of seismic waves passing through the Earth's mantle, the analysed data set was limited to the time residuals calculated for stations situated at epicentral distances from 30° to 90°. This way, the data set of 229,829 P-wave residuals compiled for 147 seismic stations of the International Monitoring System CTBTO (one of them is station VRAC operated by the Institute of Physics of the Earth, Masaryk University, and situated near Brno), located around the world (mainly on the continents), were selected and subsequently analysed using simple statistical methods. The author of this article is aware of problems using data that are not primarily collected for the purpose of seismic tomography studies (for instance, of the problem of a higher percentage of large time residuals due to great station spacing as was reviewed by Pan et al. (2023), etc. and the resulting uncertainties. However, the easy availability of the data (for institutions participating in CTBTO seismic monitoring) and simplicity of chosen methods give a great chance that the statistical

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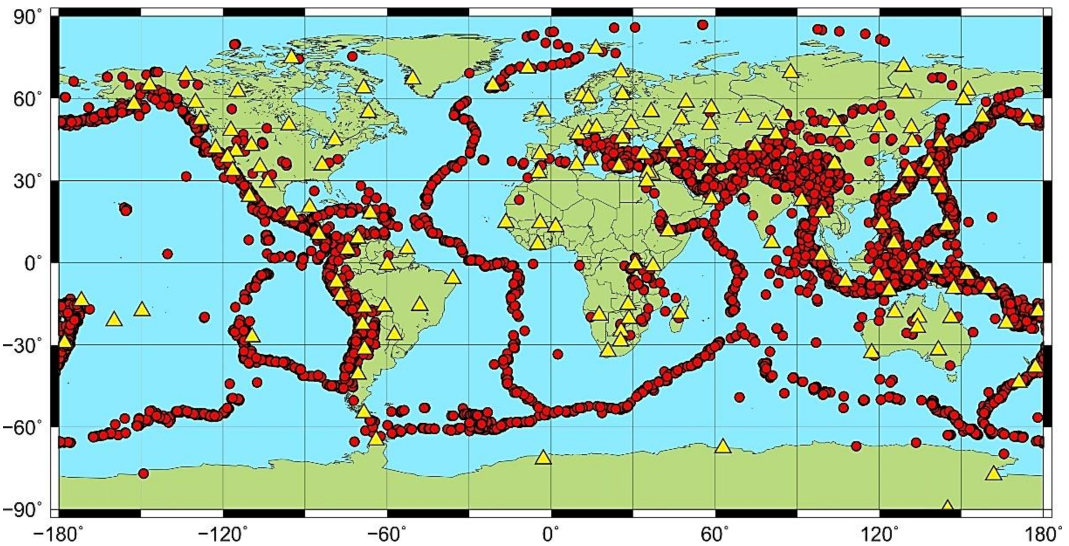

Fig. 1 Schematic map of epicentres of seismic events (red circles) and seismic stations of the International Monitoring System CTBTO (yellow triangles) used for the statistics of P-wave time residuals.

evaluation of even an imperfect data set can bring useful results, as after all happened also in the case of this study.

In the first step, the histogram of P-wave travel time residuals was plotted, and the arithmetic mean and median of these P-wave residuals were calculated for each individual station as well as for the whole data set. Only time residuals of less than 5 seconds (in absolute value) were included in this calculation. In addition, arithmetic means and medians of travel time residuals calculated for individual stations were also statistically evaluated. Histograms of time residuals plotted for individual stations show unimodal, more or less Gaussian distribution, as expected (Fig. 2). But weak bimodality can be observed on the histograms compiled for arithmetic means and for medians calculated from data of individual stations (Fig. 3).

Subsequently, with the intention to check the mentioned weak bimodality more closely, the data set was divided into three subsets according to the epicentral distances of stations detecting the P-wave: "nearest" 30° to 50°, "intermediate" 50° to 70° and "farthest" detections 70° to 90° (category names were chosen in respect of the data set consisting time residuals corresponding with detections from epicentral distances 30°to 90°). For each subset, the same simple evaluation was carried out as in the case of the whole set of data. So, the arithmetic means and medians of the P-wave travel time residuals were calculated again for each station and the data set of these arithmetic means and medians were statistically evaluated. Histograms plotted for the arithmetic means and medians for the mentioned subsets (Fig. 4) confirm the weak bimodality observed in the whole data set.

BIMODALITY AS AN EFFECT OF "FAST" AND "SLOW" LITHOSPHERE

A noticeable bimodality is clearly visible in the histograms plotted for arithmetic means and for medians calculated for time residuals of individual stations in the "farthest" category of epicentral distance from 70° to 90°, the less visible bimodality is evident in the case of subset formed for "intermediate" category of epicentral distances from 50° to 70°. The shape of these histograms evokes the sum of two Gaussian curves. The same explanation of the bimodality of time residuals was presented by Poupinet and Shapiro (2009), in that case it was the bimodality of the S-wave vertical travel time delays.

The strong bimodality of the arithmetic means and the medians of P-wave timer residuals calculated for individual stations in the case of a subset of the "farthest" category, i.e. for detections at an epicentral distance from 70° to 90°, allow these stations to be divided into two groups, the group of "fast" and the group of "slow" stations. The time difference of the modus of both Gaussian curves (for "fast" and "slow" stations), forming the bimodal curves of arithmetic means and medians of P-wave time residuals, is about 0.4 to 0.5 seconds (it is three to four time smaller value then modus difference found for S-wave vertical travel time delays by Poupinet and Shapiro (2009), which was 1.5 seconds). But the standard deviation of the arithmetic means of both ("fast" and "slow") group stations is only 0.2 to 0.25 second in the case of the subset of the "farthest" epicentral distances. That is why the individual peaks of the Gaussian curves are well visible in the histogram representing their sum. In the case of time residuals corresponding to subsets of "intermediate" detected phases (epicentral distances from 50° to 70°) or even "nearest" detected phases (epicentral distances 30° to 50°), the standard deviation is higher. For a subset of time residuals of the "nearest" category (30° to 50°), the standard deviation is comparable with the modus difference of the individual Gaussian curves of groups of "slow" and "fast" stations. The peaks of individual Gaussian curves are thus too close to each other, and the bimodal nature of distribution cannot be distinguished on this

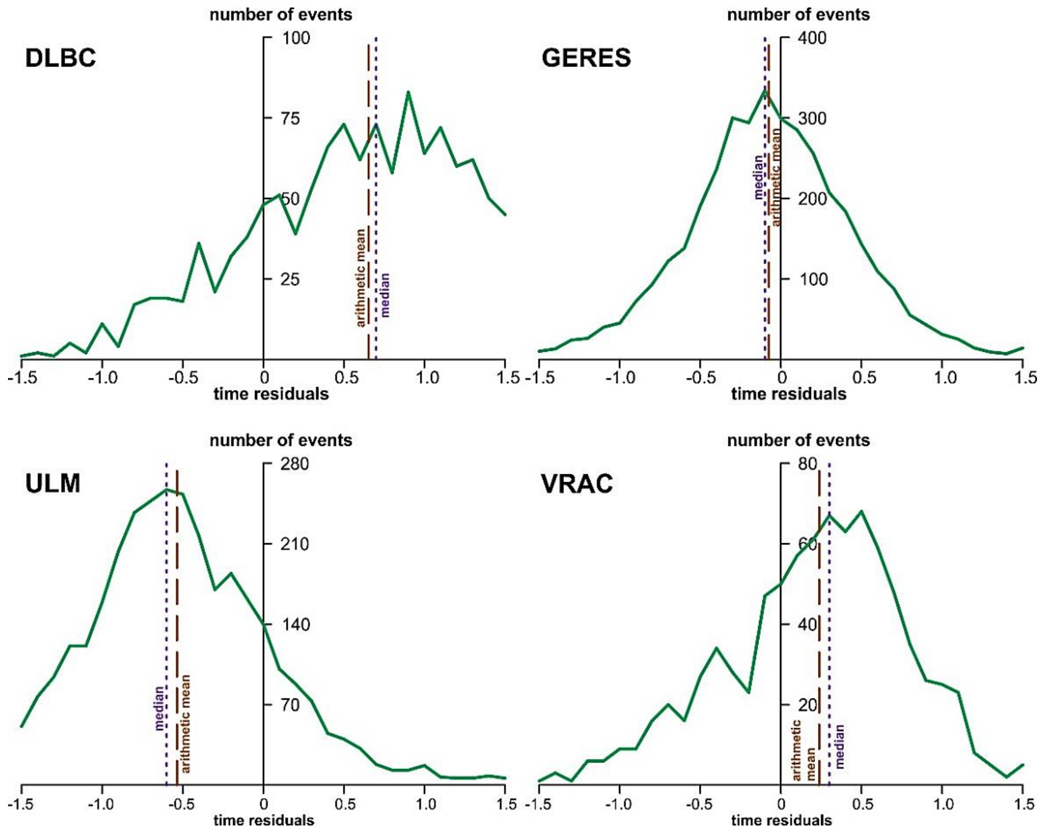

Fig. 2 Examples of histograms of P-wave travel time residuals plotted for four seismic stations of the International Monitoring System CTBTO on the basis of REB-bulletins CTBTO from 2000 to 2023 (phases of events from epicentral distances from 30° to 90°, magnitude 5 or greater, hypocentre no deeper than 50 km). For each station, the arithmetic mean and median of residuals is marked by a dashed (or dotted, respectively) line. Positive travel time residual means the delay with respect to the theoretical arrival time assumed by model IASPEI91 (Kennett, 1991).

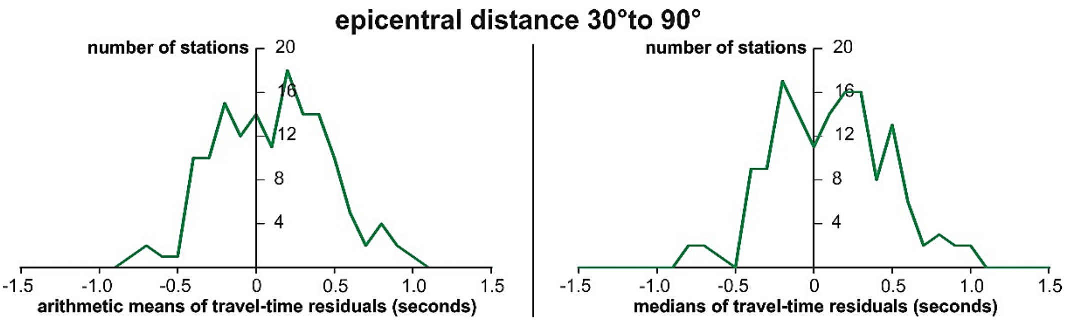

Fig. 3 Histograms of arithmetic means (left) and medians (right) of P-wave travel time residuals calculated for 147 individual seismic stations of the International Monitoring System CTBTO on the basis of REB-bulletins CTBTO from 2000 to 2023 (phases of events from epicentral distances from 30° to 90°, magnitude 5 or greater, hypocentre no deeper than 50 km). Positive travel time residual means the delay with respect to the theoretical arrival time assumed by model IASPEI91 (Kennett, 1991).

sum curve. But the curves representing the distribution of arithmetic means and medians of P-wave time residuals of "slow" stations (and "fast" stations, respectively) keep the Gaussian feature, and the modus difference of about 0.4 to 0.5 seconds remains the same for all three categories as well, including "nearest" category of detections at the epicentral distance from 30° to 50°.

These facts indicate that the source of observed bimodality affect also seismic waves of the "nearest" category, passing through the upper mantle, and should be sought in differences in the material characteristics of the upper mantle and/or crust. It is consistent with the assumption of "two kinds" of the continental lithosphere that affects large-scale seismological observations, explicitly stated by Poupinet et al. (2003), but the effect of "fast" and "slow" continental lithosphere on the travel times of seismic waves has also been discussed (at least partially) in other papers (for example Poupinet, 1979; Poupinet and Shapiro, 2009; Romanowicz and Cara, 1980).

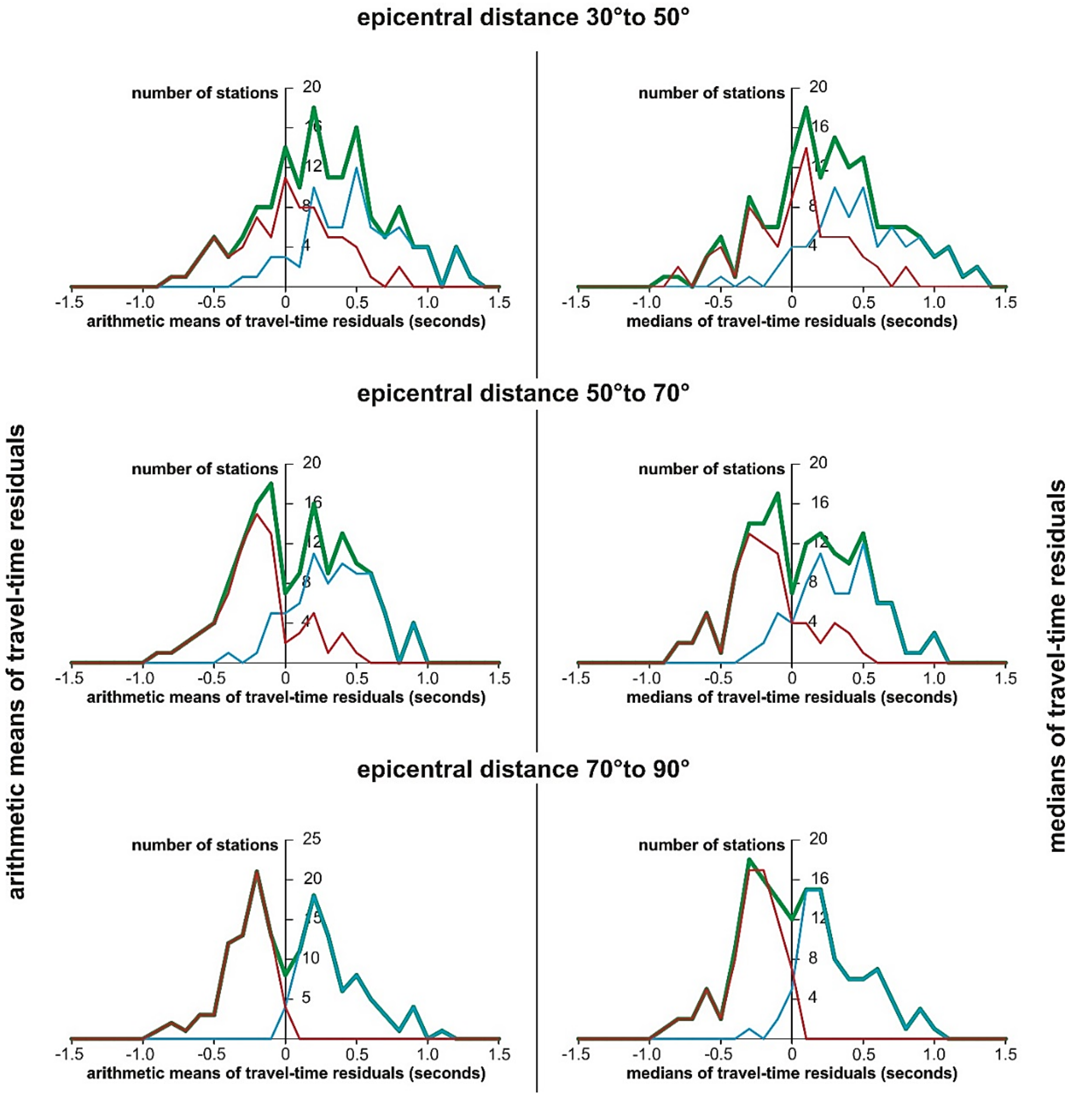

Fig. 4 Histograms of arithmetic means (left) and medians (right) of P-wave travel time residuals (green lines) calculated for individual seismic stations of the International Monitoring System CTBTO and for three intervals of the epicentral distances (73,706 phases from 30° to 50°, 74,409 phases from 50° to 70° and 95,565 phases from 70° to 90° related to 11,411 seismic events, picked on 147 stations) on the basis of REB-bulletins CTBTO from 2000 to 2023 (magnitude 5 or greater, hypocentre no deeper than 50 km). Red lines show a number of arithmetic means or medians calculated for "fast" stations (i.e. stations whose arithmetic mean of residuals calculated for phases detected at an epicentral distance from 70° to 90° is negative), blue lines show number of arithmetic means or medians calculated for "slow" stations (i.e. stations whose arithmetic mean of residuals calculated for phases detected at an epicentral distance from 70° to 90° is positive). Note that separate curves determined for groups of "fast" and "slow" stations are more or less Gaussian, even for the interval of epicentral distances of 30° to 50° (see text for more information). Positive travel time residual means the delay with respect to the theoretical arrival time assumed by model IASPEI91 (Kennett, 1991).

DISTRIBUTION OF THE "FAST" AND "SLOW" AREAS

On the map, the "fast" and "slow" stations are grouped into the "fast" and "slow" areas, which can be distinguished in some parts of the global map (Fig. 5) despite a relatively small number of seismic stations of the International Monitoring System CTBTO. These areas correspond to upper mantle velocity anomalies resulting from the published global seismic tomography studies (e.g. Antolik et al., 2003; Dziewonski and Anderson, 1983; Engdahl et al., 1998; Hosseini et al. ,2020; Houser et al., 2008; Li et al., 2008; Li and Romanowicz, 1996; Poupinet and Shapiro, 2009; Ritsema et al., 2011; Simmons et al., 2012; Vasco et al., 1994; Zhao et al., 2013). Above all, strong contrast of the "slow" western part and the "fast" eastern part of North America is clearly visible from data presented in this article, in accordance with the above-mentioned papers and with some others focused on this problem at the regional scale (e.g. Hales, 1972; Poupinet, 1979; Shinevar et al., 2023; Tauzien et al., 2013). Similarly, "fast" regions in Australia, the northern part of Asia and southern Africa and "slow" regions in the north-eastern Africa, and the easternmost Mediterranean area can also be well distinguished. "Fast" region in the central part of

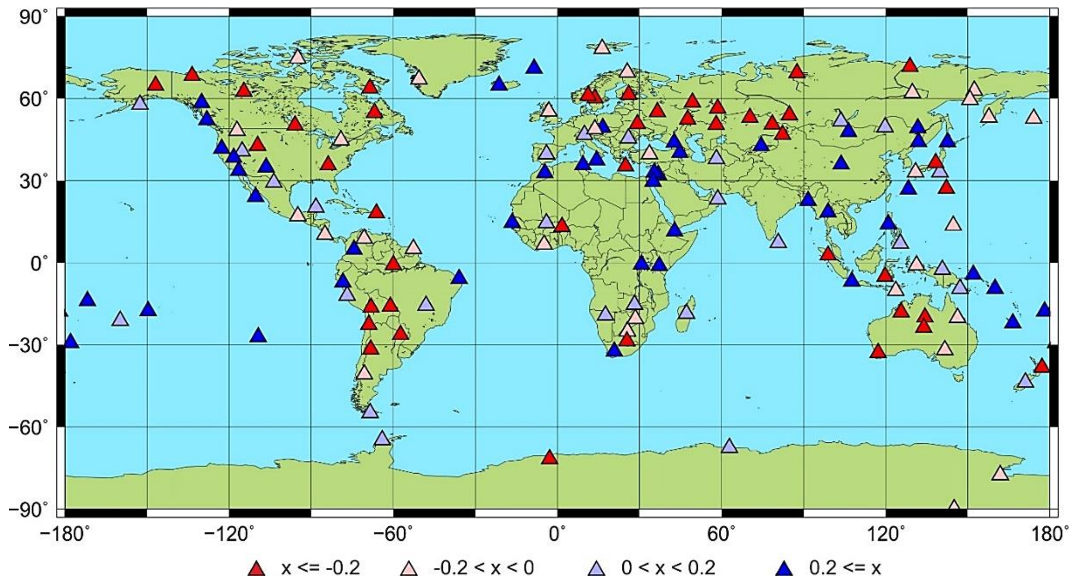

Fig. 5 Schematic map of seismic stations of the International Monitoring System CTBTO with marked "fast" (red) and "slow" (blue) stations. "Fast" stations are those for which the arithmetic mean of residuals calculated for phases detected at an epicentral distance from 70° to 90° is negative (light red colour marks the arithmetic means only between -0.2 and 0 seconds). "Slow" stations are those for which the arithmetic mean of residuals calculated for phases detected at an epicentral distance from 70° to 90° is positive (light blue colour marks the arithmetic means only between 0 and 0.2 seconds). Positive travel time residual means the delay with respect to the theoretical arrival time assumed by model IASPEI91 (Kennett, 1991).

South America is consistent with some published P-wave mantle models (e.g. Li et al., 2008; Simmons et al., 2012), but differs from the results of S-wave studies of Poupinet et al. (2003).

The existence of the "fast" and "slow" areas corresponding to the "fast" and "slow" continental lithosphere is already known and some authors explain it as the effect of different seismic wave velocities in the older (Archean) continental shields (and Poupinet and Shapiro (2009), have pointed out, that also on subduction zones) and in the younger (post-Archean) platforms and tectonically active zones (Artemieva, 2009; Condie, 2016; Currie and van Wijk, 2016; Poupinet et al., 2003; Poupinet and Shapiro, 2003).

Of course, there must also be some other phenomena influencing the observed time residuals, just because a few stations are situated on islands in oceanic regions. Rather phenomena such as higher-temperature areas, elastic anisotropy etc. (for instance see Ekström and Dziewonski (1998)) in the mantle beneath the "slow" stations represent a possible explanation in the case of oceanic regions. However, due to a small number of the stations situated in the oceanic region, the influences of these other phenomena on the results of statistics presented here are surely overshadowed by the effect of the "two kinds" of the continental lithosphere.

Matters of the continental lithosphere composition, age and temperature, and their influence on the seismic wave velocities far exceed the scope of this article, which only has the ambition to show interesting example of effect of the continental lithosphere variability leading to the bimodal feature of P-wave travel time residuals distinguishable on the data of the global seismic network CTBTO. However, in the context of the already published studies and theories based on them, the importance of the discussed bimodality of the P-wave travel time residuals as a new piece to the puzzle of general knowledge about the properties of the lithosphere is well noticeable.

CONCLUSION

Statistical evaluation of arithmetic means and medians (calculated for individual stations) of the P-wave travel time residuals listed in the REB-bulletins (CTBTO) shows bimodal distributions. This bimodality is clearly visible in the cases of phases detected at the epicentral distances from 50° to 70°, and from 70° to 90° and it could be easily explained by the sum of two Gaussian curves. The modus difference observed in the bimodal curves of arithmetic means and medians of the P-wave residuals calculated for individual stations is 0.4 to 0.5 seconds.

Nevertheless, the statistical analysis shows the effect of the discussed sum of Gaussian curves even in the data set for phases detected at the epicentral distance from 30° to 50°, although the small modus difference in respect to the width of individual Gaussian curves not allow to distinguish two modus in the sum curve in this case. So, the source of observed bimodality should be sought in the upper mantle and/or crust, which confirms the assumption of "two kinds" ("fast" and "slow") of the continental lithosphere described by Poupinet et al. (2003).

The presented result shows that even a simple statistical evaluation of the available data produced by the global network of the International Monitoring

System CTBTO can contribute to the knowledge of interesting details about the characteristics of the Earth's interior. The bimodality of the P-wave travel time residuals found on the base of simple statistical evaluation of the REB-bulletins (CTBTO) represents another confirmation of the validity of bimodal model of the continental lithosphere in sense of Poupinet et al. (2003).

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