

P- and S-Wave Travel-Time Characteristics and Station-Dependent Residuals from Local Earthquakes in Ghana

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This manuscript is a non-peer-reviewed preprint submitted to EarthArXiv. The manuscript has
been submitted to the Journal of Seismology for peer review.

Funding Declaration

The authors received no funding for this study.

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27 **Abstract**

28 Understanding P- and S-wave travel-time behaviour is important for characterizing seismic-wave
29 propagation and identifying station-dependent variability within regional seismic networks. This
30 study investigates P- and S-wave travel-time characteristics and station-dependent residuals using
31 local earthquakes recorded by the Ghana Digital Seismic Network (GHDSN). The analysis
32 reexamines the published GHDSN earthquake bulletin and waveform dataset for 2012–2014,
33 comprising 73 detected earthquakes recorded by six broadband stations. Event selection was based
34 on phase coverage, yielding nine earthquakes with paired P- and S-wave arrivals at at least five
35 stations and 47 station-level P+S observations. Hypocentral distances were calculated from
36 earthquake coordinates and focal depths, and first-order linear regressions were used to
37 characterize P- and S-wave travel times. The resulting effective velocities were 6.51 km s^{-1} for P
38 waves ($R^2 = 0.985$) and 3.88 km s^{-1} for S waves ($R^2 = 0.985$). Station median residuals ranged
39 from -0.40 to $+1.17 \text{ s}$ for P waves and -1.39 to $+1.27 \text{ s}$ for S waves. Within-event permutation
40 tests yielded $p = 0.0080$ for P waves and $p = 0.0110$ for S waves, indicating statistically
41 significant station-associated variability in the selected observations. However, the small ΔR^2
42 values indicate that the magnitude of this station-associated contribution is limited. The results
43 provide an empirical characterization of local seismic-wave propagation across the investigated
44 GHDSN stations in southern Ghana and identify station-dependent variability that warrants further
45 investigation using larger datasets, improved earthquake locations, and joint velocity–location–
46 station analyses.

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54 **1. Introduction**

55 Earthquakes generate elastic waves that provide important information about the structure and
56 physical properties of the Earth's interior. Among these waves, P and S waves are particularly
57 important in local earthquake seismology because their arrival times depend on source–receiver
58 geometry and the seismic velocity structure through which the waves propagate. Measurements of
59 P- and S-wave arrival times are therefore widely used for earthquake location, seismic velocity
60 estimation, crustal characterization, and investigation of spatial variations in seismic structure
61 (Haney 2025; Kennett & Engdahl 1991). Differences between observed and predicted arrival
62 times, commonly expressed as travel-time residuals, can additionally provide information about
63 uncertainties in the assumed velocity structure, earthquake locations, and station-dependent effects
64 (Osagie et al. 2017; Vasco et al. 1994).

65 Ghana provides an important setting for investigating local and intraplate seismicity because
66 significant earthquake activity occurs despite its location away from major active plate boundaries.
67 The country lies within the southeastern part of the West African Craton and has experienced both
68 historical damaging earthquakes and continuing local seismicity. Historical records document
69 major earthquakes, including events in 1862, 1906, and 1939, while instrumental observations
70 have documented smaller local earthquakes in southern Ghana (Amponsah 2004). Amponsah et
71 al. (2012) compiled a comprehensive earthquake catalogue covering the period 1615–2003 and
72 identified southeastern Ghana as a region of concentrated seismic activity, particularly around the
73 Akwapim Fault Zone and Coastal Boundary Fault. Earlier investigations similarly reported
74 concentrations of earthquake epicentres near the intersection of these structural features
75 (Amponsah 2002).

76 The seismicity of Ghana forms part of the broader problem of understanding earthquake activity
77 within the West African continental interior and along its passive margins. Recent work has shown
78 that West African earthquakes occur both along passive-margin structures and within the
79 continental interior, with seismicity associated in some regions with the reactivation of inherited
80 brittle structures, Precambrian shear zones, failed rifts, and other pre-existing weaknesses (Legre
81 et al. 2024). This regional context demonstrates that the absence of a major active plate boundary

does not exclude significant earthquake activity, while also highlighting the structural complexity within which Ghanaian earthquakes occur.

The development of the Ghana Digital Seismic Network (GHDSN) provided an important improvement in the instrumental monitoring of this seismicity. The National Digital Seismic Network Observatory was commissioned in December 2012 to improve the monitoring and analysis of earthquakes and other seismic events in Ghana (Ahulu & Danuor 2015). The network subsequently provided continuous broadband observations from stations distributed across southern Ghana, including KUKU, MRON, SHAI, AKOS, KLEF, and WEIJ. These observations have supported investigations of earthquake occurrence, seismic hazard, and crustal structure (Ahulu & Danuor 2015; Ahulu et al. 2018; Akpan et al. 2016).

Independent geophysical investigations indicate that the crust beneath southern Ghana is structurally complex. Akpan et al. (2016) used P-wave receiver functions, H–k stacking, and joint inversion of receiver functions with Rayleigh wave group velocities to investigate crustal structure beneath Nigeria and southern Ghana. Their analysis, which included the six Ghanaian GHDSN stations, estimated an average Moho depth of about 44 km beneath the investigated southern Ghana regions and identified variations in lower-crustal structure. These findings demonstrate that southern Ghana cannot be adequately represented by a homogeneous crustal medium and provide an important context for interpreting variations in observed seismic travel times.

A major recent development in Ghanaian seismology has been the application of machine-learning methods to the GHDSN waveform archive. Mohammadigheymasi et al. (2023) applied the EQTransformer deep-learning framework to GHDSN recordings from 2012–2014 to detect local earthquakes and identify P- and S-wave arrivals. The resulting dataset contains 73 local earthquakes, 559 P- and S-phase arrivals, and recordings from six broadband stations. The authors subsequently used these observations in a joint inversion of hypocentral parameters and a one-dimensional velocity model. The dataset therefore provides an opportunity for further investigation of local seismic-wave propagation beyond its original application to earthquake detection, phase picking, earthquake location, and velocity-model estimation.

P- and S-wave travel times provide a direct means of examining this propagation behaviour. For a simplified or effective medium, travel time can be expressed as a function of source–receiver distance:

112
$$t = a + bD$$

113 where t is travel time, D is source-receiver distance, and b represents the effective slowness. The
114 reciprocal of the slope therefore provides an effective seismic velocity. Such a relationship can
115 describe the dominant distance-dependent behaviour of a dataset without necessarily representing
116 a formal layered velocity model. This distinction is important in regions such as southern Ghana,
117 where independent studies demonstrate substantial crustal structure (Akpan et al. 2016).

118 Travel-time residuals provide an additional way of examining departures from the dominant
119 distance-dependent relationship (Lakshminarasimhan et al. 2018). A residual can be expressed as

120
$$r = t_{\text{obs}} - t_{\text{pred}}$$

121 where t_{obs} is the observed arrival time and t_{pred} is the predicted arrival time. Systematic residual
122 patterns may contain information about velocity heterogeneity, earthquake-location uncertainty,
123 propagation-path differences, or station-dependent effects (Vasco et al. 1994). However, residuals
124 can arise from multiple sources and should not automatically be attributed to a particular
125 geological or site effect. Earthquake-location errors, for example, can alter both calculated source–
126 receiver distances and predicted arrival times, while uncertainty in identifying the exact P or S
127 wave onset can introduce additional timing errors.

128 Previous regional studies have demonstrated the usefulness of station-dependent travel-time
129 analysis. Osagie et al. (2017) investigated P-wave travel-time residuals and station corrections
130 across stations in Peninsular Malaysia, Singapore, and southern Thailand by comparing observed
131 and predicted travel times using one-dimensional velocity models. Their analysis demonstrated
132 systematic differences among stations and highlighted the potential importance of station-specific
133 travel-time behavior. However, their methodology involved formal station corrections relative to
134 specified one-dimensional (1D) Earth models and ray-tracing calculations, whereas the present
135 study derives residuals relative to empirical distance-based travel-time relationships. The residuals
136 examined here are therefore treated as station-dependent empirical patterns rather than formal
137 station corrections.

138 Although previous studies have substantially improved understanding of Ghanaian seismicity,
139 several aspects remain comparatively less explored. Existing work has focused primarily on
140 historical and instrumental earthquake catalogues, earthquake detection, hypocentral

determination, seismic hazard, crustal structure, and velocity-model inversion (Ahulu & Danuor 2015; Ahulu et al. 2018; Akpan et al. 2016; Amponsah et al. 2012; Amponsah 2002; 2004; Mohammadigheymasi et al. 2023a). In particular, the deep-learning-based GHDSN study established a valuable earthquake and phase-arrival dataset and investigated earthquake locations and a one-dimensional velocity model, but did not specifically focus on the empirical station-by-station behaviour of P- and S-wave travel-time residuals after accounting for the dominant distance–time relationship.

The present study addresses this gap by reanalyzing the GHDSN earthquake bulletin and associated phase-arrival dataset to characterize local P- and S-wave travel-time behaviour in southern Ghana. The study specifically aims to (1) characterize the relationship between P- and S-wave travel times and hypocentral distance, (2) estimate effective P- and S-wave velocities from the empirical travel-time relationships, (3) quantify station-dependent travel-time residuals, (4) evaluate observed versus predicted travel times, and (5) test whether the observed station-dependent residual structure is distinguishable from random within-event station reassignment.

The study therefore provides an empirical characterization of local seismic-wave propagation across the investigated GHDSN stations and complements previous earthquake-catalogue, crustal-structure, and velocity-model investigations of Ghana. By separating the dominant distance-dependent travel-time trend from station-dependent residual variation, the analysis provides a reproducible framework for examining local P- and S-wave arrivals while avoiding attribution of observed residuals to a specific geological or site effect without independent structural evidence.

2. Study Area and Seismic Network

Ghana is located in West Africa on the African Plate, along the southeastern margin of the West African Craton. Despite its predominantly intraplate setting, Ghana experiences recurrent seismic activity, particularly in southern Ghana. This seismicity has been associated with inherited structures such as the Akwapim Fault Zone and Coastal Boundary Fault (Amponsah 2002; Amponsah et al. 2012). The region also includes contrasting geological domains, including the Volta Basin and Dahomeyide belt, which may influence seismic-wave propagation. The present study focuses on southern Ghana within the coverage of the Ghana Digital Seismic Network (GHDSN), using six stations to investigate local P- and S-wave travel-time behaviour and station-dependent residuals.

The GHDSN was established to improve digital monitoring and analysis of earthquakes and other seismic events in Ghana and was commissioned in December 2012 (Ahulu & Danuor 2015). The network used in the dataset analyzed here comprises six broadband stations: AKOS, KLEF, KUKU, MRON, SHAI, and WEIJ, distributed across southern Ghana as shown in Figure 1. The stations operated at a sampling rate of 100 Hz, providing broadband waveform observations suitable for local earthquake analysis (Mohammadigheymasi et al. 2023a, b).

The seismic dataset covers the period 2012–2014 and contains waveform records and a SEISAN-format earthquake bulletin for 73 detected local earthquakes. The original dataset contains 559 P- and S-wave arrival times, comprising 292 P arrivals and 267 S arrivals (Mohammadigheymasi et al., 2023a). In the present study, a subset of these observations was selected according to P- and S-phase station coverage for the travel-time analysis.

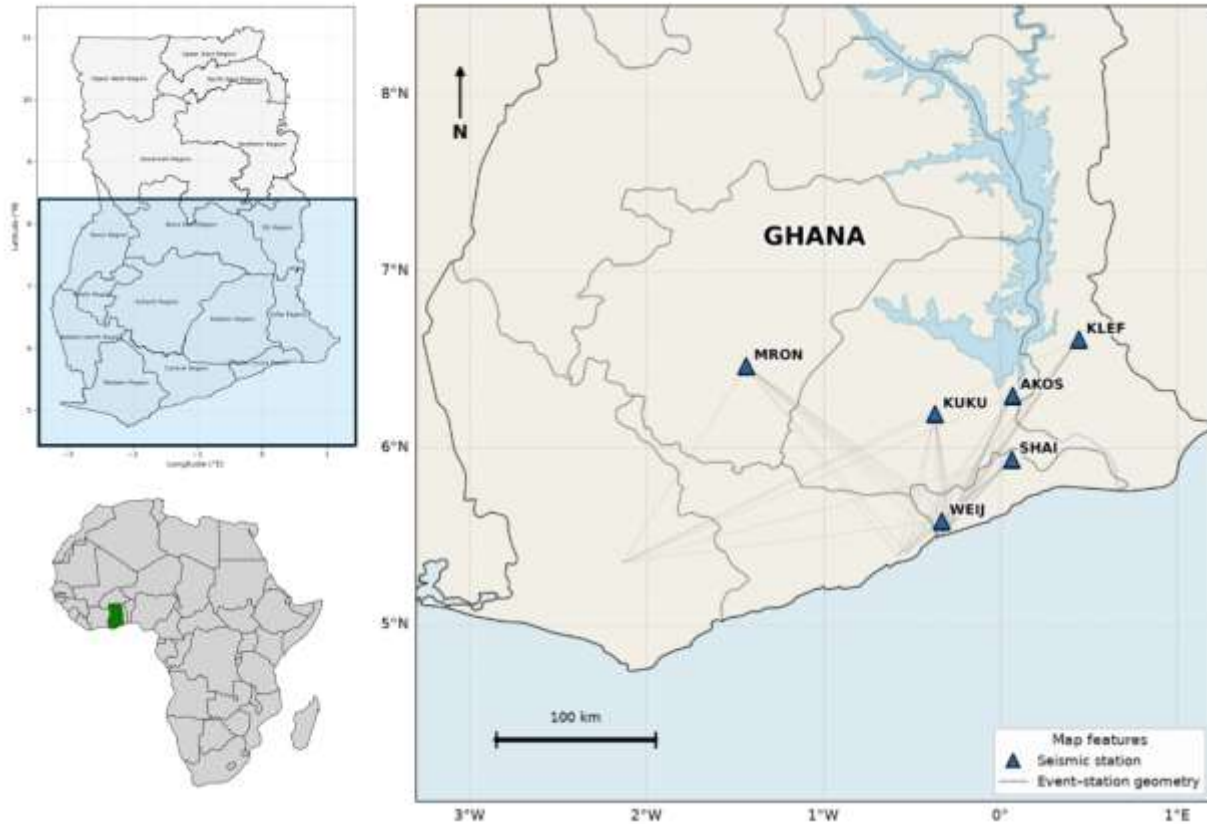


Figure 1 shows the spatial distribution of the six GHDSN stations used in this study and the corresponding event–station geometry for the observations retained for analysis. The lines represent the geographic source–station geometry of the selected observations and are not calculated seismic ray paths.

3. Data and Methods

3.1. Seismic dataset

The study used the earthquake bulletin and waveform records of the Ghana Digital Seismic Network (GHDSN) for the period 2012–2014. The dataset comprises recordings from six broadband stations and 73 detected local earthquakes, with 559 P- and S-wave phase arrivals. The dataset was originally generated using EQTransformer, an attention-based deep-learning model for simultaneous earthquake detection and P- and S-phase picking (Mousavi et al., 2020), and subsequently processed for earthquake association and hypocentral analysis by Mohammadigheymasi et al. (2023a, b). In this study, the published bulletin and associated

waveforms were reanalysed to investigate empirical P- and S-wave travel-time characteristics and station-dependent travel-time residuals.

3.2. Waveform examination and P–S phase identification

To provide a direct waveform-level illustration of the observations used in the analysis, Event 0 was examined at five stations (WEIJ, SHAI, KUKU, KLEF and MRON). The vertical components were detrended and band-pass filtered between 1 and 15 Hz for visualization. The P- and S-arrival times marked on the representative seismograms were taken from the validated bulletin picks rather than newly estimated from the filtered display. Thus, the filtering was used to improve visual presentation and did not alter the arrival-time dataset used in the travel-time analysis. Waveform handling was performed with ObsPy following standard seismological waveform-processing procedures (Beyreuther et al. 2010).

3.3. Event and phase selection

Event selection was based primarily on P- and S-phase coverage rather than earthquake magnitude. From the 73 events in the original bulletin, 55 contained paired P- and S-wave arrivals at three or more stations, 29 at four or more stations, and nine at five or more stations. The final dataset therefore consisted of nine earthquakes and 47 station-level P+S observations distributed across the six GHDSN stations. The selected events were 0, 1, 10, 12, 26, 31, 44, 45, and 68.

For each event–station pair, P- and S-wave arrival times were extracted from the bulletin. The S–P time difference was calculated as

$$\Delta t_{s-p} = t_s - t_p$$

where t_p and t_s represent the P- and S-wave arrival times, respectively. Only observations satisfying $t_s > t_p$ were retained, and waveform records were consulted for quality control where necessary.

3.4. Event–station distances

Earthquake and station coordinates, together with earthquake focal depths, were used to calculate event–station distances. Epicentral distance was first determined from the geographic coordinates, and hypocentral distance was then calculated as

$$D_h = \sqrt{D_e^2 + h^2}$$

Where D_h = hypocentral distance, D_e = epicentral surface distance and h = earthquake focal depth. Hypocentral distance was used because it accounts for the three-dimensional separation between the earthquake source and seismic station. This procedure is particularly appropriate for a dataset containing events with appreciably different focal depths, such as the selected Ghana earthquakes.

3.5. P- and S-wave travel-time analysis

P- and S-wave travel times were related to hypocentral distance using first-order linear regression:

$$t_P = a_P + b_P D_h$$

and

$$t_S = a_S + b_S D_h,$$

where a is the empirical time intercept, and b is the travel-time slope. Effective wave velocities were estimated from the reciprocal of the slopes:

$$V_P = \frac{1}{b_P}, \quad V_S = \frac{1}{b_S}.$$

The resulting velocities are treated as empirical effective velocities derived from the observed travel-time slopes, rather than as a formal one- dimensional or three- dimensional crustal velocity model.

3.6. Travel-time residuals and station dependence

Predicted travel times were calculated from the fitted travel-time relationships, and residuals were defined as

254
$$r_i = t_i - \hat{t}_i,$$

255 where t_i is the observed travel time and $\hat{t}_i$ is the corresponding predicted travel time. Positive
 256 residuals indicate arrivals later than predicted, while negative residuals indicate earlier arrivals.

257 Residuals were grouped by station and summarized using the median separately for P and S waves.
 258 The station-level residuals were interpreted as station-dependent travel-time patterns, rather than
 259 definitive station corrections or direct indicators of a particular geological structure. Such residuals
 260 can reflect near-surface or lateral velocity variations, differences between actual propagation paths
 261 and the simplified travel-time model, earthquake-location uncertainty, and phase-picking
 262 uncertainty (Pavlis & Booker 1983; Vasco et al. 1994).

263

264 **3.7. Permutation test**

265 A within-event permutation test was applied to assess whether the observed station-dependent
 266 residual structure could arise from random station assignment. Station labels were randomly
 267 reassigned within each earthquake while preserving the event identity and number of observations.
 268 A total of 1,000 permutations were performed, and the additional explanatory contribution of
 269 station identity was quantified using

270
$$\Delta R^2 = R_{\text{station}}^2 - R_{\text{base}}^2$$

271

272 where R_{base}^2 represents the coefficient of determination of the model without station identity and
 273 R_{station}^2 represents the corresponding value when station identity is included.

274 The empirical p-value was calculated from the proportion of randomized ΔR^2 values equal to or
 275 exceeding the observed ΔR^2 . The resulting statistical values are presented in Figure 7.

276

277 **3.8. Computational analysis**

278 All data processing and statistical analyses were performed using a Python-based workflow. The
 279 workflow included extraction of event and phase information, event screening, distance
 280 calculation, travel-time regression, residual analysis, station-level summaries, permutation testing,

and generation of the study figures. ObsPy was used for waveform processing where applicable (Beyreuther et al. 2010).

4. Results

4.1. Earthquake selection and dataset characteristics

The Ghana seismicity bulletin contained 73 detected earthquake event headers. Phase-coverage screening identified 55 events with both P- and S-wave observations at three or more stations, 29 events with four or more stations, and nine events with at least five stations providing both phases. These nine earthquakes-Events 0, 1, 10, 12, 26, 31, 44, 45, and 68- were retained for the principal multi-event analysis. The selected events yielded 47 station-level P+S observations distributed across AKOS, KLEF, KUKU, MRON, SHAI, and WEIJ. The selected events span approximately ML 3.0–4.0 and hypocentral distances of about 8–308 km. Event 1 is notably deep (78 km), whereas Event 68 is very shallow (1.7 km).

4.2. Representative waveform observations and phase arrivals

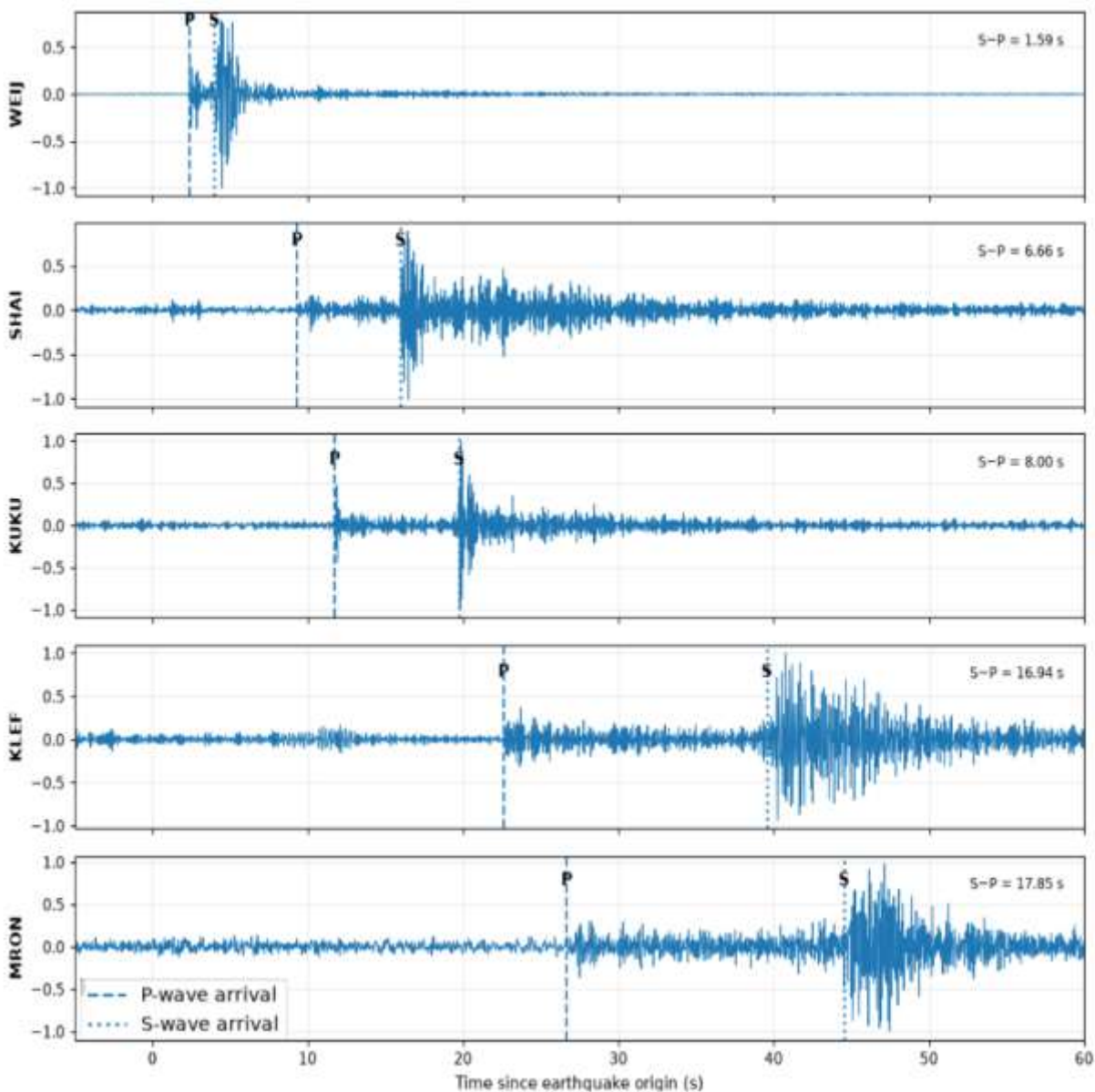


Figure 2. Representative vertical-component seismograms for Event 0 recorded at five GHDSN stations. The S-P intervals increase from 1.59 s at WEIJ to 17.85 s at MRON, illustrating the variation in phase arrival times among stations.

Event 0 provides an illustrative waveform-level example of the seismic observations underlying the travel-time dataset. Paired P- and S-wave arrivals are identifiable at five stations, satisfying the minimum phase-coverage criterion used in the principal event selection. The S-P intervals increase progressively among the stations, ranging from 1.59 s at WEIJ to 17.85 s at MRON, providing a

direct visual illustration of the distance-dependent variation in phase arrival times subsequently quantified using hypocentral-distance regression (Figure 2). Event 0 was selected for waveform presentation because clear P- and S-wave arrivals could be identified across multiple stations, making it suitable for demonstrating the characteristics of the observations used in the analysis. This selection was made solely for illustrative purposes and does not imply that Event 0 was preferentially selected for the quantitative analysis or that its waveform characteristics are representative of all earthquakes in the dataset. All nine earthquakes were retained for the subsequent travel-time and residual analyses according to the predefined phase-coverage criteria.

4.3. P- and S-wave travel-time relationships

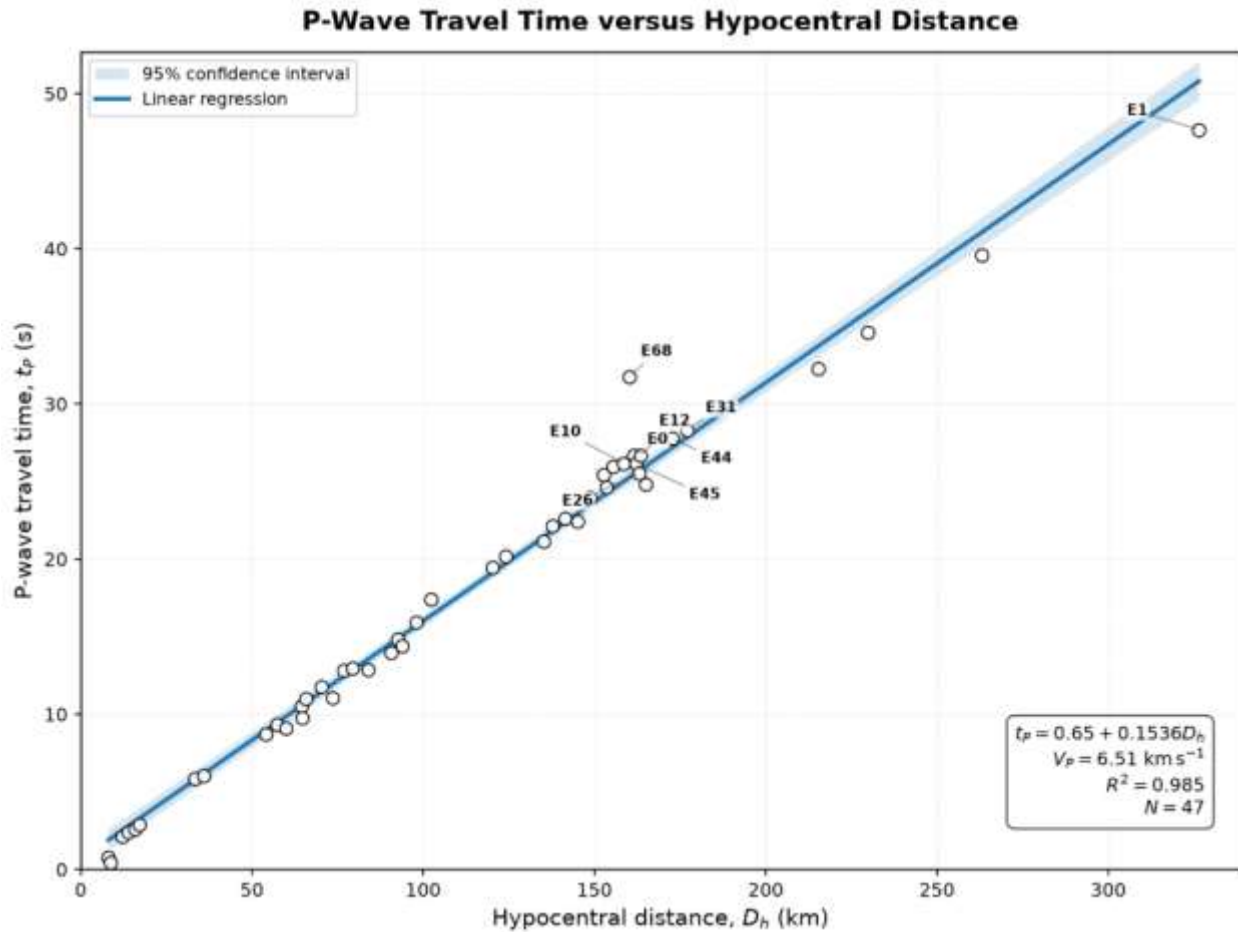


Figure 3. P-wave travel time as a function of hypocentral distance for the 47 station-level observations. The fitted line represents the distance-based linear regression, and the shaded region indicates its 95% confidence interval.

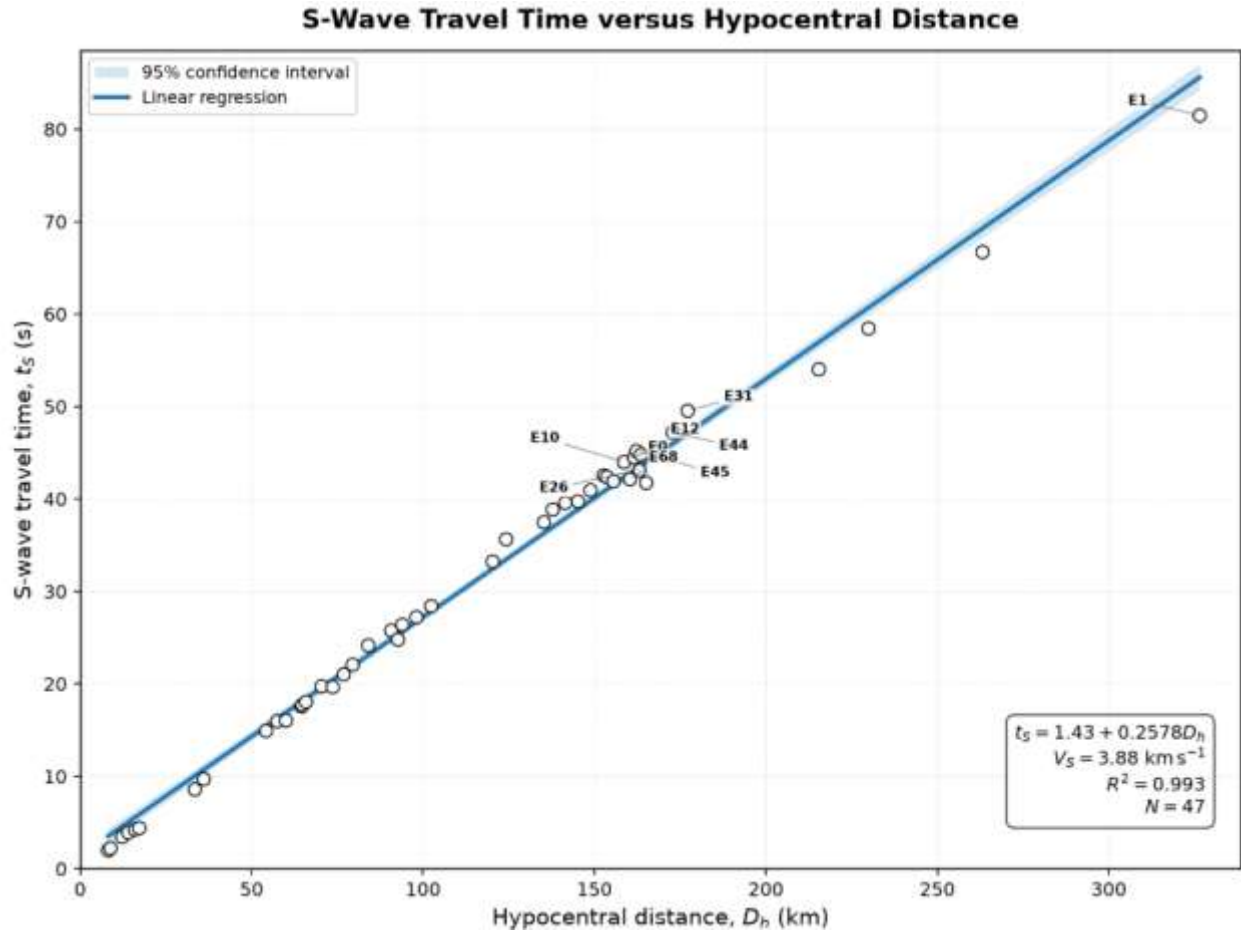


Figure 4. S-wave travel time as a function of hypocentral distance for the 47 station-level observations. The fitted line represents the distance-based linear regression, and the shaded region indicates its 95% confidence interval.

P- and S-wave travel times increase systematically with hypocentral distance (Figures 3 and 4). The P-wave regression is $t_p = 0.6511 + 0.0153611D_h$, giving an effective velocity of 6.51 km s^{-1} with $R^2 = 0.985$. The S-wave regression is $t_p = 1.43 + 0.2578D_h$, giving an effective velocity of 3.88 km s^{-1} with $R^2 = 0.993$. The fitted slopes therefore capture most of the first-order variation in travel time within the selected dataset. However, these slopes are interpreted as empirical regional travel-time characteristics rather than as parameters of a formal seismic velocity model.

4.4. Station-dependent travel-time residuals

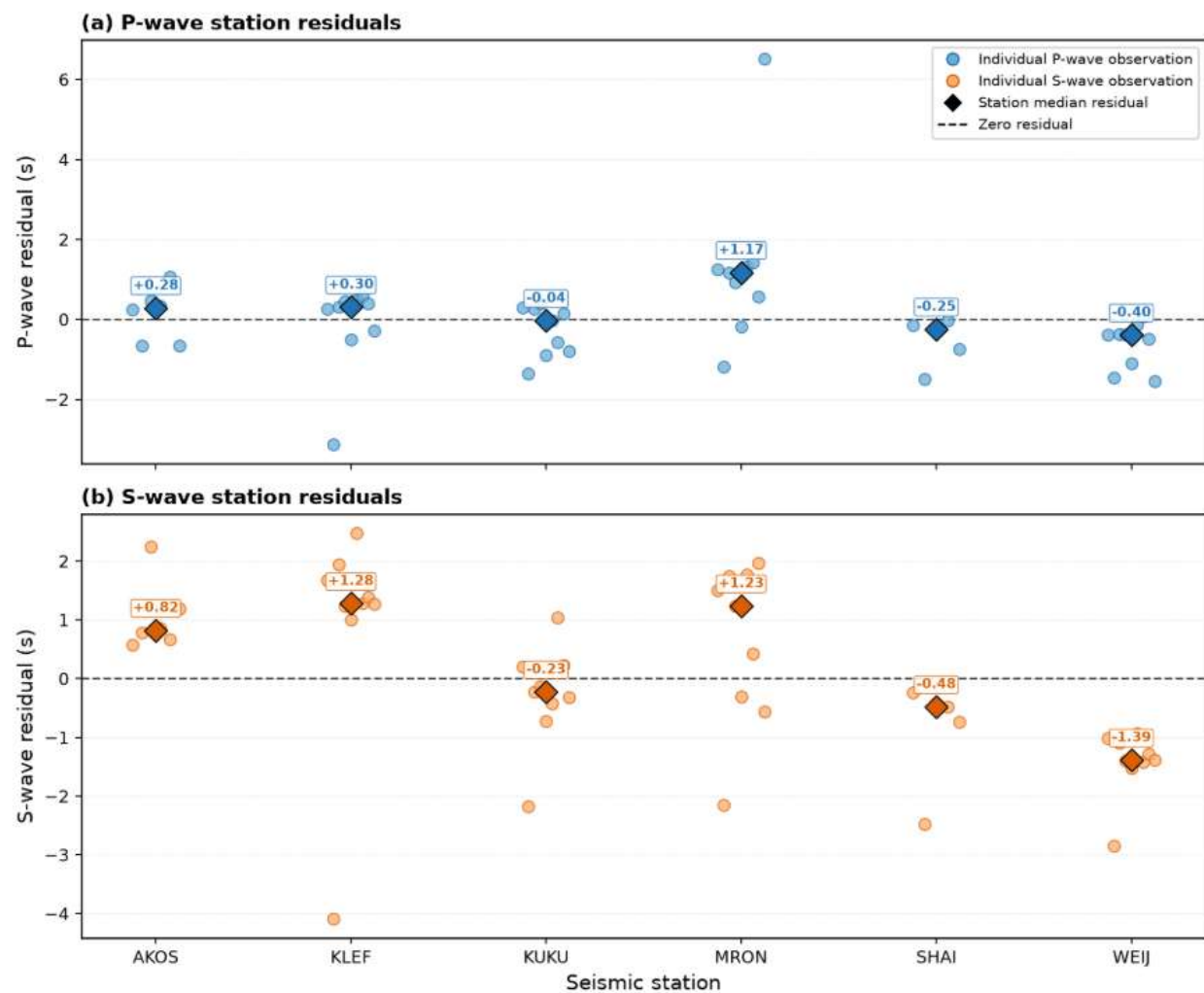


Figure 5. Station-dependent P- and S-wave travel-time residuals. Circles represent individual observations and diamonds represent station median residuals. Residuals are defined relative to the corresponding distance-based travel-time regression.

P-wave median residuals range from -0.40 s at WEIJ to +1.17 s at MRON. S-wave median residuals range from -1.39 s at WEIJ to +1.27 s at KLEF (Figure 5). Positive residuals indicate arrivals later than predicted by the distance-only relationship, whereas negative values indicate earlier arrivals. The station-associated patterns differ between the two phases, with WEIJ exhibiting negative median residuals for both P and S waves, whereas KLEF and MRON show positive median residuals. These patterns describe systematic station-associated variability but, in

the absence of independent structural constraints, do not by themselves establish a geological or site-specific cause.

4.5. Observed versus predicted travel times

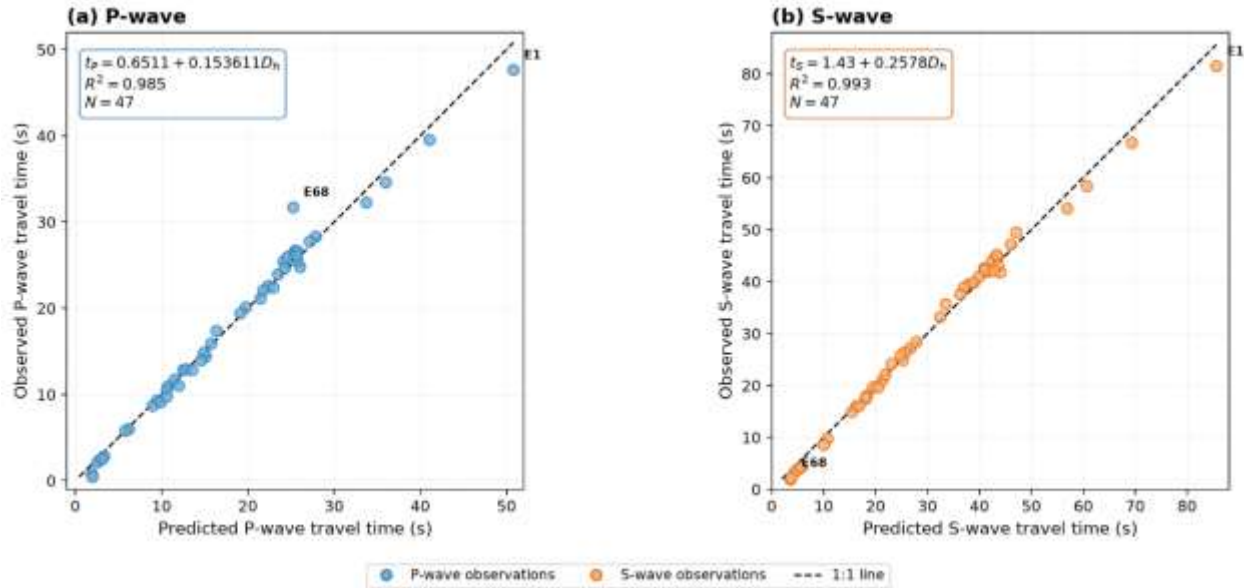


Figure 6. Observed versus predicted P- and S-wave travel times. The dashed line represents the 1:1 relationship. The fitted equations and R^2 values correspond to the final distance-based regressions.

Observed and predicted travel times cluster closely around the 1:1 line for both phases, consistent with the high R^2 values obtained from the distance-based regressions. The largest visible departures occur for a small number of observations, including the deep Event 1 at large distances and the shallow Event 68 at shorter distances (Figure 6). These departures indicate that hypocentral distance captures the dominant first-order travel-time trend, while some residual variability remains unexplained by the simple distance-based relationship.

4.6. Permutation-test assessment

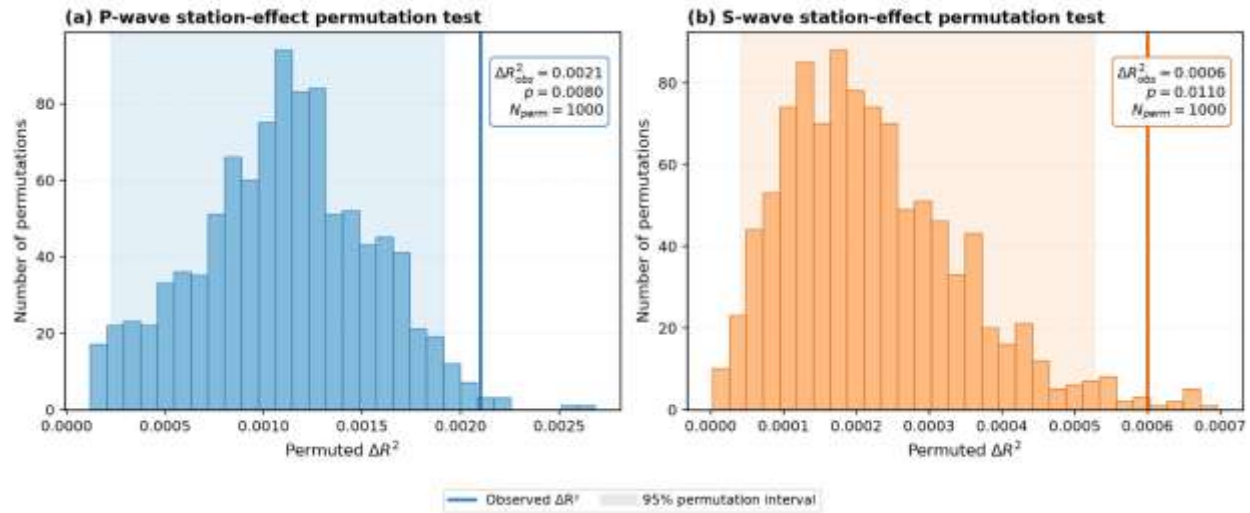


Figure 7. Permutation distributions for the station-dependent change in explained variance. Vertical lines indicate the observed ΔR^2 values and shaded regions represent the central 95% of the permutation distributions.

The within-event station-label permutation analysis produced an observed P-wave ΔR^2 of 0.0021 with $p = 0.0080$, and an observed S-wave ΔR^2 of 0.0006 with $p = 0.0110$ (Figure 7). Thus, the observed station association occurred relatively infrequently in the randomized distributions. However, the small absolute ΔR^2 values suggest that the statistically significant station-associated variability represents a relatively small contribution to the overall travel-time variance and should not be interpreted as evidence of a substantial physical station effect.

5. Discussion

5.1. Waveform observations and travel-time behaviour

The representative Event 0 seismograms provide a direct observational link between the GHDSN waveform archive and the arrival-time analysis. Clear P- and S-wave arrivals were identified at five stations, with S–P intervals increasing from 1.59 s at WEIJ to 17.85 s at MRON. This

systematic increase is consistent with the greater source–station separation of the more distant stations and provides a direct waveform-level illustration of the travel-time behaviour investigated in the regression analysis. The waveform observations therefore support the physical basis of the subsequent travel-time analysis rather than relying solely on the tabulated phase arrivals.

This is particularly relevant because the underlying GHDSN dataset was originally developed for automated earthquake detection and P- and S-phase picking using EQTransformer, followed by phase association and earthquake analysis (Mohammadigheymasi et al. 2023a, b). The present study makes a different use of the same resource. Rather than focusing primarily on earthquake detection or catalogue construction, it examines the relationship between the reported phase arrival times and source–station distance and then investigates the residual structure that remains after the dominant distance dependence is removed.

The increase in S–P time with distance is also consistent with the fundamental difference between P- and S-wave propagation: P waves travel faster and therefore progressively separate from the slower S waves as the propagation distance increases. This provides a physical explanation for why S–P time is useful as an indicator of source–receiver separation. At the same time, the waveform example should be regarded as representative rather than exhaustive because only one event is displayed and the final quantitative analysis includes nine earthquakes and 47 station-level P+S observations.

5.2. Comparison of effective P- and S-wave velocities with previous Ghana studies

The fitted travel-time relationships yielded effective velocities of 6.51 km s^{-1} for P waves and 3.88 km s^{-1} for S waves, with a corresponding V_P/V_S ratio of approximately 1.68. These values preserve the expected physical relationship $V_P > V_S$ and fall within a range that is broadly compatible with seismic-wave propagation through continental crust.

The comparison with previous investigations of southern Ghana is particularly important. Mohammadigheymasi et al. (2023) used the GHDSN earthquake dataset to derive a six-layer one-dimensional velocity model, with P-wave velocities increasing from approximately 5.9 to 7.2 km s^{-1} and a V_P/V_S ratio of approximately 1.70. The V_P/V_S ratio obtained in the present analysis is therefore remarkably close to that reported in the previous GHDSN velocity study.

This agreement is encouraging because the two analyses are based on the same general seismic network and regional earthquake observations, despite using substantially different approaches. The present study obtains $V_P/V_S \approx 1.68$, whereas Mohammadigheymasi et al. (2023) obtained approximately 1.70. The difference of about 0.02 is small relative to the differences in methodology and dataset treatment.

However, the similarity should not be interpreted as demonstrating that the present regression has independently recovered the crustal velocity model of Mohammadigheymasi et al. (2023). The earlier study used joint inversion of earthquake hypocentral parameters and velocity structure, whereas the present study estimates the reciprocal slopes of simple travel-time versus hypocentral-distance regressions. The two quantities therefore represent different physical and mathematical constructs. The earlier result describes a layered velocity structure, whereas the present values are effective velocities summarizing the average travel-time behaviour of the selected observations.

This distinction is important because southern Ghana is not seismically or geologically homogeneous. Akpan et al. (2016), using receiver functions and complementary constraints, demonstrated significant vertical and regional variations in crustal properties beneath southern Ghana. Their results indicate that the crust cannot appropriately be represented as a single homogeneous medium. Consequently, the 6.51 km s^{-1} and 3.88 km s^{-1} values should be interpreted as compact empirical descriptors of the selected travel-time dataset rather than as evidence that seismic waves propagate through Ghana's crust at uniform velocities.

5.3. Why the present velocities differ from a formal velocity model

The strong linear relationships obtained in this study might initially suggest that a simple homogeneous-medium model adequately describes the observations. The high coefficients of determination $R^2 = 0.985$ for P waves and $R^2 = 0.993$ for S waves demonstrate that hypocentral distance explains most of the observed variation in travel time within the selected dataset. However, a high R^2 does not mean that the underlying Earth structure is homogeneous. Rather, it indicates that distance is the dominant first-order predictor of travel time within this particular dataset. The remaining variation may contain information about the effects that are not represented by the simple distance-only model. These include lateral and vertical velocity variations,

differences in propagation paths, earthquake-location uncertainties, and phase-picking uncertainties. This interpretation is consistent with the more detailed crustal studies of southern Ghana. Akpan et al. (2016) identified substantial crustal structure beneath the region, while Mohammadigheymasi et al. (2023) demonstrated that the GHDSN observations could support a layered velocity model. The present analysis therefore should not be viewed as competing with those studies. Instead, it provides a simpler empirical description of the same general seismic propagation problem. The advantage of the present approach is its transparency: the dominant travel-time relationship can be visualized directly and summarized using a small number of parameters. Its limitation is that it collapses potentially complex three-dimensional propagation into a single distance-dependent relationship.

5.4. Station-dependent residuals and comparison with previous studies

After removing the dominant distance-dependent component of the travel times, systematic differences remained between stations. The median P-wave residuals ranged from approximately -0.40 to $+1.17$ s, whereas the S-wave residuals ranged from approximately -1.39 to $+1.27$ s. The existence of both positive and negative residuals is important. A positive residual indicates that arrivals at a station tend to occur later than predicted by the pooled distance relationship, whereas a negative residual indicates earlier-than-predicted arrivals. Thus, the results indicate that the simple distance relationship does not describe every station in exactly the same way. This observation is consistent with the broader travel-time residual literature. Vasco et al. (1994) demonstrated that coherent travel-time residuals can contain contributions from velocity heterogeneity, earthquake mislocation, and station-dependent effects. Their analysis, however, involved a much larger dataset and a robust inversion capable of simultaneously considering velocity structure, earthquake locations, and station parameters. The present study does not attempt such a joint inversion and therefore makes a more limited interpretation of the residuals.

A particularly useful comparison is provided by Osagie et al. (2017), who investigated P-wave travel-time residuals and station corrections for seismic stations in Peninsular Malaysia, Singapore and southern Thailand. Their analysis similarly examined observed versus predicted travel times and identified systematic differences among stations. However, Osagie et al. (2017) calculated station corrections relative to specified one-dimensional velocity models and used ray-based

calculations, whereas the present study derives residuals relative to an empirical distance-based regression.

Therefore, the two studies demonstrate a similar concept: that systematic station-to-station travel-time differences can be detected, but they do not produce directly equivalent station corrections. This distinction strengthens the interpretation of the present results. The residual patterns demonstrate that station identity contains information about travel-time variability, but they do not by themselves establish whether the underlying cause is near-surface geology, deeper crustal structure, propagation geometry, earthquake-location uncertainty, or systematic phase-picking differences.

5.5. What the permutation test adds

The station residual plots demonstrate the observed differences, but they do not independently establish whether those differences are bigger than would be expected from the structure of the dataset itself. This is the reason for the within-event permutation analysis. The observed P-wave ΔR^2 was 0.0021, with $p = 0.0080$, while the S-wave ΔR^2 was 0.0006, with $p = 0.0110$. The relatively small p-values indicate that station-associated improvements in explained variance of at least the observed magnitude occurred infrequently under the randomized station-label distributions. These results therefore provide statistical support for the presence of non-random station association in the current dataset. This is stronger evidence than simply observing different median residuals on a plot. Nevertheless, the magnitude of the effect must be considered alongside its statistical significance. The absolute increase in R^2 is only 0.0021 for P waves and 0.0006 for S waves. Consequently, the station variable contributes only a small additional amount of explanatory information after the dominant distance relationship has already been accounted for.

This distinction between statistical significance and physical significance is important. The permutation test demonstrates that the station association is unlikely to be reproduced frequently under the particular randomization scheme, but it does not demonstrate that the stations have a large physical effect. Nor does it identify the geological cause of the residual pattern. Thus, the

most defensible interpretation is that the analysis provides evidence for statistically detectable station-associated structure, while the physical origin of that structure remains unresolved.

5.6. Possible physical and methodological causes of the residuals

Several mechanisms could contribute to the observed station-dependent residuals. First, near-station geological structure could affect the recorded arrival times. Variations in shallow sedimentary cover, weathered material, basement depth, or local crustal properties can modify the travel time of seismic waves before they reach a station. However, the present dataset does not contain sufficient independent geological or near-surface velocity information to attribute individual residuals to a particular material or geological unit. Second, lateral velocity heterogeneity may affect the propagation paths. The regression treats hypocentral distance as the primary predictor, but two event–station pairs with similar distances can traverse substantially different parts of the subsurface. A distance-only model therefore does not account explicitly for the three-dimensional structure of the crust. Third, earthquake-location uncertainty can influence both the calculated hypocentral distance and the predicted travel time. This is especially relevant because the selected earthquakes have different depths, including the relatively deep Event 1 at approximately 78 km and the shallow Event 68 at approximately 1.7 km. Errors in depth or epicentral position can therefore translate into errors in the calculated source–station geometry. Fourth, phase-picking uncertainty may contribute to the residuals. The underlying dataset was generated through automated deep-learning phase picking, and although the bulletin provides a consistent source of phase information, automated picks are not necessarily equivalent to individually reviewed manual picks for every observation. Systematic differences in phase identification could therefore contribute to station-associated residual patterns.

Finally, origin-time uncertainty may also contribute. An error common to all stations for a particular earthquake could alter the travel-time residuals of that event and subsequently influence apparent station patterns. These possibilities cannot be separated using the present analysis alone. This is precisely why the residuals should be considered diagnostic quantities rather than interpreted as direct measurements of geological structure.

5.7. Tectonic and regional implications

The results should also be considered within the tectonic setting of southern Ghana. Ghana lies within the broader intraplate setting of West Africa, away from a major active plate boundary. Nevertheless, southern Ghana has a well-documented history of earthquake activity, particularly around southeastern Ghana (Amponsah 2002; Amponsah et al. 2012). Previous studies have related Ghanaian seismicity to the regional tectono-structural framework, including structures such as the Akwapim Fault Zone and Coastal Boundary Fault. Amponsah et al. (2012) emphasized the importance of the tectonic structure of southeastern Ghana in understanding the country's earthquake history, while Ahulu et al. (2018) demonstrated the importance of the region for seismic-hazard assessment. More recently, Legre et al. (2024) demonstrated that West Africa possesses a measurable intraplate stress field, providing broader geodynamic context for continuing earthquake activity within the continental interior.

The present results are compatible with this regional seismic context but should not be interpreted as evidence for a particular active fault. The travel-time analysis does not provide focal mechanisms, fault-plane solutions, stress inversions, or detailed hypocentral relocation. Consequently, it cannot determine the mechanism responsible for the individual earthquakes or establish that a particular station residual is caused by a specific fault. The contribution of the present study is instead complementary: it characterizes how seismic-wave travel times behave across the existing GHDSN network and identifies systematic station-associated deviations that can be investigated in future structural studies.

5.8. Limitations and implications for future work

The strong P- and S-wave regressions demonstrate that hypocentral distance provides a useful first-order description of travel-time variation within the selected observations. However, several limitations constrain the interpretation. First, the analysis is based on only nine earthquakes and 47 station-level P+S observations selected from the original 73 events based on phase coverage; therefore, the results should not be considered representative of all Ghanaian earthquakes. Second, the event–station geometry is uneven, limiting the ability to fully separate station-associated variability from spatial path effects. Third, the earthquakes span different focal depths, and

hypocentral distance alone does not capture variations in ray geometry or layered crustal structure. Fourth, the effective velocities are empirical regression parameters rather than those of a jointly inverted velocity model. Similarly, the station residuals should not be interpreted as formal station corrections, which would require joint treatment of velocity structure, earthquake locations, and station terms (Pavlis and Booker 1983; Vasco et al. 1994). Finally, uncertainties in the automated phase information may contribute to the observed residual variability.

Future studies should therefore expand the analysis to a larger and more spatially balanced earthquake dataset, incorporate improved earthquake locations and uncertainty-weighted or manually reviewed phase picks, and apply joint velocity–location–station correction methods to better resolve the physical sources of the observed travel-time variability.

6. Conclusion

This study investigated P- and S-wave travel-time characteristics and station-dependent residuals from local earthquakes recorded by the Ghana Digital Seismic Network (GHDSN). A quality-controlled subset of nine earthquakes, six stations, and 47 station-level paired P+S observations was extracted from the original 73-event GHDSN bulletin. Event selection was based on phase coverage, retaining earthquakes with paired P- and S-wave arrivals at at least five stations. The representative waveform analysis of Event 0 demonstrates the seismic observations underlying the travel-time analysis. P- and S-wave arrivals were identifiable at five stations, with S–P intervals ranging from 1.59 to 17.85 s. Across the 47 observations, P-wave travel time followed $t_p = 0.6511 + 0.153611D_h$, corresponding to an effective velocity of 6.51 km s^{-1} ($R^2 = 0.985$), while S-wave travel time followed $t_s = 1.43 + 0.2578D_h$, corresponding to an effective velocity of 3.88 km s^{-1} ($R^2 = 0.993$). These results indicate that hypocentral distance provides a strong first-order predictor of P- and S-wave travel times within the selected dataset.

Station-dependent residuals ranged from approximately -0.40 to $+1.17$ s for P waves and -1.39 to $+1.27$ s for S waves. Within-event permutation tests yielded $p = 0.0080$ for P waves and $p = 0.0110$ for S waves, indicating that the observed station-associated variability is unlikely to result from random reassignment of station identities within events. However, because the absolute ΔR^2

values were small, these results are interpreted as evidence of systematic station-associated variability rather than a large physical station effect.

Overall, this study provides an empirical baseline for local P- and S-wave propagation across the investigated GHDSN stations in southern Ghana. The effective velocities should not be interpreted as a formal crustal velocity model, and the station residuals should not be treated as definitive site corrections without joint inversion and independent structural constraints. Future studies using a larger number of earthquakes, improved earthquake locations, uncertainty-weighted phase picks, and joint velocity–location–station correction analyses can build on these results to investigate the physical origins of the observed travel-time variations.

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