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ORIGINAL RESEARCH PAPER

A comparative analysis of time–depth relationships derived from scientific ocean drilling expeditions

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Abstract

Time–depth relationships (TDR) are required for correlating geological information from drill sites with seismic reflection profiles. Conventional time–depth domain conversion is implemented using P-wave velocity data, derived from downhole sonic logs, calibrated with vertical seismic check-shots. During scientific ocean drilling expeditions, immediate seismic correlation is carried out using laboratory velocities measured on recovered core material. As these three velocity measurements vary significantly in signal frequency, resolution and acoustic pathways, they carry potential for substantial TDR differences and consequent miscorrelation to seismic profiles. Our analytical work uses the comprehensive scientific ocean drilling dataset to quantify these differences in core-seismic integration. TDRs are calculated and compared at sites where check-shot, sonic log, and laboratory velocity measurements cover the same depth segments of the drill hole. We find that the maximum differences between the TDRs (TDR $diff_{max}$) reach up to 55%, which can cause fundamental errors in the seismic correlation. No direct relationship to porosity and bulk density of the cored material is observed. Instead, higher TDR variability is found at sites with carbonate content > 70%, particularly with coarser grain texture. Sites containing primarily igneous and siliciclastic sequences show less than 10% TDR $diff_{max}$. This semi-quantitative criterion indicates that downhole logging should be conducted during drilling expeditions, especially at sites with carbonate sequences, or low core recovery, to ensure accurate core-seismic integrations.

Keywords Time–depth relationship · Scientific ocean drilling · P-wave velocity measurement · Seismic check-shot · Downhole sonic log

Introduction

The correlation between drilling information in a depth domain (meters below seafloor) and stratigraphy imaged by seismic reflection profiles in a time domain (two-way travel time, TWT) is a crucial process during drilling expeditions. It extends geological data beyond the borehole into a regional seismic grid, to provide accurate resource estimations, region-wide scientific interpretation and guidance for ongoing drilling operations. For this conversion, Time–depth relationships (TDR) calculated from measured P-wave velocities are used.

Conventionally, P-wave velocities are derived from downhole sonic logs, and calibrated with vertical seismic profiling (VSP) data (Fig. 1). During scientific ocean drilling expeditions, velocities are routinely measured on the recovered core material, using P-wave caliper (PWC) and Multi-Sensor Core Logger (MSCL) in onboard laboratories (e.g., Blum 1997; Fig. 1). However, the logistical demands

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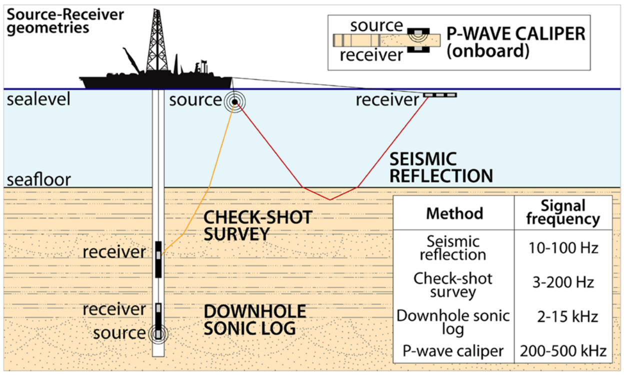

Fig. 1 Overview of velocity measurements included in this study and their differences in source-receiver geometry and approximate signal frequency ranges

of conducting additional downhole measurements mean that about 90% of all drill sites lack the complementary sonic logs and check-shot surveys.

These methods to measure P-wave velocities differ in signal frequency, spatial resolution and source-receiver geometry, which can lead to significant differences in signal dispersion and recorded velocities of the signal travelling through a system. Differences in signal travel times between these methods and possible causes have been analyzed in detail by numerous previous studies [e.g., Harvey and Lovell (1998), sonic logs versus check-shots: e.g., Goetz et al. (1979), Stewart et al. (1984), Strick (1971), Thomas (1978), Ward and Hewitt (1977), laboratory versus sonic logs: e.g., Fulthorpe et al. (1989), Urmos and Wilkens (1993), and laboratory vs seismic: e.g., Carlson et al. (1986), Winkler (1986)].

During check-shot surveys/VSP, geophones are deployed in various depths of the borehole, recording average signal velocities from the source deployed at the sea level [e.g., Bartel et al. (2006), Lowrie (1997)], with frequencies of tens of Hz (Versatile Seismic Imager: 3–200 Hz, Schlumberger; Fig. 1). This source-receiver setup and frequency range are closest to those of seismic reflection data [e.g., Mutter and Balch (1988); Fig. 1]. The downhole sonic measurement [e.g., dipole sonic imager (DSI)] provides velocity data in higher spatial resolution detecting small-scale variances, as source and receiver are deployed closely within the borehole (Fig. 1). However, the operating frequency of this sonic equipment is thousands of Hz and higher than the seismic source (Thomas 1978).

Velocities recorded by sonic logs are usually higher than VSP velocities, particularly with increasing borehole depth, due to stronger seismic dispersion of the VSP signals and formation of short-path multiples (Stewart et al. 1984). It is therefore preferred to combine both VSP and DSI measurements which provides a precise and unequivocal core-seismic-integration. However, as downhole logging demands temporal and logistic efforts that rely on favorable hole quality and environmental conditions, only two-thirds of all scientific ocean drill sites have DSI measurements and only 5% have additional VSP with good coverage for accurate calibration.

P-wave caliper (PWC) and Multi-Sensor Core Logger (MSCL) in onboard laboratories (e.g., Blum 1997) provide velocity information with a short measuring interval (0.02–1 m) and TDR curves that are helpful in real-time coring and decision-making during ongoing expeditions. However, both instruments transmit ultrasonic pulses with high frequencies of kHz (MSCL–230 kHz, PWC–500 kHz; IODP; Fig. 1). Additionally, mechanical disturbance and loss of overburden pressure and changes in temperature after material recovery lead to generally lower laboratory velocities compared to velocities derived from seismic data (Blum 1997; Carlson et al. 1986). The resulting TDRs carry potential to overestimate the signal travel time for a certain corresponding depth.

During the past 60 years, many studies investigated geoacoustic properties and signal propagation through marine sediments and hard rocks [e.g., Biot (1956a,b), Hamilton (1976), Stoll (1977), Hamilton (1980), Carlson et al. (1986), Fulthorpe et al. (1989), Stoll (1989), Ballard and Lee (2017)]. Calcareous materials have been discussed in detail, as their acoustic properties are significantly different to other materials. Carlson et al. (1986) calculated empirical curves to correct for the laboratory-seismic offset and decompaction of the material, and observed a prominent misfit when applied on calcareous material. Fulthorpe et al. (1989) followed up on the exceptionality of carbonates and explained their acoustic behavior with complex intra-particle porosities which are not influenced by material decompaction and, therefore, has to be corrected differently than other lithologies. Consequently, Urmos and Wilkens (1993) defined a correction factor for laboratory and sonic log velocity of carbonates ($CaCO_3 > 60\%$) by fitting an empirical exponential equation to the plot of velocity difference with depth.

Here, we test and extend the results from these previous comparative studies, by analyzing data from all three velocity measurements (PWC, DSI, VSP) and investigating relationships of TDR differences with cored lithologies and petrophysical properties. The lack of complementary downhole data during scientific drilling expeditions indicates the need to independently quantify the accuracy of laboratory versus in situ velocity measurements, and its effect on TDR variability for core-seismic (mis-)correlations. Determining the relationship between TDR differences with petrophysical and lithological properties of the cored material, helps to predict the accuracy of TDRs for future drilling operations, and provides guidance to identify under which circumstances downhole, particularly VSP, measurements are highly required.

Data and methods

For this analysis, data from the comprehensive global scientific ocean drilling database with 1016 drill sites is used (http://iodp.org/resources/access-data-and-samples, time range: 1986–2016). Only 29 sites (Fig. 2) show continuous coverage of all three velocity records (laboratory, sonic log and VSP) over the same depth segments in the borehole and are suitable for comparison. We analyze the onboard measured petrophysical data from these sites and quantify the differences in TDRs derived from the three velocity measurement methods. Among the laboratory measurements, we use data from the PWC method instead of the MSCL records, because it is not limited by partially-filled liners. Furthermore, PWC can measure discrete samples of lithified units which provides a complete coverage of the entire borehole. The TDR differences are compared alongside related petrophysical properties of bulk density, porosity and overall lithology.

Check-shot (VSP) correction

Check-shot or VSP stations record the average signal velocity from the seismic source at the mean sea level to the receiver in the borehole. In contrast, PWC and processed DSI measurements are both referenced from the seafloor. Therefore, the check-shot data need to be corrected for the travel time through the water column.

This adjustment is a crucial step, considering that 45% of the selected sites are in water depth < 1000 m in which water-column velocities vary greatly with temperature and salinity (Wilson 1998). However, in many cases, these variations are not accounted for, because direct water velocity profiling is not part of a normal VSP routine, and rarely conducted before either coring at a site or drilling a common production borehole. Instead, an average velocity of 1500 m/s is often assumed. For this study, water column sonic velocity is derived using the Del Grosso (1974) equation [detailed discussions by e.g., Dushaw et al. (1993), Pike and Beiboer (1993)]. The required data on sea surface temperature (Maturi et al. 2014) and salinity (NASA 2015, Aquarius project) were extracted for each drill site during the time of the check-shot survey. The calculated sonic velocities differ up to 60 m/s from the average velocity 1500 m/s.

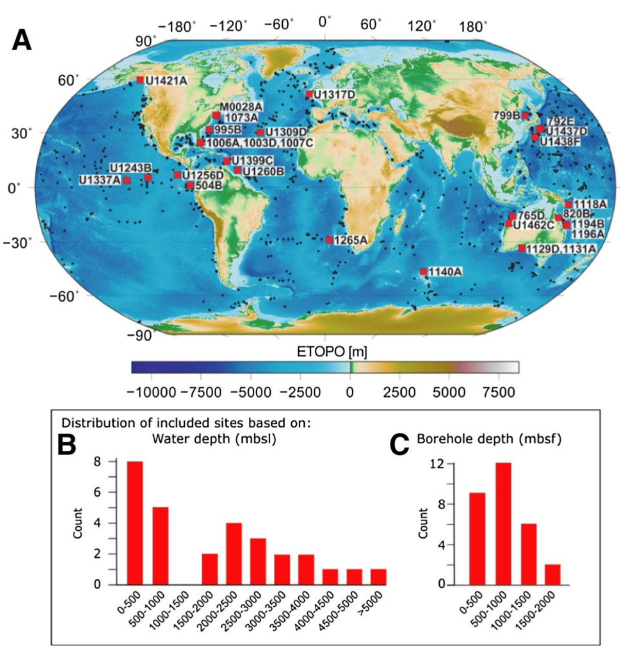

Fig. 2 **a** Overview map (ETOPO-1; Amante and Eakins 2009) of all scientific ocean drill sites. Red squares denote sites used for this study, with their distribution in terms of **b** water, and **c** borehole depth

Standard equation for calculating TDRs

The equivalent TWT Ti_n for a given borehole *depth* is calculated from the P-wave velocity Vp_n and the TDR is defined as a cumulative value of Ti_n:

The incremental TWT Ti_n (in ms) is:

$$Ti_n = \left(depth_n - depth_{n-1}\right)/Vp_{n-1} * 2 * 1000 \tag{1}$$

The cumulative TWT Tc_n:

$$Tc_n = Tc_{n-1} + Ti_n \tag{2}$$

and adjusted to the seafloor TWT, Ta_0:

$$Ta_n = Ta_{n-1} + Tc_n \tag{3}$$

The TDR curve is a plot of TWT_{adj} (ms) against metres below the seafloor (mbsf).

Statistical analysis

For each site, we collate and compare the three TDRs. We (1) restrict the TDR comparison to only depth segments where data from all three methods overlap; and (2) compute the mean (μ), standard deviation (σ), coefficient of variation (cv), and percentage difference (*diff*) between the overlapping segments of the TDR curves.

The coefficient of variation is a simple tool to quantify the extent of variability of the velocities with respect to the mean, calculated as the ratio of the standard deviation to the mean:

$$cv = \sigma/\mu \tag{4}$$

The relative percentage difference between two velocities V_1 and V_2 is calculated as:

$$diff = \left(V_1 - V_2\right)/\left(\left(V_1 + V_2\right)/2\right) * 100 \tag{5}$$

For this study, TDR dissimilarity for each site is represented by the maximum percentage difference ($diff_{max}$) among all three velocity measurements.

To analyze the resulting TDR differences, porosity and bulk density data for each site are characterized in terms of mean (μ), standard deviation (σ), coefficient of variation (*cv*) and coefficient of determination (R^2). The drilled material is also qualitatively divided into four classes based on the dominant lithology (Fig. 3). A more quantitative correlation between overall composition and TDR differences utilizes the average calcium carbonate content (wt%) data which has been extracted from the scientific drilling database (Fig. 4a). Additionally, we analyze the possible influence of the present water depth and the maximum age of the sequence at each site (Fig. 5c).

Results

Our results show a wide range of TDR variability with different velocity methods and drilled lithologies (Fig. 3). Among the three calculated TDRs for each site, the $diff_{max}$ values range from 0.7% (Site 995B) up to 55.3% (Site 1196A, Fig. 3b) and the *cv* values range from 0.006 to 0.352 (Fig. 4a). The three sites with more than 30% difference between the calculated TDRs contain primarily carbonate sequences (> 70%; Fig. 4a). Six additional sites that consist of fine-grained carbonate and mixed-carbonate units show $diff_{max}$ between 10% and 20%. The majority (69%) of the 29 drill sites, including all sites dominated by siliciclastic and igneous sequences, have $diff_{max} < 10\%$.

The influence of lithological composition on the variability of TDRs is quantitatively illustrated in the plot of carbonate content against $diff_{max}$ and *cv* (Fig. 4a). As with the lithological discrimination, the relationship between the TDR metrics and carbonate content is not straightforward, but the sites are clearly contained within an envelope (Fig. 4a) that defines an increase in the scatter of $diff_{max}$ with higher carbonate content. Seven sites with carbonate content higher than 70% have the largest $diff_{max}$ range from 3 to 55%. Within this group, three sites (1129D, 1194B, 1196A) with the highest $diff_{max}$ > 30% are coarse-grained skeletal bioclastic pack-, grain- to floatstones (Feary et al. 2004; Isern et al. 2002) dominated by particles with grain sizes above 30 µm (after Dunham (1962), Wright (1992); example: Fig. 4c). In contrast, drill sites 1265A, 1003D, 1131A and 1007C

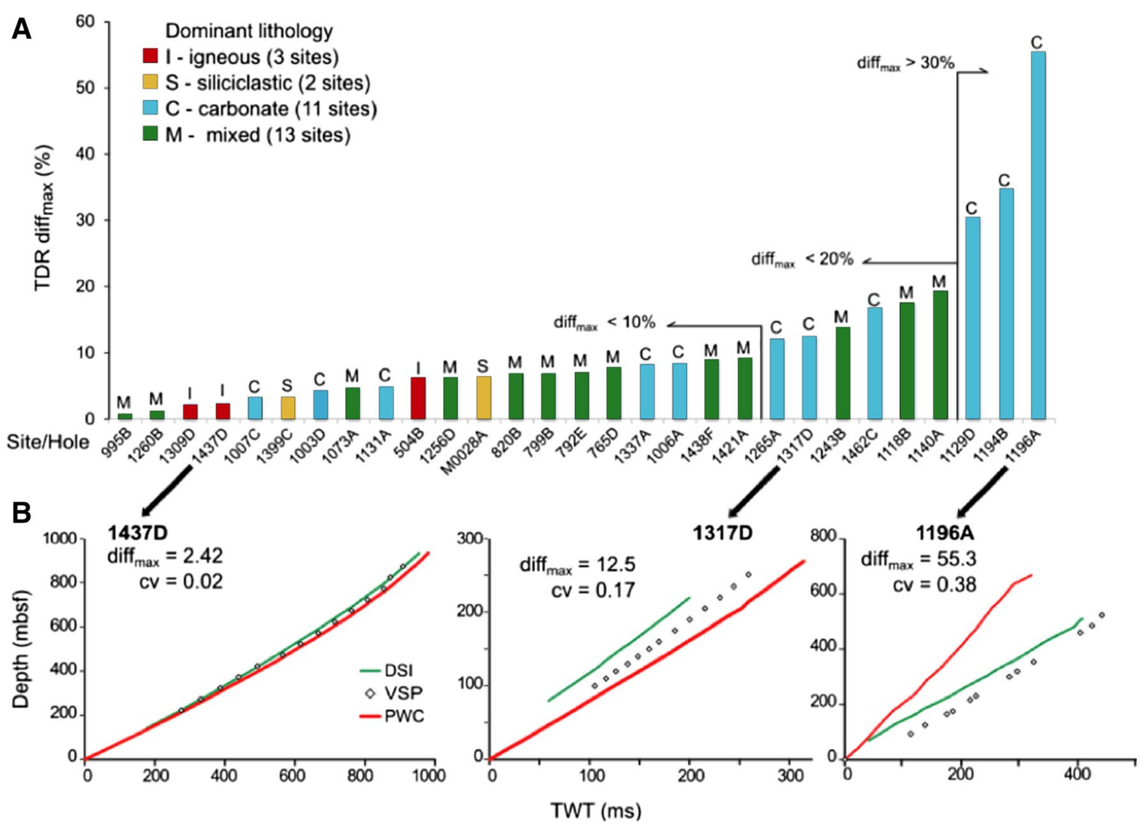

Fig. 3 A) Maximum percentage of TDR difference ($diff_{max}$) with dominant lithology of each site (labels, see legend). B) Representative sites showing TDRs derived from laboratory PWC (red line), downhole DSI (green line) and check-shot or VSP (white points). The corresponding velocity, density and porosity data from these representative sites are presented in the supplementary information (Fig. 6)

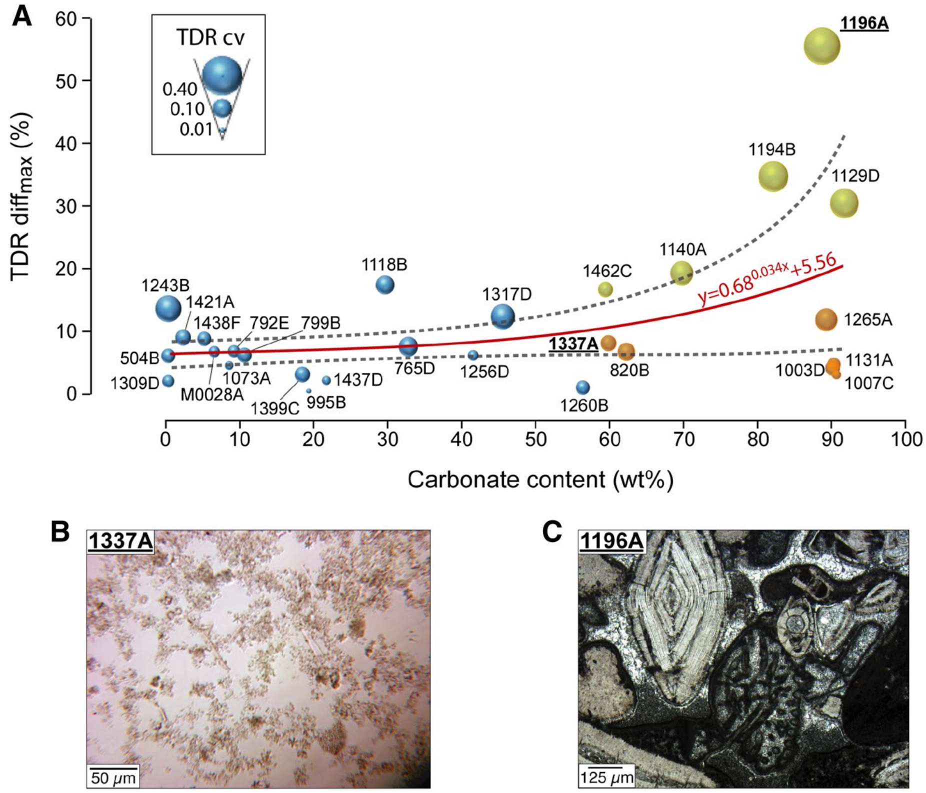

Fig. 4 **a** Carbonate content (wt %) with TDR difference ($diff_{max}$) for each site (labels, see legend). Point size represent the coefficient of variation (*cv*). Yellow and orange data points represent carbonate-rich sites, dominated by coarse (> 30 µm) and fine (< 30 µm) grains, respectively. The trend is illustrated by an exponential curve (solid red line) with the 95% confidence interval (dashed lines). Two representative photomicrographs of carbonate-rich lithologies are shown from: **b** Site 1337A dominated by fine-grained biogenic ooze (Pälike et al. 2010), and **c** site 1196A with dominantly coarse grainstone matrix (Isern et al. 2002)

with $diff_{max}$ < 20% consist of relatively fine-grained biogenic ooze/chalk, mud- and wackestones (Eberli 1997; Feary et al. 2004; Zachos et al. 2004) containing primarily particles with grain size < 30 µm (example: Fig. 4b).

This influence of carbonate texture on TDR $diff_{max}$ could be reflected in petrophysical properties such as porosity and bulk density. However, no direct correlation between TDR $diff_{max}$ values against mean porosity and carbonate content (Fig. 5a), or the coefficient of variation of porosity and bulk density (Fig. 5b), is observed. Additionally, no clear TDR $diff_{max}$ relationship to age and water depth can be detected (Fig. 5c). Carlson et al. (1986) discussed this non-correlation between age and velocity in detail, concluding that mechanical and chemical processes occurring during sediment deposition and compaction last a short geological time period and, therefore, is not reflected in the correlation between maximum age and velocity.

Discussion

Our study shows that the TDR functions derived from PWC, DSI and VSP velocity measurements can differ by up to 55%. This extreme variation is well-illustrated at site 1196A (Fig. 3b). The total depth of 500 mbsf is equivalent to 250 ms (TWT) based on the PWC-derived TDR function, and 450 ms (TWT) from a VSP-calculated TDR function. As TDR curves often follow a quadratic trend, significant TWT differences tend to be amplified with depth and lead to larger mis-ties in core-log-seismic correlation. This is a substantial problem, especially in homogenous sequences that lack high-amplitude seismic reflections and lithologic markers to verify the correlation.

Consistent with previous studies, we observe a unique acoustic behavior of carbonates. Drill sites with > 70% carbonate exhibit the most variable TDR, compared to sites with mixed lithology, igneous or siliciclastic rocks. Our separation at $CaCO_3$ > 70% is close to the limit established by Urmos and Wilkens (1993). They defined a correction factor for laboratory-seismic velocity offsets for drilled material high in carbonate content (> 60%), which, however, overestimates in situ values for material with $CaCO_3$ < 60% and increased mixture with other minerals, particularly clays, which have lower P-wave velocities.

Additionally, we categorize the carbonate group into two subsets: more coherent TDR curves with $diff_{max}$ < 25% are associated with fine-grained (< 30 µm) carbonate textures whereas coarser bioclastic deposits have strongly dissimilar TDRs ($diff_{max}$ > 30%, Fig. 4). In contrast to siliciclastic sediments, carbonates form under complex biological and diagenetic processes leading to the formation of a wider range of grain shapes and internal structures (e.g., Moore and Wade 2013; Neto and Misságia 2012; Pedley and Carannante 2006; Weill et al. 2013; Fig. 4b,c). This complex grain

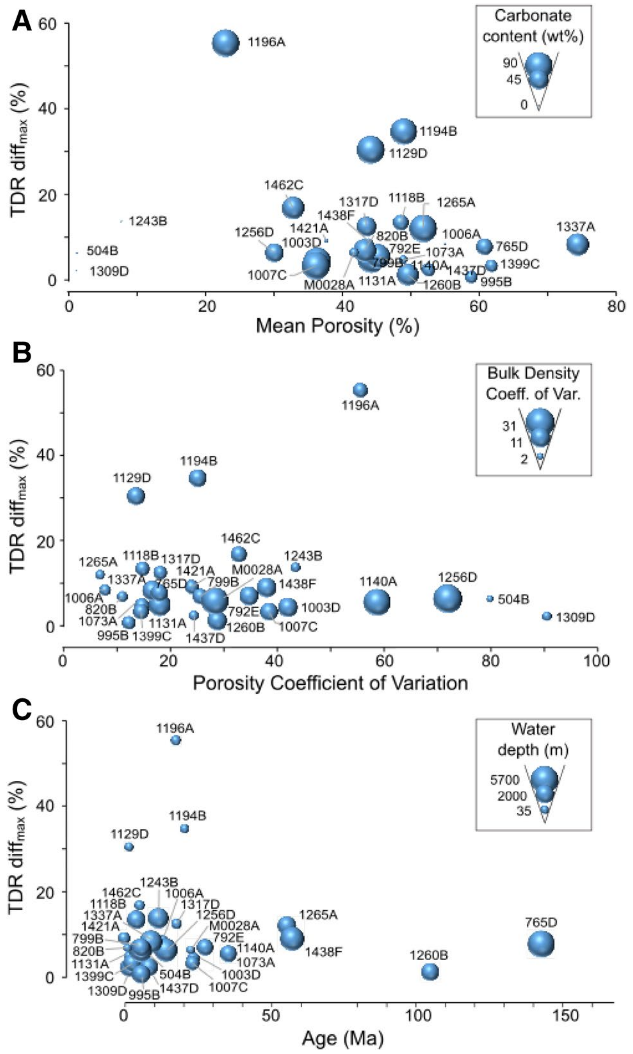

Fig. 5 TDR difference ($diff_{max}$) for each site (labels, see legend) against **a** mean porosity, **b** porosity coefficient of variation and **c** maximum age. Point sizes represent carbonate content (wt %; **a**), bulk density coefficient of variation (*cv*; **b** and water depth (m; **c**)

morphology and internal texture affect the transmission of compressional velocities (e.g. Moore and Wade (2013)). This effect is likely to be enhanced with coarser grain sizes and a reason for our observed increased TDR $diff_{max}$ values. Another possible reason is the higher percentage of intraparticle porosity (within individual grains) compared to the interparticle porosity (between grains) in coarse-grained carbonates. Fulthorpe et al. (1989) explains the unique acoustic behavior of carbonates with increased intraparticle porosities, which, after Eberli et al. (2003), causes higher elastic rigidity of the material and results in higher signal velocity in a laboratory setup. In our case, this might explain the observed high TDR differences, e.g. at drill site 1196A (Fig. 2b) which is dominated by coarse-grained (> 30 µm) skeletal bioclastic grain- and floatstones (Fig. 3c). After Eberli et al. (2003) the velocity and permeability of carbonates strongly depend on pore types (e.g., intra-, interparticle porosity), but also their filling (e.g., cementation, diagenesis) and the degree of lithification, which can cause velocity differences over 2500 m/s, even if the measured porosity is constant. However, as only interparticle porosity can be measured on laboratory samples, the relationship to intraparticle porosity cannot be captured in our approach.

Our analysis confirms that carbonate content plays a key role in the scatter between TDRs from downhole and laboratory velocity measurements. This outcome cautions about the use of correction factors simply based on petrophysical characterization or depth fitting. Other qualitative parameters should be analyzed, such as pore type, grain morphology, pore filling and degree of lithification which greatly influences velocity (Eberli et al. 2003; Fulthorpe et al. 1989).

Conclusion

Time–depth relationships are crucial for correlating seismic sections and drill hole information. A global comparative study is conducted, computing TDRs using all three velocity measurements (DSI, VSP and PWC) from the comprehensive scientific ocean drilling dataset. We show that resulting TDRs can differ significantly, but the differences cannot be directly related to petrophysical properties such as bulk density or porosity. This implies that the TDR variations are influenced by a complex interaction of effects caused by formation properties, lithologic heterogeneity, burial depth, consolidation and lithification. This makes any simplified empirical TDR corrections difficult and not recommended.

Nonetheless, our results show that sequences with carbonate content > 70% appear to be more prone to TDR variability. Carbonate sequences with finer-grained texture display less TDR scatter compared to sites with coarser skeletal bioclastic deposits (dominated by grains larger than 30 µm). In these cases, VSP surveys are crucial to establish the correct TDR. However, considering the strong variability and complexity of the determinant factors even for low-carbonate deposits, we highly recommend conducting VSP surveys, to ensure a correct core-log-seismic integration with an accurate TDR function.

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References

Amante C, Eakins BW (2009) ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis. http://www.ngdcnoaagov/mgg/global/globalhtml. https://doi.org/10.7289/v5c8276m

Ballard MS, Lee K (2017) The acoustics of marine sediments. Acoust Today 13:11–18

Bartel DC, Busby M, Nealon J, Zaske J (2006) Time to depth conversion and uncertainty assessment using average velocity modeling. In: SEG Technical Program Expanded Abstracts 2006. Society of Exploration Geophysicists, pp 2166–2170. https://doi.org/10.1190/1.2369965

Biot MA (1956a) Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range. J Acoust Soc Am 28:168–178. https://doi.org/10.1121/1.1908239

Biot MA (1956b) Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range. J Acoust Soc Am 28:179–191. https://doi.org/10.1121/1.1908241

Blum P (1997) Physical properties handbook: a guide to the shipboard measurement of physical properties of deep-sea cores. ODP Tech, College Station

Carlson R, Gangi A, Snow K (1986) Empirical reflection travel time versus depth and velocity versus depth functions for the deep-sea sediment column. J Geophys Res 91:8249–8266. https://doi.org/10.1029/JB091iB08p08249

Del Grosso VA (1974) New equation for the speed of sound in natural waters (with comparisons to other equations). J Acoust Soc Am 56:1084–1091. https://doi.org/10.1121/1.1903388

Dunham RJ (1962) Classification of carbonate rocks according to depositional textures. In: Ham WE (ed) Classification of carbonate rocks. AAPG, Tulsa, pp 108–121

Dushaw BD, Worcester PF, Cornuelle BD, Howe BM (1993) On equations for the speed of sound in seawater. J Acoust Soc Am 93:255–275

Eberli GP et al (1997) Proceedings of the Ocean Drilling Program, initial reports; Bahamas Transect, covering Leg 166 of the cruises of the Drilling Vessel JOIDES Resolution, San Juan, Puerto Rico, to Balboa Harbor, Panama, sites 1003–1009, 17 Feb–10 Apr 1996. Texas A & M University, Ocean Drilling Program, College Station, TX, USA. https://doi.org/10.2973/odp.proc.ir.166.1997

Eberli GP, Baechle GT, Anselmetti FS, Incze ML (2003) Factors controlling elastic properties in carbonate sediments and rocks. Lead Edge 22:654–660. https://doi.org/10.1190/1.1599691

Feary DA, Hine AC, James NP, Malone MJ (2004) Leg 182 synthesis: exposed secrets of the Great Australian Bight. In: Proceedings of the Ocean Drilling Program, Scientific Results, pp 1–30. https://doi.org/10.2973/odp.proc.ir.182.2000

Fulthorpe CS, Schlanger SO, Jarrard RD (1989) In situ acoustic properties of pelagic carbonate sediments on the Ontong Java Plateau. J Geophys Res 94:4025–4032. https://doi.org/10.1029/JB094iB04p04025

Goetz J, Dupal L, Bowler J (1979) An investigation into discrepancies between sonic log and seismic check spot velocities. APPEA J 19:131–141. https://doi.org/10.1071/AJ78014

Hamilton EL (1976) Shear-wave velocity versus depth in marine sediments: a review. Geophysics 41:985–996. https://doi.org/10.1190/1.1440676

Hamilton EL (1980) Geoacoustic modeling of the sea floor. J Acoust Soc Am 68:1313–1340. https://doi.org/10.1121/1.385100

Harvey PK, Lovell MA (1998) Core-log integration controls (Special Publications). Geological Society, London, p 136

IODP International Ocean Discovery Program Database. http://iodp.org/resources/access-data-and-samples. Accessed 2017–2018

Isern A, Anselmetti F, Blum P (2002) Proceedings of the Ocean Drilling Program. Initial Reports Leg 194. College Station, TX (Ocean Drilling Program). https://doi.org/10.2973/odp.proc.ir.194.2002

Lowrie W (1997) Fundamental of geophysics. Cambridge University Press, Cambridge

Maturi E, Sapper J, Harris A, Mittaz J (2014) GHRSST level 4 OSPO global foundation sea surface temperature analysis (GDS version 2). National Oceanographic Data Center, NOAA, Dataset. https://doi.org/10.7289/v5sq8xfh. Accessed 2017–2018

Moore CH, Wade WJ (2013) Carbonate reservoirs: porosity and diagenesis in a sequence stratigraphic framework, vol 67. Elsevier, Amsterdam

Mutter J, Balch A (1988) Vertical Seismic Profiling (VSP) and the Ocean Drilling Program (ODP): Report of a Workshop. Joint Oceanogr. Inst./US Science Advisory Comm.

NASA (2015) Aquarius Official Release Level 3 Sea Surface Salinity Standard Mapped Image Monthly Data V4.0., 4.0. edn. https://doi.org/10.5067/aqr40-3smcs

Neto IdAL, Misságia RM (2012) Estimate of elastic properties including pore geometry effect on carbonates: a case study of Glorieta-Paddock reservoir at Vacuum field, New Mexico. Revista Brasileira de Geofísica 30:519–532

Pälike H, Lyle M, Nishi H, Raffi I, Gamage K, Klaus A (2010) The expedition 320/321 scientists. In: Proceedings of the Integrated Ocean Drilling Program, p 321. https://doi.org/10.2204/iodp.proc.320321.2010

Pedley HM, Carannante G (2006) Cool-water carbonates: depositional systems and palaeoenvironmental. Geological Society of London, London

Pike J, Beiboer F (1993) A comparison between algorithms for the speed of sound in seawater, Special Publication No. 34. Hydrographic Society

Stewart RR, Huddleston PD, Kan TK (1984) Seismic versus sonic velocities: a vertical seismic profiling study. Geophysics 49:1153–1168. https://doi.org/10.1190/1.1441745

Stoll RD (1977) Acoustic waves in ocean sediments. Geophysics 42:715–725. https://doi.org/10.1190/1.1440741

Stoll RD (1989) Sediment acoustics

Strick E (1971) An explanation of observed time discrepancies between continuous and conventional well velocity surveys. Geophysics 36:285–295. https://doi.org/10.1190/1.1440169

Thomas D (1978) Seismic applications of sonic logs. The Log Analyst 19. Document ID: SPWLA-1978-vXIXn1a3

Urmos J, Wilkens RH (1993) In situ velocities in pelagic carbonates: new insights from Ocean Drilling Program Leg 130, Ontong Java Plateau. J Geophys Res 98:7903–7920. https://doi.org/10.1029/93JB00013

Ward R, Hewitt M (1977) Monofrequency borehole traveltime survey. Geophysics 42:1137–1145. https://doi.org/10.1190/1.1440779

Weill P, Mouazé D, Tessier B (2013) Internal architecture and evolution of bioclastic beach ridges in a megatidal chenier plain: field data and wave flume experiment. Sedimentology 60:1213–1230. https://doi.org/10.1111/sed.12027

Wilson J (1998) Global Temperature-Salinity Profile Programme (GTSPP)—overview and future. Intergovernmental Oceanographic Commission Technical Series. UNESCO, Paris, p 49

Winkler KW (1986) Estimates of velocity dispersion between seismic and ultrasonic frequencies. Geophysics 51:183–189. https://doi.org/10.1190/1.1442031

Wright V (1992) A revised classification of limestones. Sediment Geol 76:177–185. https://doi.org/10.1016/0037-0738(92)90082-3

Zachos J, Kroon D, Blum P, Bowles J, Gaillot P, Hasegawa T, Hathorne E (2004) Proceedings of the Ocean Drilling Program, Initial Reports, Volume 208. College Station, TX (Ocean Drilling Program). https://doi.org/10.2973/odp.proc.ir.208.2004