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A preliminary study on the acoustic properties of seafloor sediment in the southern U-boundary of the South China Sea*

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Abstract The acoustic properties of seafloor sediment are essential parameters in the exploration of marine resources, ocean scientific research and ocean engineering. Seafloor sediment samples were collected at the southern U-boundary of the South China Sea (SCS), and the acoustic and physical properties were measured in the laboratory. The correlation between physical and sound speed ratio (SSR) was discussed, and SSR-physical property empirical regressions in the Sunda Shelf were established for the first time. Compared with the northern continental shelf of SCS, the Sunda Shelf are mainly silty and sand sediment, and the SSR ranges from 0.994 9 to 1.094 4, which has higher SSR than the northern continental shelf, implies that the Sunda Shelf is a high SSR area. Since the same kind of sediment has different physical properties, the single physical parameter of sediment cannot fully represent the acoustic properties of sediment, therefore, the multiple parameter prediction model should develop in the future to improve the prediction precision.

Keyword: acoustic properties; seafloor sediment; South China Sea (SCS); U-boundary

1 INTRODUCTION

Seafloor sediments are generally regarded as solid–liquid two-phase media at the bottom of the sea water and seabed sediment interface, and their acoustic properties are an important part of the ocean acoustic field environment and have important application value in marine scientific research, marine resource exploration, and ocean engineering. When sound waves travel through shallow seas, sound waves will interact with the seafloor, resulting in sound transmission loss; therefore, the sediment type and its acoustic properties are important parameters in

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the science of underwater acoustics (Hou et al., 2014; Potty et al., 2019; Li et al., 2021).

Many scholars have studied the correlation between acoustic and physical properties of seafloor sediments for a long time (Hamilton and Bachman, 1982; Buckingham, 2014, 2020; Endler et al., 2016; Li et al., 2021). Based on sediment sampling measurements and laboratory remodeling measurements, several researchers have discussed the spatial distribution relationship between acoustic parameters and physical parameters through statistical analysis of the plane distribution and vertical structure of acoustic parameters and studied the influence of sediment consolidation on acoustic propagation (Lyu et al., 2021; Yang et al., 2021). Hamilton and Bachman (1982) and Bachman (1989) analyzed the correlation between sound velocity and the attenuation coefficient of sediment and physical parameters, such as porosity, density, and grain size, and they proposed typical geo-acoustic models and regression equations of different geomorphic units, such as shallow continental shelves, deep-sea hills, and deep-sea plains. Kim et al. (2017) collected 157 samples from the Ulleung Basin in the East China Sea, divided the study area into five regions according to the acoustic and physical properties of the sediments, and studied the differences in the acoustic properties of sediments between different regions. Pan (2003) studied the gradient variation of vertical sound velocity of sediments in the northern South China Sea (SCS) and analyzed the main factors affecting the vertical change of sound velocity, found the regional change from the coastal area to deep sea basin and directly related with water depth, sediment types, and other factors. Liu et al. (2013) conducted offshore experiments in the Yellow Sea with in-situ acoustic measurement instruments, established a sound velocity equation between the in-situ sound velocity and physical properties of sediments, and pointed out that porosity was the main physical parameter affecting the in-situ sound velocity. Hou et al. (2015, 2018) established empirical equations of sound velocity in the northern, southern, and central regions of the SCS and found that sediments in different regions had different acoustic properties. Based on more than three hundred columnar sediment samples, Li et al. (2021) established the sound velocity ratio empirical formula of abyssal sediment in the SCS and found that the composition of sediment and sedimentary environment have a certain effect on sediment acoustic properties. Since the shallow continental shelf area has complex terrain, the acoustic characteristics are changeable, it is necessary to find out the geo-acoustic properties and establish regression equations in the key areas of the SCS.

The U-shaped boundary of the SCS is the largest and deepest marginal sea in China's offshore waters and is also an important maritime channel for China's "One Belt and One Road" construction. The U-boundary of the SCS was divided into five zones: the northeastern zone, northwestern zone, eastern zone, western zone, and southern zone according to the terrain characteristics (Liu et al., 2019). The acoustic properties of seafloor sediment in the southern zone of the U-boundary of the SCS are still unknown, and how the sediment and its acoustic properties are distributed. It is necessary to study the acoustic properties and establish sound velocity empirical equations in the southern zone of the U-boundary of the SCS, which is of great practical significance for marine engineering, resource exploration, and underwater acoustics areas.

2 MATERIAL AND METHOD

2.1 Study area

The research area is in the Sunda Shelf of the SCS around the southern zone of the U-boundary (Liu et al., 2019) (Fig.1). The Sunda Shelf, a stable platform, is the largest continental shelf in the world's oceans outside the polar regions, with an area of 1.85×10^6 km^2 and a width extending up to 800 km. Most of the platform is covered by shallow seas—including the southern South China Sea, the Gulf of Thailand, and the Java Sea—with depths averaging less than 100 m. The Sunda Shelf consists of the Indochina Peninsula in the north, the Malay Peninsula in the west, the Indonesian island arc in the south, and Borneo in the east. These regions transport large amounts of suspended sediments to the Sunda Shelf and the adjacent South China Sea each year, making the region one of the largest terrigenous debris inputs in the world (Milliman et al., 1999).

2.2 Method

The sediment samples were collected during the SCS expedition U1 voyage using a box sampler, and a short core sediment sample was obtained by inserting a poly vinyl chloride (PVC) tube into a box sampler. The sediment sampling stations are shown in Fig.1.

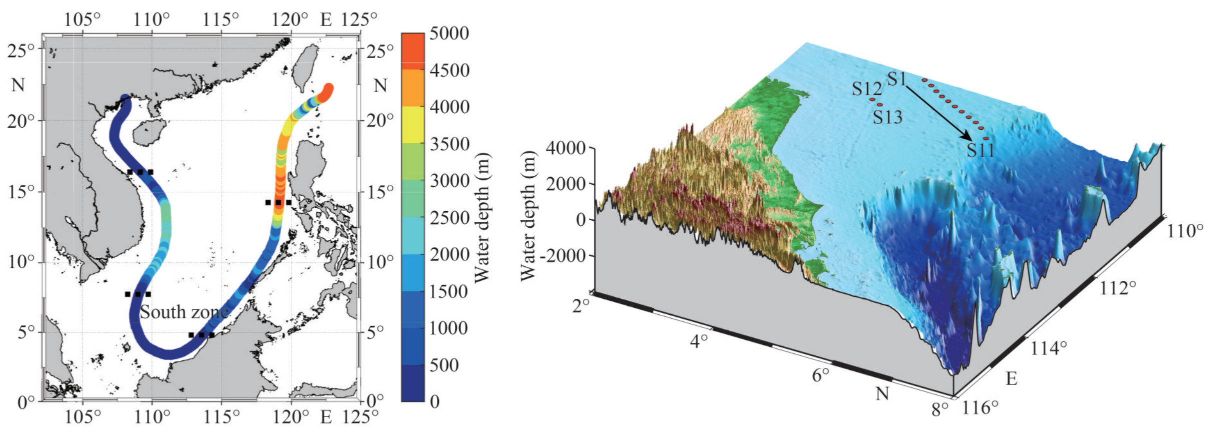

Fig.1 The study area is in the south zone of the U-boundary (left) and sampling stations in the Sunda Shelf (right)

The black dots are the demarcation points for each area.

The acoustic properties were measured using coaxial gap measurements (Fig.2) with a WSD-4 Digital sonic instrument produced by Chongqing Pentium CNC Technology Institute. This method uses time-of-flight (TOF) measurements of acoustic wave speed along the sediment, and details on the measuring procedure are described in Hou et al. (2015). The calculation of sound velocity is:

$$V_{\mathrm{p}} = \frac{\Delta L}{\Delta t} = \frac{L_1 - L_2}{t_2 - t_1}, \tag{1}$$

V_{p} is the sediment sound velocity, L_1 and L_2 are the length of sediments, and t_1 and t_2 represent the travel time in sediments.

The sediment attenuation coefficient is calculated by comparing the energy loss at the two sediments:

$$\alpha = 10 \times \frac{\log\left(\dfrac{E_{\mathrm{s1}}}{E_{\mathrm{s2}}}\right) - \log\left(\dfrac{E_{\mathrm{w1}}}{E_{\mathrm{w2}}}\right)}{\Delta L}, \tag{2}$$

where E_{s1} and E_{s2} are the signal energies at the two sediments, E_{w1} and E_{w2} are the inherent loss of the transducer, and ΔL is the distance between the two receiving probes.

The sound speed ratio (SSR) is defined as the ratio of the measured sediment sound speed to the pore-water sound speed at same temperature, salinity, and pressure:

$$\mathrm{SSR} = \frac{V_{\mathrm{sediment}}}{V_{\mathrm{pore\text{-}water}}}. \tag{3}$$

The sand-silt-clay components and mean grain size were measured with a particle size analyzer at the South China Sea Institute of Oceanology, Chinese Academy of Sciences. The wet bulk density was measured using the cutting-ring method, and the porosity was calculated by the wet weight and specific gravity.

3 RESULT

Generally, the physical properties of marine sediments are good indicators of the environmental conditions during and after the depositional process. Their study is of high interdisciplinary interest and follows various geoscientific objectives. The coring

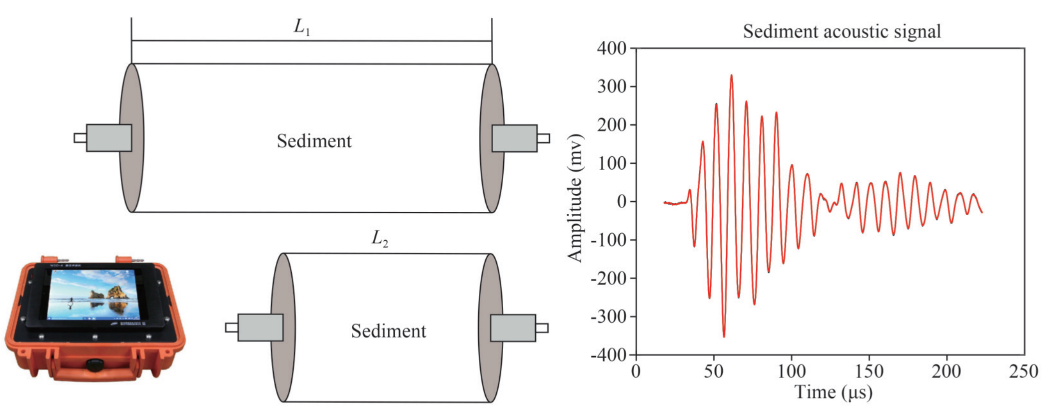

Fig.2 The coaxial gap measurement and sediment acoustic signal

samples were collected by a box sampler, and the average sample length was 30 cm. The acoustic properties of seafloor sediment in the study area are presented in Table 1, and the results show that the Sunda Shelf of the SCS is mainly composed of sandy silty and silty sand, with part of the clay silty sand and fine sand sediment (Table 1). Since these samples were collected on the continental shelf, the sediment grains are coarser, the smallest mean grain size is 7.195 1φ at station S11, and the sediment type is clay silty; its wet bulk density is also the smallest at 1.342 2 g/cm^3. In the following section, the correlation between physical and sound velocities will be discussed in detail, and empirical regressions in the study area are established.

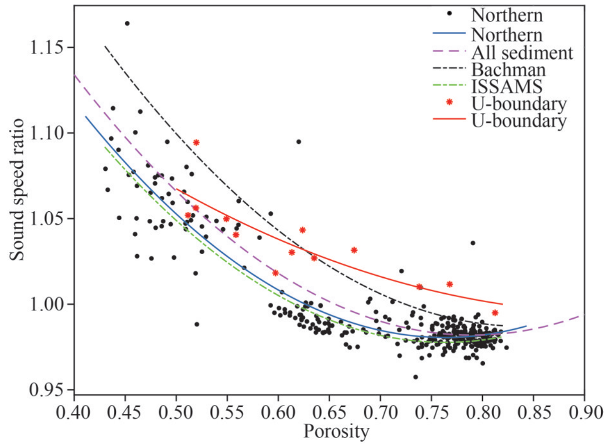

Fig.3 Sound velocity-porosity empirical regression

SSR=$(3.81e^{-05})n^2$–$0.007137n$+1.329; 50<n<82, R^2=0.715 4, 50%<n<82%.

4 DISCUSSION

Director laboratory sound velocity measurements are not always available. Therefore, SSR-physical parameter empirical regressions are one of the main means to obtain information on the sound velocity of seafloor sediments. The SSR-porosity (n), SSR-wet bulk density (ρ), and SSR-mean grain size (Mz) empirical regressions in this study are presented in Figs.3–5.

The sediment is comprised of a particle framework and pore fluid, and the physical properties of marine sediments depend on the properties and arrangement of the solid and fluid constituents. In water-saturated sediments, the pore fluid fills the grain pores, the sound wave interacts with the particles and pore fluid when it propagates in the sediment, and the pores between particles are the channels through which sound travels. Thus, the porosity of sediments is extremely important for the acoustic properties of sediments, and Hamilton and Bachman (1982) believes that porosity is the primary factor affecting the acoustic properties of sediments.

Figure 3 shows the SSR-porosity relationship in this study and compares the regressions from the Bachman (1989), Richardson and Briggs (all sediments in Appendix, 2004) (Richardson and Briggs, 2004), Jackson and Richardson (ISSAMS, 2007) (Jackson and Richardson, 2007), and northern SCS (Li et al., 2021). The U (U-boundary) regression is crossed with the B (Bachman) curve, higher than the N (northern SCS) curve, A (all sediments in

Table 1 Acoustic properties of seafloor sediment in the study area

Station	Sound velocity (m/s)	Sound-speed ratio	Porosity (%)	Density (g/cm^3)	Mean grain size (φ)	Sediment type
S1	1 585.20	1.031 5	67.43	1.573 1	4.917 3	Sandy silty
S2	1 578.09	1.026 9	63.51	1.631 9	3.605 4	Silty sand
S3	1 564.70	1.018 2	59.73	1.694 9	3.754 0	Silty sand
S4	1 583.21	1.030 3	61.33	1.668 3	4.061 9	Silty sand
S5	1 681.81	1.094 4	51.97	1.829 1	3.332 4	Fine sand
S6	1 598.99	1.040 5	55.85	1.759 5	3.870 3	Silty sand
S7	1 616.54	1.051 9	51.16	1.837 7	4.046 4	Silty sand
S8	1 623.06	1.056 2	51.93	1.824 9	3.952 3	Silty sand
S9	1 613.24	1.049 8	54.91	1.784 2	4.274 7	Sandy silty
S10	1 603.26	1.043 3	62.38	1.658 3	5.431 1	Sandy silty
S11	1 528.96	0.994 9	81.24	1.342 2	7.195 1	Clay silty
S12	1 552.33	1.010 2	73.80	1.460 5	4.451 9	Silty sand
S13	1 554.61	1.011 6	76.79	1.415 3	5.001 6	Sandy silty

Appendix) curve, and JR (ISSAMS) curve, (these empirical regressions can be seen in Appendix). The porosity of sediments in the northern SCS ranges from 43% to 83% and is concentrated in high porosity (60%–80%), while the porosity of sediments in the Sunda Shelf ranges from 50% to 82%, and relatively scattered, maybe this is because of the small number of our samples. From the sediment type, we also can find that the sediment types of the northern SCS are more abundant and the provenance is extensive.

The SSR-porosity regression formula in this study is also shown in Fig.3, and the application condition of the regression formula is 50%<n<82%.

Figure 4 shows the SSR-wet bulk density relationship in this study and compares it with the A, B, JR, and N regressions. Hamilton and Bachman (1982) found the wet bulk density and porosity are linearly positively correlated. Like the porosity, the SSR-wet bulk density regression is crossed with the B curve, and higher than the N (northern SCS) curve, A (all sediments in Appendix) curve, and JR (ISSAMS) curve. The wet bulk density of the Sunda Shelf ranges from 1.3 g/cm^3<ρ<1.85 g/cm^3, and the sample distribution is relatively scattered, the regression curve of this study is higher than the other regression curves. Like porosity, the density of sediments in the northern SCS is mainly low-density sediments (1.3 g/cm^3<ρ<1.5 g/cm^3), which is different from the density range of the Sunda Shelf (Li et al., 2021). The SSR-wet bulk density relationship also shows that this study area is high SSR area. The SSR-wet bulk density regression formula in this study is also shown in Fig.4, and the application condition of the regression formula is 1.3 g/cm^3<ρ<1.85 g/cm^3.

Figure 5 shows the SSR-mean grain size relationship in this study and compares it with the A, B, JR, and N regressions. The particle grain size parameters of sediments remain unchanged in situ or in the laboratory, and the shape, arrangement and grain size distribution determine the elasticity property of the sediment, so grain size parameters are one of the important indicators of marine scientific research. In Fig.5, the curves of the A, B, JR, and N regressions are cross with the U regression, this is because the grain size in the Sunda Shelf ranges from 3.3φ<Mz<7.2φ, mainly coarse sediment (3.3φ<Mz<5.5φ), with only one station is fine sediment (7.2φ). The grain size of sediments in the northern SCS ranges from 3φ<Mz<9φ, mainly fine sediment (6φ<Mz<9φ), which implies the different sediment type between the

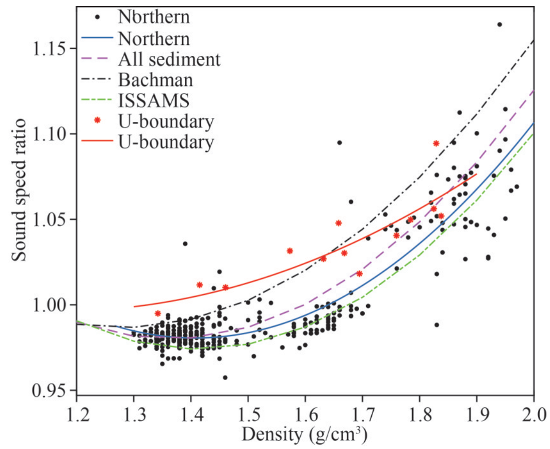

Fig.4 Sound velocity-wet bulk density empirical regression

SSR=0.1492ρ^2–0.3479ρ+1.199, R^2=0.728, 1.3 g/cm^3<ρ<1.85 g/cm^3.

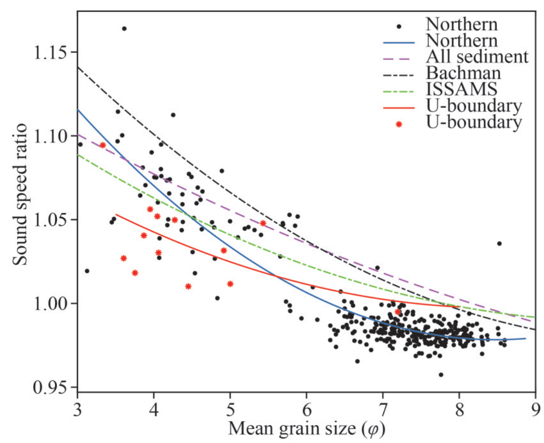

Fig.5 Sound velocity-mean grain size empirical regression.

SSR=0.00221Mz^2–0.03769Mz+1.158, R^2=0.350 5, 3.3φ<Mz<7.2φ.

northern SCS and the sunda shelf (Li et al., 2021). The SSR-mean grain size regression formula in this study is also shown in Fig.5, and the application condition of the regression formula is 3.3φ<Mz<7.2φ.

The acoustic properties of seafloor sediment under the influence of various physical parameters and a single physical parameter cannot fully reflect the acoustic properties of sediment; for example, the acoustic properties of sediments with the same porosity are quite different because although they have the same porosity, other physical properties, such as particle size and density, may be different. The traditional regression analysis method is not suitable for processing multidimensional data, in another article by the author (Hou et al., 2019), the author has compared the prediction precision of the machine learning model and single parameter model, and it shows that the machine learning model with multiple parameters has higher accuracy. Therefore, the single parameter regression formulas have limitations, and it is necessary to build a comprehensive prediction model based on multiple parameters in the future work.

The dispersion relationship of acoustic characteristics of seafloor sediments has always been the basis and difficulty of acoustic research (Jackson and Richardson, 2007). When the phase velocity varies with the frequency, the waveform of the acoustic pulse signal propagating in the sediment will be distorted. This velocity dispersion is accompanied by the correlation between attenuation and frequency. The dependence of velocity on frequency satisfies the Kramers-Kronig dispersion relation (O'Donnell et al., 1981). Turgut and Yamamoto (2008) analyzed the variation of acoustic parameters with frequency from hundreds of hertz to hundreds of kilohertz, and the results showed that when the frequency was lower than 300 kHz, the speed of sound showed a trend of slow increase with frequency. In this study, we also measured the sound velocity of sediment at frequencies of 25 kHz, 50 kHz, and 100 kHz. The degree of dispersion is obtained by subtracting the maximum speed of sound from the minimum speed of sound and then dividing by the minimum speed of sound. From 25 kHz to 100 kHz, the degree of dispersion of this study is 1.08% to 3.87%, with an average of 2.77% (Fig.6). From Fig.6, we see that from 25 kHz to 100 kHz, the sound velocity fluctuates slightly with frequency, some stations (such as Stations S1, S6, and S7) have a slight downward trend from 25 kHz to 50 kHz, and then it goes up again in 100 kHz. On the whole band (25–100 kHz), the sound velocity slowly increases as the frequency increases, which is consistent with Turgut and Yamamoto (2008)'s research and consistent with the prediction results of the Biot theoretical model and grain-shearing (GS) model (Biot, 1956; Buckingham, 2014). Due to the insufficient number of samples and measurement frequency bands in this paper, sediment samples will be collected and measurement frequency bands will

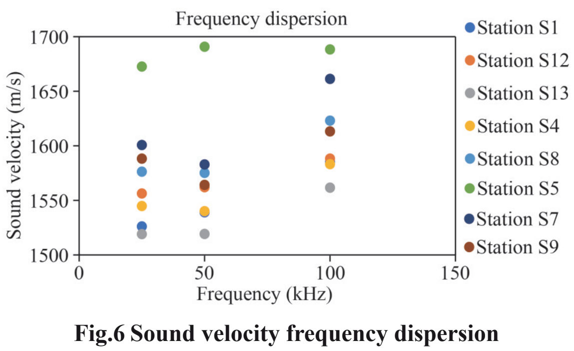

Fig.6 Sound velocity frequency dispersion

be added in the follow-up work to further analyze the influence of frequency on acoustic characteristics of sediment.

5 CONCLUSION

Having preliminarily explored the acoustic properties of seafloor sediments in the Sunda Shelf of the South China Sea, empirical regressions among physical parameters of porosity, density, and mean grain size, the sound speed ratio were established for the first time in the southern zone of the U-boundary of the South China Sea. We conclude that:

(1) Compared with the northern SCS, the sediment type and physical properties of the Sunda Shelf are different. The Sunda Shelf of the SCS is composed of coarse sediment, mainly sandy silt and silty sand, with part of the clay silty sand and fine sand sediment, and the acoustic properties belong to a high SSR area, while the northern SCS has more abundant sediment types.

(2) The porosity and density empirical formulas established in Sunda Shelf are similar to the Bachman empirical formulas. However, the mean grain size formula is very different from the Bachman empirical formula. Using only a single physical parameter to establish the regression method is of limitation, and a single physical parameter of sediment cannot fully represent the acoustic properties of sediment. Therefore, a multiple-parameter prediction model should be developed in the future to improve the prediction precision.

6 DATA AVAILABILITY STATEMENT

All data generated and/or analyzed during this study are contained in Table 1 and Appendix.

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Appendix
The empirical regressions used in the article

Author	Property or types	Equation	R^2
Bachman (1989)	Porosity	$SSR=1.675-0.0164n+0.0000976n^2$	0.86
	Wet density	$SSR=1.513-0.824\rho+0.32249\rho^2$	0.88
	Mean grain size	$SSR=1.296-0.0601Mz+0.00283Mz^2$	0.92
	All sediments	$SSR=1.184-0.0307Mz+0.0010Mz^2$	0.82
Jackson and Richardson (2007)	All sediments	$SSR=1.606-0.0158n+0.0001n^2$	0.95
	All sediments	$SSR=1.649-0.9807\rho+0.3595\rho^2$	0.93
Northern (Li et al., 2021)	Porosity	$SSR=1.587-1.591n+1.042n^2$	0.82
	Wet density	$SSR=1.692-1.011\rho+0.3591\rho^2$	0.80
	Mean grain size	$SSR=1.307-0.07763Mz+0.004578Mz^2$	0.82