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PAPER

An empirical porosity–depth model for Earth's crust

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Abstract
Porosity is one of the most basic physical properties of a stratum. Previous studies have shown that porosity generally decreases with depth. There are five main types of empirical models available for describing such a porosity–depth relationship: the linear model, the exponential model, the power law model, the reciprocal model, and the parabolic model. For the majority of past and existing studies, each tends to focus on one study area, and thus does not present enough data to cover a large depth range and represent the general attenuation of porosity through Earth's crust. Whether those models can deal with a larger depth scale or not remains unknown. This paper proposes a new empirical porosity–depth model that can describe the decrease of porosity through the entire Earth's crust. Porosity–depth data are collected from the literature and the proposed model fits the data very well. The model improves the agreement between calculated and measured porosity values and can be used to describe the porosity–depth relationship for continental crust, oceanic crust, sedimentary rocks, and unconsolidated sediments. The proposed model tends to slightly overestimate the measured data for Earth's continental crust in the depth range of 5–15 km. It is also difficult for a model to fit the near-surface porosity data well for unconsolidated sediments. This study improves the usefulness of the empirical models in estimating porosity where measured data are unavailable, in discerning abnormal strata, and in supporting regional groundwater studies.

Keywords Porosity · Continental crust · Oceanic crust · Sedimentary rocks · Unconsolidated sediments

Introduction

Porosity is of great importance in hydrogeological investigations that determine the capacity of an aquifer and evaluate geologic characterization of a reservoir (Pinneker 2010; Şen 2015; Fetter 2018). Observation data show that porosity of sedimentary rocks generally decreases with depth (e.g., Athy 1930; Hedberg 1936; Chilingarian 1983; Ramm and Bjørlykke 1994). Porosity–depth relationships have been widely used to study the generation and migration of hydrocarbons and some abnormal cases of strata (Rieke and Chilingarian 1974; Schmoker and Halley 1982; Halley and Schmoker 1983; Wygrala 1989). Porosity attenuation in sedimentary rocks has been shown to be associated with many physical, geological, and mineralogical factors (Hedberg 1936; Dickinson 1953; Maxwell 1964; Gregory 1977; Ramm 1992).

Various empirical models have been proposed to describe the porosity–depth relationship. Previous studies on porosity–depth models basically focused on sedimentary rocks (e.g., Athy 1930; Hedberg 1936; Dickinson 1953; Schmoker and Halley 1982). The most frequently used models can typically be catalogued into two types: the linear model and the exponential model. The exponential model was proposed by Athy (1930) and it has been widely used to describe the porosity–depth relationships of various sedimentary rocks, including shale, mudstone, limestone and dolomites, and sandstone (Rubey and Hubbert 1959; Steckler and Watts 1978; Sclater and Christie 1980; Schmoker and Halley 1982; Goff 1983; Halley and Schmoker 1983; Baldwin and Butler 1985; Bethke 1985; Ramm and Bjørlykke 1994; Armstrong et al. 1998; Kominz and Pekar 2001; Jiang et al. 2010; Tanikawa et al. 2016, 2018; El-Shari 2017; Carlino et al. 2018; Ojha and

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Lewis 2018; Aschwanden et al. 2019; Das et al. 2019; Farahzadi et al. 2019; Guy et al. 2019; Licciardi et al. 2019; Morris et al. 2019; Zhu and Li 2019; Fang et al. 2020; Martín-Martín and Robles-Marín 2020). Researchers have also proposed modified forms of the exponential model (Robinson and Gluyas 1992; Bjørkum et al. 1998). The double exponential model is proposed to better describe additional porosity loss at shallow depths (Bond et al. 1983; Schneider et al. 1996; Dutta et al. 2009; Saul and Lumley 2013; Saul et al. 2013; Guy et al. 2019; Martín-Martín and Robles-Marín 2020). The linear model is the most intuitive one that is generally applied to sandstone datasets (Hedberg 1936; Wilson and McBride 1988; Ramm and Bjørlykke 1994). It has also been widely used because most study areas cover limited depth ranges and the porosity reduces to values far away from zero.

There are also other models, like the reciprocal model (Falvey and Middleton 1981; Falvey and Deighton 1982; Guidish et al. 1985; Rieser et al. 2006), the power law model (Baldwin and Butler 1985; Curtis et al. 1986; Huang and Gradstein 1990), the parabolic model (Huang and Gradstein 1990; Wold 1994), and the piecewise model (Ramm and Bjørlykke 1994; Li et al. 2009; Cao et al. 2017; Wu et al. 2019). These models have been relatively less frequently used. Although many studies have been conducted on porosity, most of them are restricted to specific study areas and the porosity–depth data presented are limited. As a result, a synthesis of the existing data in the literature and a model that can describe the porosity–depth relationship through the entire crust are needed.

This paper proposes a new model for describing the porosity–depth relationship for Earth's crust. Evaluation of the model was made by comparing the calculated porosity values with measured data. Porosity–depth data for the continental crust, the oceanic crust, and unconsolidated sediments were collected from the literature. Factors affecting the porosity–depth relationship are also briefly discussed.

Materials and methods

Proposed model

A new model that can provide reasonable surface porosity values and estimate the decreasing porosity rate is proposed, which can be written as

$$\phi(z) = \frac{\phi_0}{(1+mz)^n} \quad (1)$$

where ϕ is the porosity, ϕ_0 is the porosity at ground surface ($z = 0$), z is the depth, and m and n are fitting parameters. There are three parameters in Eq. (1), i.e., ϕ_0, m, and n. The parameter ϕ_0 is controlled by measured surface porosity values. The model decreases from ϕ_0 at a reasonable rate with depth. Equation (1) with $n = 1$ has been shown to fit the porosity–depth data better than the exponential model, as it can provide better description of the rapid porosity decrease near the surface and the slow porosity decrease at greater depths (e.g., Falvey and Middleton 1981; Guidish et al. 1985; Rieser et al. 2006).

Data

Porosity datasets in the literature were collected to evaluate the proposed model. Most of the selected datasets are for sedimentary rocks. As an essential factor affecting porosity, lithology is a key point for the discussion of porosity–depth relationships (Maxwell 1964; Magara 1980; Wygrala 1989). Thus, the porosity data of sedimentary rocks were divided into those for mudstone, carbonate rocks, and sandstone. Each category contains three or more data sources to make sure it can represent the general situation. No attempt was made to differentiate other factors that also contribute to scattering in the porosity–depth plots. Datasets were also combined to generate profiles for Earth's continental crust, oceanic crust, and unconsolidated sediments.

The Levenberg-Marquardt nonlinear least squares method (Marquardt 1963; Press et al. 1992) was used to fit the model to each data category, including continental crust, oceanic crust, and unconsolidated sediments. The fitted parameters of the model are listed in Table 1. It should be noted that the porosity–depth data for mudstone, carbonate rocks, and sandstone are not fitted separately; the parameters for "continental crust" of the model in Table 1 are used to calculate porosity values for these rocks. The performances of the models are evaluated based on the coefficient of determination, R^2 (Table 1). The higher the R^2 value, the better the performance of the model.

Table 1 Fitted parameters and coefficient of determination for the proposed model

Type	m	n	ϕ_0	R^2
Continental crust	0.071	5.989	0.474	0.583
Mudstone	0.128	3.899	0.541	0.622
Carbonate	0.195	2.889	0.494	0.684
Sandstone	0.005	70.72	0.432	0.442
Oceanic crust	0.008	89.53	0.678	0.850
Sediments	0.304	2.191	0.572	0.718

Results

Earth's continental crust

The porosity–depth data were synthesized to produce a depth profile as deep as possible for Earth's continental crust (Fig. 1). In this figure, data from sandstone, carbonate, and mudstone were grouped together. Seven groups of data were collected for mudstone, including the Mid-Atlantic Outer Continental Shelf (COST B-2 well; Smith et al. 1976), Gulf Coast (Magara 1974), Scotian Shelf off Canada (Mudford 1988), Soluq Depression in Libya (El-Shari 2017), Taranaki Basin in New Zealand (Armstrong et al. 1998), Viking Graben in the North Sea (Goff 1983), and Wairarapa in New Zealand (Wells 1990). Six groups of data were collected for carbonate, including Abadan Plain (Farahzadi et al. 2019), BMB (Barnowko-Mostno-Buszewo) Field in Poland (Kasza et al. 2006), laboratory data (Terzaghi 1940; Fruth et al. 1966; Robertson 1967; Morelock and Bryant 1971; Halley and Schmoker 1983), Soluq Depression in Libya (El-Shari 2017), South Florida Basin in America (Schmoker and Halley 1982), and Tarim Basin in China (Wei et al. 2017). Ten groups of porosity data were collected for sandstone, including the Mid-Atlantic Outer Continental Shelf (COST B-2 well; Smith et al. 1976), the Mid-Atlantic Outer Continental Shelf (COST B-3) well (Kominz and Pekar 2001), Eromanga Basin in Australia (Gallagher and Lambeck 1989), Gulf of Mexico (Dutta et al. 2009), Junggar Basin in China (Pang et al. 2012), Liaohe Basin in China (Wei et al. 2016), Niuzhuang Sag in China (Liu et al. 2014), North Ordos Basin in China (Xia et al. 2018), Norwegian Shelf (Ramm and Bjørlykke 1994), and Viking Graben in the North Sea (Zervos 1986). In addition, data from Franciscan rocks from central and northern California, USA (Stewart and Peselnick 1977; Bray and Karig 1985), Kola borehole in Russia (Kozlovsky 1987; Lobanov et al. 2002; Trčková et al. 2002; Zharikov et al. 2003), and KTB borehole in Germany (Berckhemer et al. 1997) are also shown in the figure. The datasets from the Kola and KTB boreholes are predominantly igneous rocks with pervasively low porosity. When the sedimentary rocks are taken as a whole, they cluster together and show explicit consistency. Lithology may exert an influence on the shape of the porosity–depth profile within a limited range, but it does not change the overall pattern of the porosity–depth relationship at a larger scale.

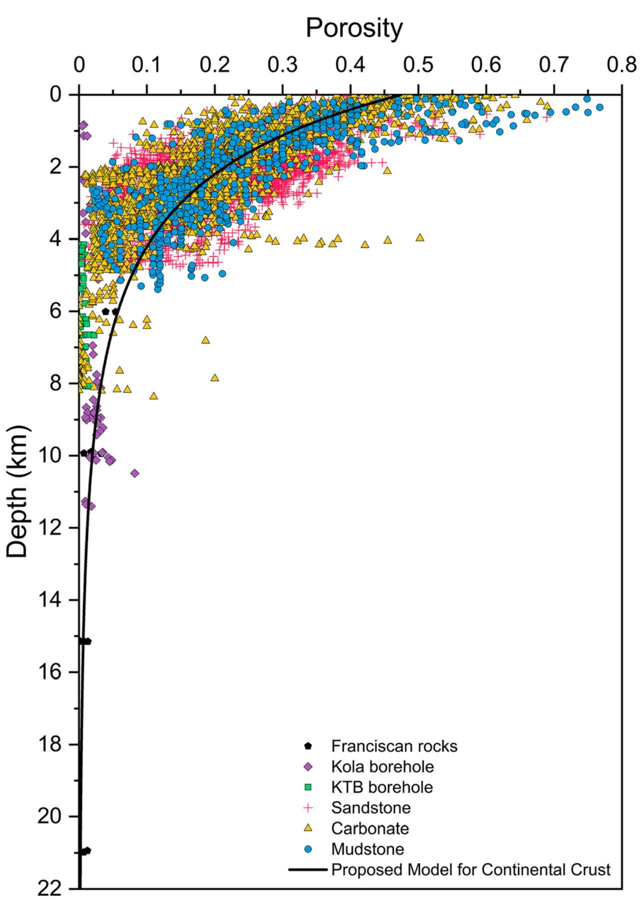

Fig. 1 Comparison of calculated and measured porosity data for Earth's continental crust in general

The proposed model provides an overall good fit to the porosity–depth data (Fig. 1). The surface porosity ϕ_0 provided by the proposed model is 0.474, which is a reasonable value. The proposed model describes the decreasing trend very well over the depth range of 0–5 km. But the agreement between measured and calculated data in the range of 5–15 km depth is not so good. The proposed model tends to slightly overestimate the measured data. This is probably due to fact that there are not enough measured data in this depth range. The model porosity decreases to almost zero when depth is greater than about 18 km. The near-surface porosity values show a wide range, as presented in Fig. 1. The model performance will not be very good near the surface due to the scattering of the data. As there are three fitting parameters in the proposed model, the parameters and the shape of the curve may change when more data are available with depths greater than 5 km, especially greater than 10 km.

Sedimentary rocks

Figure 2 shows the proposed model with data for mudstone. There are seven groups of porosity–depth data from the literature and they can represent the porosity–depth profile of mudstone in general. The data start from the ground surface to a depth of 5.5 km, with porosity varying from over 0.75 to 0.03. In fact, the porosity–depth relation of mudstone (mostly shale) has been generally represented by an exponential model in previous studies (e.g., Magara 1974; Goff 1983; Mudford 1988; Armstrong et al. 1998; Kominz and Pekar 2001). It can be seen from Fig. 2 that the proposed model also performs well globally in this depth range. The proposed model with the

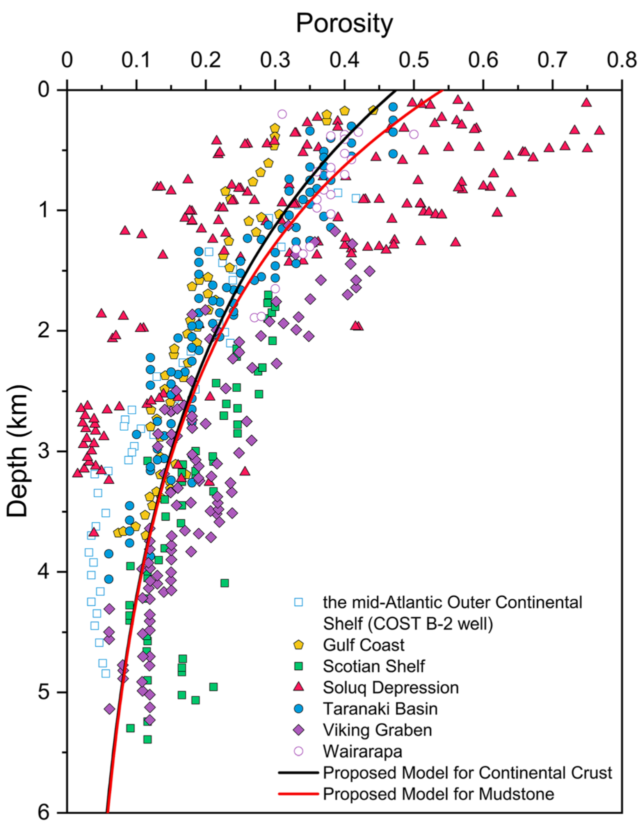

Fig. 2 Comparison of calculated and measured porosity data for mudstone

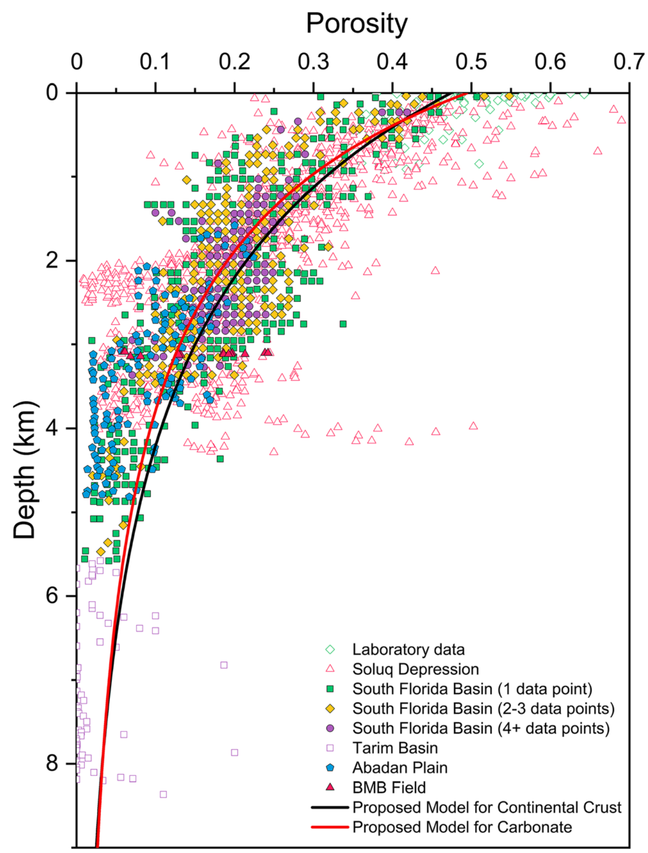

Fig. 3 Comparison of calculated and measured porosity data for carbonate rocks

set of parameters for "continental crust" can provide a reasonable description of the porosity–depth data for mudstone, but it tends to slightly underestimate the porosity values with shallow depth (less than 1 km). The proposed model was also fitted to the data separately and the fitted parameters are shown in Table 1. The fitted surface porosity value for mudstone is higher than that for continental crust and these fitted data improve the agreement between measured and calculated data in the depth range of 0–1 km (Fig. 2). Although the parameter sets for continental crust and mudstone are different from each other (Table 1), the two curves become indistinguishable when depth is greater than about 3 km.

A comparison of the proposed model with porosity–depth data for carbonate rocks is shown in Fig. 3. The data cover a depth range over 8 km from ground surface where the porosity is about 0.5 on average. The data presented by Schmoker and Halley (1982) fall into three groups (1 data point, 2–3 data points, and more than 4 data points), but no distinction is made here. Porosity data obtained from borehole TS1 in northern Tarim Basin cover a depth range of 6 to 8 km (Wei et al. 2017). In the carbonate data set, the porosity values are generally close to zero, but some of the porosity values show significant anomalies because of hydrothermal dissolution of dolomite rocks (Wei et al. 2017). The proposed model with the set of parameters for "continental crust" can provide a reasonable fit to the data overall. However, the model tends to overestimate the porosity values when depth is greater than about 5 km. The proposed model was also fitted to the data separately. The fitted parameters are shown in Table 1. Figure 3 shows that the proposed model curve is now closer to the measured porosity data than the curve for continental crust when depth is greater than about 5 km. The measured near-surface porosity values also show a wide range.

Figure 4 shows a comparison of the proposed model with the porosity–depth data for sandstone. This figure combines 10 groups of data and the porosity values are relatively scattered. The data are distributed in the depth range of 0–5 km. Differing from mudstone and carbonate, the data in this case show a general linear decreasing trend. This linear trend for sandstone is due to the dominance of primary porosity (Magara 1980). The porosity–depth relationship is initially almost a straight line, and its variances have been shown to be caused by factors like pressure, temperature, cementation, and deposition environment (Selley 1978; Wilson and McBride 1988; Ramm and Bjørlykke 1994). The proposed model with the set of parameters for "continental crust" describes the general decreasing trend reasonably well. The proposed model was also fitted to the data separately and the fitted parameters are shown in Table 1. Although the fitted surface porosity is slightly lower, the continental crust curve

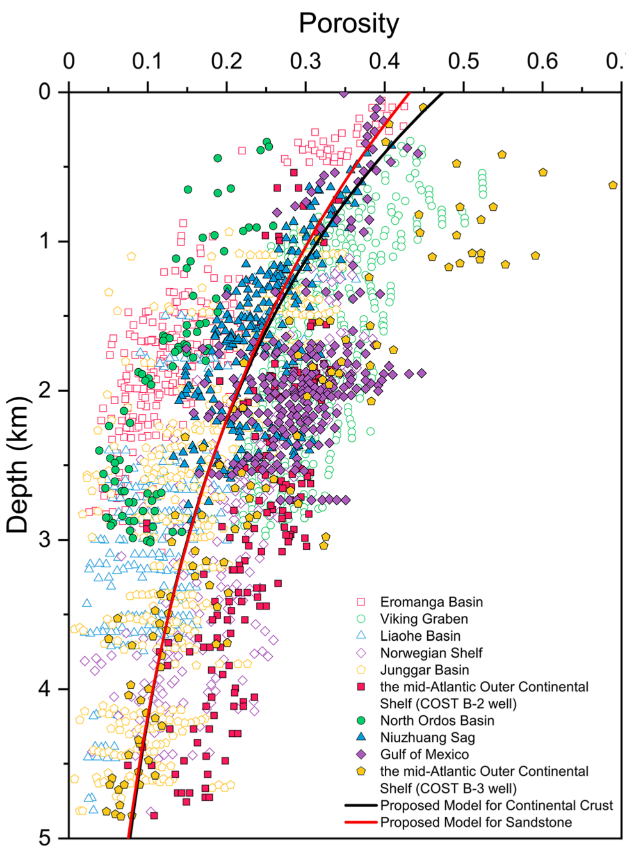

Fig. 4 Comparison of calculated and measured porosity data for sandstone

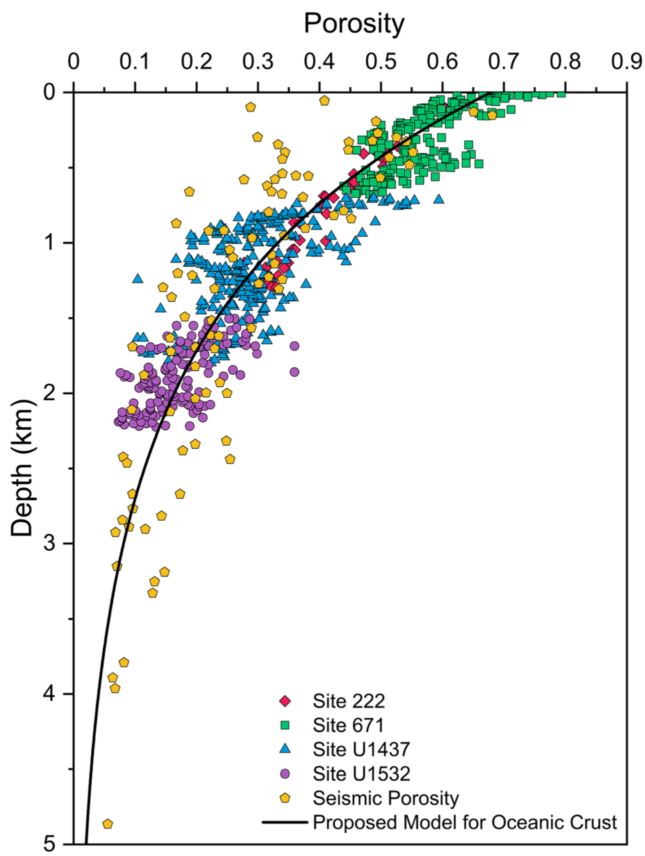

Fig. 5 Comparison of calculated and measured porosity data for Earth's oceanic crust in general

and sandstone curve become indistinguishable when depth is greater than about 2 km.

Earth's oceanic crust

The decreases of porosity with depth for Earth's oceanic crust are shown in Fig. 5. Most of the data were collected from boreholes of the Deep Sea Drilling Program (DSDP), Ocean Drilling Program (ODP), and Integrated Ocean Drilling Program (IODP; Hamilton 1976; Taylor and Leonard 1990; Expedition 317 Scientists 2010; Busby et al. 2017). Data sources are as follows: site 222 in the Arabian Sea (Hamilton 1976), site 671 in the Barbados forearc (Taylor and Leonard 1990), site U1437 in the Izu-Bonin-Mariana arc (Busby et al. 2017), site U1352 within the Canterbury Bight (Expedition 317 Scientists 2010), and seismic porosity (Shor 1962; Shor and Von Huene 1972; Montecchi 1976; Curray et al. 1977; Muruachi and Ludwig 1980; Ladd et al. 1978; Ibrahim et al. 1979; Von Huene 1979; Kieckhefer et al. 1980; Nasu et al. 1982; Bray and Karig 1985). Seismic data from accretionary prisms are also used to extend the depth range for this category (Bray and Karig 1985). The data sets cover the depth range of 0–5 km. In contrast to Earth's continental crust, near-surface porosity for the oceanic crust is exclusively high. The proposed model agrees very well with the porosity data of Earth's oceanic crust (Fig. 5). The highest R^2 value is also obtained in this case (Table 1).

Unconsolidated sediments

A comparison of calculated and measured porosity–depth data for unconsolidated sediments is shown in Fig. 6. Data sources are as follows: (1) all over the world (Borst 1982), (2) Taranaki Basin in New Zealand (Funnell et al. 1996), (3) an unspecified location (Lux et al. 2014), and Honshu and Hokkaido in Japan (Aoyagi 1983). The observed data are highly scattered in a small depth range near the surface (0–0.5 km). Compared with sedimentary rocks, unconsolidated sediments near the surface have greater porosity values, which are close to those of the oceanic crust (Fig. 5). The proposed model also performs well and the R^2 value is also relatively high. The agreement between the model and measured data is globally good and the surface porosity of 0.572 is also reasonable; however, it is hard for a model to match the near-surface porosity values well due to the scattering of the data.

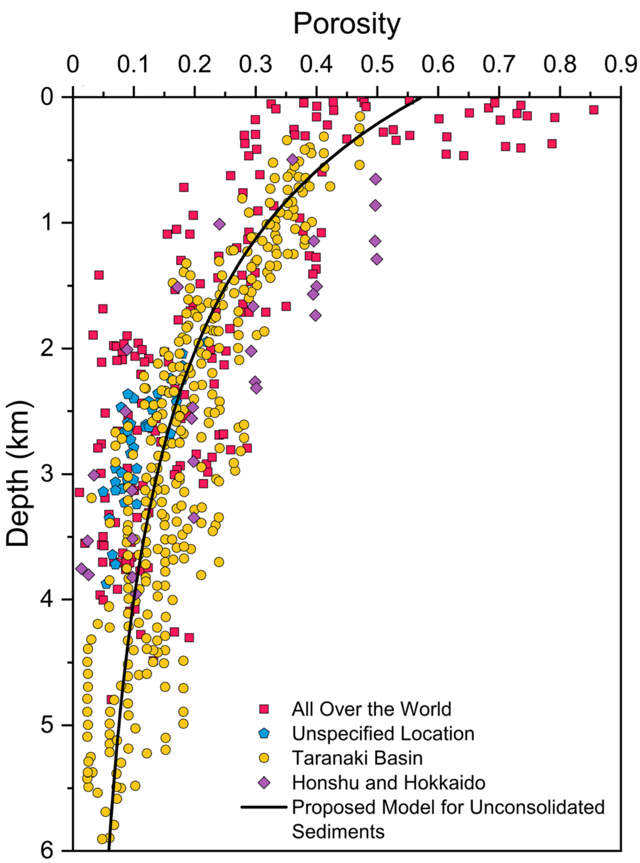

Fig. 6 Comparison of calculated and measured porosity data for unconsolidated sediments

Discussion

The proposed model provides a reasonable decreasing porosity rate over depth for Earth's continental crust, oceanic crust, and unconsolidated sediments. The fitted surface porosity ϕ_0 of the proposed model is also a reasonable value. Furthermore, three fitting parameters in the proposed model make the model flexible. The parameters in the model can be improved when more porosity–depth data are available, especially porosity–depth data for large depths.

Many other factors such as initial porosity, time, clay content, temperature, cementation, and effective stresses, also affect the porosity–depth relationship (Dickinson 1953; Chilingarian and Wolf 1976; Wygrala 1989; Ramm 1992). Relatively low porosity values within a certain depth range are associated with the existence of secondary porosity, erosion of upper strata, and uplift from historical maximum burial depth (Wilson and McBride 1988; Ehrenberg et al. 2009). It is difficult to separate the effect of each single factor and express the relationship simply as a function of depth (Magara 1978; Ramm and Bjørlykke 1994). Nevertheless, burial depth is demonstrated to be the single major factor determining porosity in some study areas (e.g., Scholle 1977; Sonnenberg 2013). Some studies on other factors affecting porosity loss, like content of total clay and stable framework grain ratio, generate multifactor models based on the exponential and the linear porosity–depth model (Scherer 1987; Ramm 1992; Ramm and Bjørlykke 1994). The empirical models represent the general condition for porosity–depth profiles, but do not ensure that it works in all cases and should be used in awareness of its limitations. It should be noted that a predictive porosity–depth model requires both improved understanding of different mechanisms affecting porosity and more porosity data from a greater depth range. More studies on the mechanisms of porosity loss caused by other factors, and further development of direct or indirect ways for porosity data acquisition at greater depth range, are therefore needed. These improvements will provide better estimates for porosity in more specific cases and lead to better porosity–depth models than the existing ones.

Conclusions

A new model for describing the decrease of porosity with depth is proposed. The proposed model was compared with measured porosity–depth data. Porosity–depth data for Earth's continental crust, oceanic crust, and unconsolidated sediments were collected from the literature. The proposed model gives a reasonable decreasing porosity rate and can describe the porosity–depth relationship over the entire range of depth. The surface porosity values fitted by the proposed model are also reasonable. Although the proposed model agrees well with measured data globally, it tends to slightly overestimate the measured data for Earth's continental crust in the depth range of 5–15 km. The proposed model also tends to slightly overestimate the measured data for carbonate rocks in the same range of depth. It is also difficult for the model to match the near-surface porosity–depth data of unconsolidated sediments well due to the scattering of the measured data. There are three parameters in the model and the model is flexible in fitting measured porosity–depth data. The proposed model is mathematically simple and can be readily used in various studies. It can be used to estimate porosity values for study areas lacking observed data, to discern abnormal strata, and to support regional groundwater studies.

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