Exploration Geophysics (1997) ***28**, 114-118*

Estimation of Effective Porosity, Tirrawarra Sandstone, Cooper Basin, Australia

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ABSTRACT

Estimation of effective porosity in shaly sand formations is the prime parameter for reserve calculation and for good understanding of the behaviour of a formation during production. The Late Carboniferous to Early Permian, fluvio-deltaic Tirrawarra Sandstone is a kaolinite-bearing sandstone and an important hydrocarbon reservoir in the Cooper Basin. Petrographic point count and image analysis data from 130 samples, together with data from about 650 core samples and wireline log data from 14 wells of the Tirrawarra Sandstone in the Moorari and Fly Lake Fields, have been used to estimate effective porosity from sonic log.

Based on integration of all data and with the knowledge of the volume fraction of kaolinite and associated microporosity (20% for kaolinite masses in the Tirrawarra Sandstone in the studied samples) effective porosity can be expressed as:

$$\phi_e = \phi_{sonic} - 0.2V_k \ ,$$

where ϕ_e is effective porosity and ϕ_{sonic} is sonic porosity, and V_k is volume fraction of kaolinite.

On average, estimated effective porosity is 2 porosity units less than the total porosity and it varies for depositional environments which have different kaolinite contents.

Keywords: Tirrawarra Sandstone, microporosity, sonic porosity, effective porosity

INTRODUCTION

The time required for a sonic wave to travel a given distance in a formation is measured by the sonic log. This travel time depends on many factors, including porosity, pore geometry, pore fluid type and transit time, matrix transit time, fluid saturation, pore pressure, clay content, and consolidation. Many workers, over the years, have tried to find a universal equation to translate sonic transit time to porosity.

The Wyllie time average equation (Wyllie et al., 1956) has been used for many years to determine porosity from logs:

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \qquad (1)$$

where Δt is rock transit time, Δt_{ma} is the transit time of the rock matrix, and Δt_{fl} is the pore fluid transit time.

Many other equations have been proposed to improve the Wyllie equation for translating sonic transit time to porosity (Pickett, 1963; Raymer et al., 1980; Raiga-Clemenceau et al., 1988; and Vernik, 1994). Most of the proposed equations show a linear relationship between transit time and porosity in the following form:

$$\Delta t = a\phi + b \ . \qquad (2)$$

Equations of this form directly reflect the Wyllie transit time equation in which a and b are empirical coefficients and can be defined as:

$$a = \Delta t_{fl} - \Delta t_{ma} \qquad (3)$$

and

$$b = \Delta t_{ma} \ . \qquad (4)$$

In further studies (Tosaya and Nur, 1982; Kowallis et al., 1984; Han et al., 1986; and Eberhart-Phillips et al., 1989), other parameters such as clay content, pressure and temperature, were also added to the general equation.

In the present study, an empirical equation is introduced for translating sonic wave transit time to porosity for the Tirrawarra Sandstone. The equation, which has a Wyllie equation style, estimates total porosity (macroporosity and microporosity). To estimate macroporosity alone a new equation is introduced, in which the reduction of sonic wave velocity in shaly sand formations is attributed to microporosity associated with kaolinite.

Geological setting

The Permo-Triassic Cooper Basin of central Australia is Australia's largest onshore hydrocarbon province. The basin consists mainly of lacustrine–fluvial deposits with local glacio-fluvial deposits (Battersby, 1976; Thornton, 1979; Stuart, 1976; Fairburn, 1989). The basin is unconformably underlain by the early Paleozoic marine and volcanic rocks of the Warburton Basin (Gatehouse, 1986) and unconformably overlain by the Jurassic–Cretaceous sedimentary units of the Eromanga Basin (Armstrong and Barr, 1986). About 95% of the Cooper Basin oil occurs in the Tirrawarra Sandstone of the Tirrawarra Field (Heath, 1989). Additional oil reserves are found at the same stratigraphic interval in the Moorari and Fly Lake Fields (Figure 1). The two fields were discovered in 1971 and are fault-bounded anticlinal structures.

Several palaeoenvironments of deposition are recognised in the Tirrawarra Sandstone in the Moorari and Fly Lake Fields, including lacustrine, parallel beach-barrier, back-barrier marsh with outwash beds, distal and medial braid-delta, meandering fluvial system and aeolian depositional environments (Rezaee and Lemon, 1996).

Tirrawarra Sandstone diagenesis

The Tirrawarra Sandstone in the Moorari and Fly Lake Fields consists mainly of medium-grained, moderately sorted sublitharenites (mostly mica schist and phyllite, shale and siltstone clasts) (classification of Folk, 1974). A variety of authigenic minerals are recognised, including syntaxial quartz overgrowths, kaolinite, minor illite, and siderite.

Quartz is the dominant pore-filling cement in most samples. Cathodoluminescence microscopy indicated the presence of three main quartz cement zones in the Tirrawarra Sandstone (Rezaee and Tingate, 1996; 1997). Quartz cementation was initiated prior to major compaction, but probably continued until relatively recent times.

Pore-filling euhedral and vermiform kaolinite booklets are common, and are sometimes intergrown with the outer margin of quartz overgrowths. The kaolinite is believed to have formed mainly as a replacement product of feldspars, and to a lesser extent, micas. In 44 carbon-coated polished sections that were impregnated by blue-dye epoxy, microporosity within kaolinite booklets was measured using image analysis of back-scattered electron (BSE) images from scanning electron microscopy (SEM). The average measured microporosity within the kaolinite masses in the Tirrawarra Sandstone is 20%.

Authigenic illite has rare fibrous, lath-like habit and is thought to have formed as a replacement of chemically unstable rock fragments.

Siderite cements are common in minor amounts in most samples, usually as disseminated, pore-filling cement. Three generations of siderite cement are recognised (Rezaee and Schulz-Rojahn, 1996), separated by dissolution boundaries.

Porosity from sonic log for the Tirrawarra Sandstone

An empirical equation for translation of sonic transit time to porosity is presented for the Tirrawarra Sandstone. To derive the equation, several corrections have been applied to the data, including those described below.

1. Zonation of sonic log data and core porosity. One of the important problems that makes comparison of core and log measurements difficult is the different volume investigated by log and core plugs (Marion and Pellerin, 1994). In order to reduce this problem, log data and core porosity were averaged for the intervals with the same lithological properties. During core logging, the Tirrawarra Sandstone was divided into eleven classes based on visual grain size, porosity, sorting, clay content and consolidation. Core and sonic data were separated into intervals with similar lithological properties.
2. A porosity reduction of 5% between conventional (ambient pressure) and reservoir (overburden pressure) core analysis for the Cooper Basin has been derived by Morton (1990) as:

$$\phi_{overburden} = \phi_{ambient} * 0.95 \tag{5}$$

All core porosity data are corrected for overburden pressure using equation (5).

3. Deletion of problematic core data. Many plugs were found to be completely unsuitable for core analysis due to the presence of microfractures, surface bedding and pebbles in the plugs. Some plugs were from very thin unrepresentative intervals. These sorts of data points were deleted during this study.
4. Precise core and log depth matching. Several methods were used for core and log depth matching, including: core gamma scan; comparison of lithology and gamma-ray and comparison of sonic log and core porosity.

The new empirical equation has the same style as the equation $\Delta t = a\phi + b$ in which empirical coefficients, a and b, refer to apparent matrix and pore fluid transit time. Apparent matrix and pore fluid transit time are determined from the relationship between core porosity and sonic transit time (Figure 2a, b). Apparent matrix transit time is the intersection of a regression line at zero porosity and apparent pore fluid transit time is the intersection of regression line at 100% porosity. The apparent matrix transit time and apparent pore fluid transit time in Moorari Field are 193 μs/m and 583 μs/m, respectively, and in the Fly Lake Field are 193 μs/m and 600 μs/m, respectively.

The equation for relating sonic transit time to porosity in the Moorari Field is

$$\phi = \frac{\Delta t - 193}{390} \tag{6}$$

and for Fly Lake Field is

$$\phi = \frac{\Delta t - 193}{407} \ . \tag{7}$$

The crossplot of measured sonic porosity from the above equations and core porosity show a good correlation ($r^2 = 0.8$) (Figure 3).

A new approach for estimation of effective porosity

The reduction of acoustic wave velocity was attributed by Kowallis et al. (1984) to the presence of microporosity associated with clay minerals (Neashem, 1977; Pittman and Thomas, 1978). Thus, sonic porosity includes both microporosity and macroporosity. The relation between total porosity and effective macroporosity can be expressed by

$$\phi_t = \phi_e + \phi_{mic} \ , \tag{8}$$

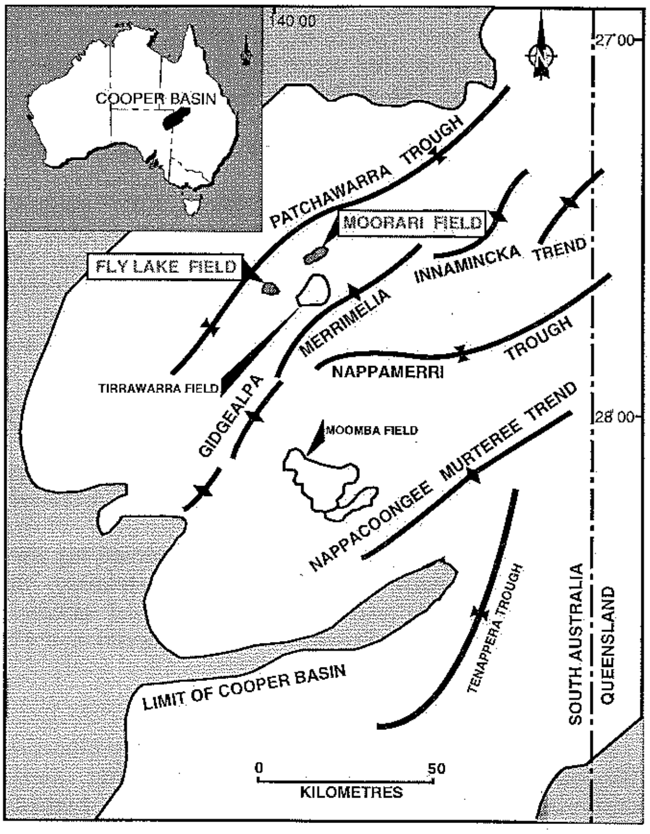

Figure 1. Map of the southern Cooper Basin showing the major structural elements and the location of the Moorari and Fly Lake Fields in the Patchawarra Trough, Cooper Basin (modified from Stuart et al., 1988).

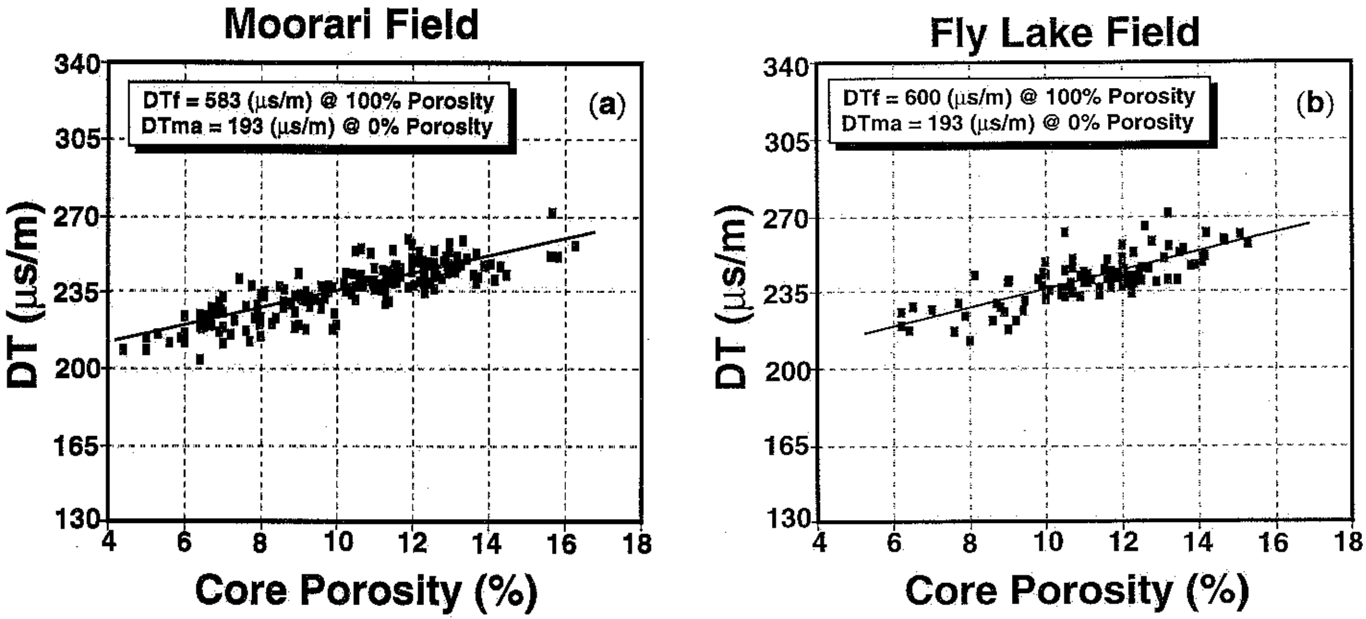

Figure 2. Crossplot of core porosity (%) versus sonic wave transit time (μs/m) in the Moorari (a) and Fly Lake (b) Fields, DTf = pore fluid transit time; Dtma = matrix transit time; DT = rock transit time.

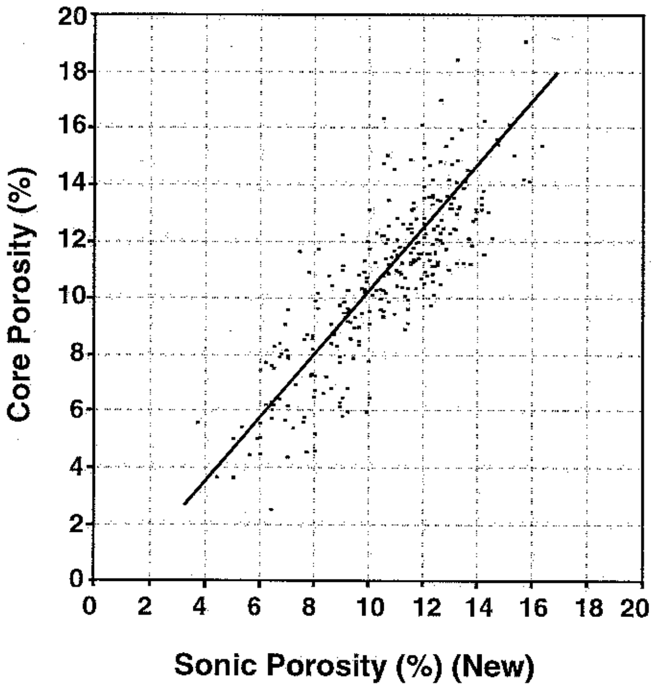

Figure 3. A crossplot of porosity calculated using the new equation shows good correlation ($r^2 = 0.8$) with measured core porosity.

where ϕ_t is total porosity, ϕ_e is effective porosity and ϕ_{mic} is microporosity associated with clay minerals.

As sonic porosity is equal to total porosity, and Back-Scattered Electron (BSE) image analysis of the clay minerals in the Tirrawarra Sandstone indicates an average of 20% microporosity in the kaolinite, equation (8) can be rearranged as

$$\phi_e = \phi_{sonic} - 0.2V_k \ , \qquad (9)$$

where ϕ_{sonic} is sonic porosity and V_k is volume fraction of kaolinite.

Knowledge of volume fraction of clay allows determination of the amount of effective porosity for the Tirrawarra Sandstone.

Petrographic point count data were used to evaluate equation (9). Point count intergranular porosity is considered as effective porosity and sonic porosity is estimated from equations (6) and (7). On average, the estimated effective porosity is 2 porosity units less than the total porosity, with a correlation coefficient of about 0.9. To find a better estimation of effective porosity with less variation of values, different subsets were tried. The best subsets were those classified according to depositional environment where variations of effective and sonic porosity were less, thereby suggesting a better estimation of effective porosity. The difference between effective and total porosity in each sedimentary environment indicates that the volume fraction of kaolinite is different in each environment.

The crossplots of sonic porosity versus effective porosity for samples from each sedimentary environment (Figure 4a-e) show a good correlation. The equations from the regression line of the crossplots can be used for each sedimentary environment to estimate effective porosity.

For all samples the relation between effective and sonic total porosity is

$$\phi_e = 0.95\phi_t - 1.4 \qquad (10)$$

The relationships between sonic total porosity and effective porosity for the individual paleoenvironment subsets are plotted in Figure 4.

As the determination of kaolinite from wireline log data for the present wells is difficult and not reliable, the equations (Figure 4) will allow estimation of effective porosity for Tirrawarra Sandstone in the Moorari and Fly Lake fields.

DISCUSSION AND CONCLUSION

The reduction of acoustic velocity in kaolinite-bearing Tirrawarra Sandstone is related to microporosity among kaolinite booklets. This indicates that sonic porosity includes both macroporosity and microporosity. In the present study, new equations are introduced for the Tirrawarra Sandstone in the Moorari and Fly Lake Fields.

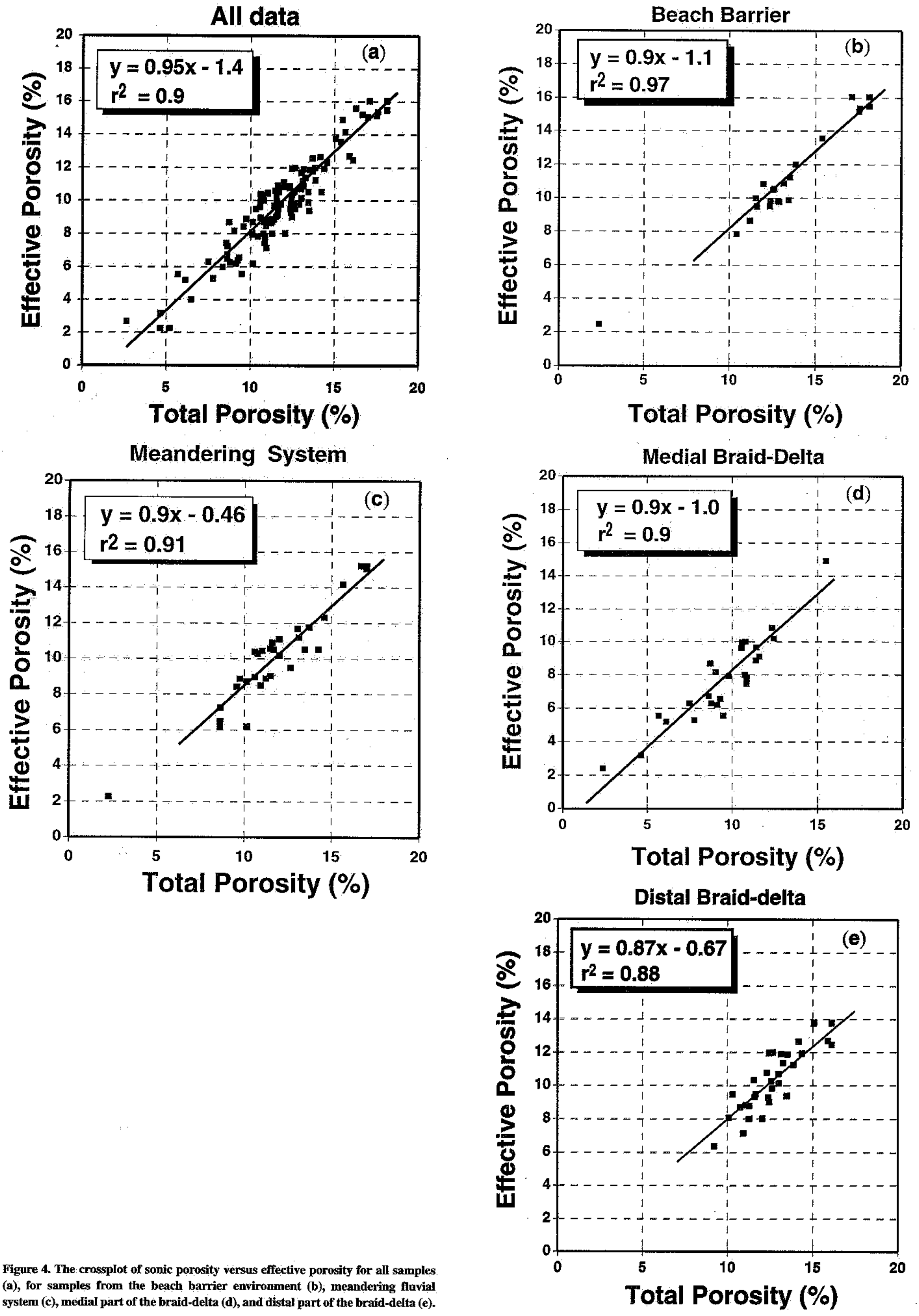

Figure 4. The crossplot of sonic porosity versus effective porosity for all samples (a), for samples from the beach barrier environment (b), meandering fluvial system (c), medial part of the braid-delta (d), and distal part of the braid-delta (e).

$$\phi = \frac{\Delta t - 193}{390} \qquad \text{Moorari Field}$$

$$\phi = \frac{\Delta t - 193}{407} \qquad \text{Fly Lake Field}$$

The plot of sonic porosity derived from the new equations and core porosity shows an r^2 value of 0.8. These equations calculate total porosity. In this study, a new equation is suggested for kaolinite-rich sandstones to estimate macroporosity from sonic porosity

$$\phi_{mac} = \phi_{sonic} - aV_k \ .$$

In this equation a value of 20% was used for microporosity within kaolinite masses (a) in the Tirrawarra Sandstone. The equation can be applied to other kaolin-bearing sandy formations provided that the amount of microporosity associated with kaolinite (a) be assessed for the formation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support by the NCPGG and SANTOS Ltd. We thank SANTOS Ltd. (operator on behalf of the Cooper Basin consortium) for permission to publish this work.

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