

MICROBIALITES IN A LOWSTAND REEF: IMPLICATIONS FOR PETROPHYSICAL PROPERTIES

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KEY FINDINGS

- Plugs sample the exception: much of core ES-103 is unconsolidated skeletal sand. The plugs represent only intervals lithified by microbialites, cement, or coral, not reef-scale properties.
- Microbialites turn loose reef debris into tight, stiff, stable rock: they have the lowest porosity and permeability (medians 23.6%, 1.1 mD), plot most brittle, and 9 of 12 plugs survived testing intact.
- Permeability and fragility go together: 5 of 7 plugs that broke below 5 MPa exceed 1,000 mD. Some high permeabilities may reflect damage, so damaged plugs must be separated before deriving transforms.
- Velocity follows porosity ($r = -0.70$) but is blind to breakage and permeability: Archie m (2.4–6.4) records pore connectivity, yet predicting flow requires direct pore-geometry data.

INTRODUCTION AND SIGNIFICANCE

This study evaluates 37 carbonate plugs from core ES-103, offshore Mozambique, containing microbialites, mixed microbialite-sediment, cemented skeletal sediments, and pure corals. Much of core ES-103 consists of unconsolidated skeletal sand and rubble; the plugs therefore sample its lithified intervals. The objective is to define first-order relationships among porosity, permeability, compressional velocity, resistivity, and cementation exponent m , while evaluating mechanical stability during pressure-dependent acoustic testing. Many samples either visibly broke at low effective pressure or developed poor acoustic signals; the latter are interpreted as likely internal breakage not always visible after testing. Carbonate properties depend on pore volume, pore size and shape, connectivity, cement distribution, and frame rigidity (Weger et al., 2009). These controls are especially important in microbial and reefal carbonates, where growth fabrics, early cementation,

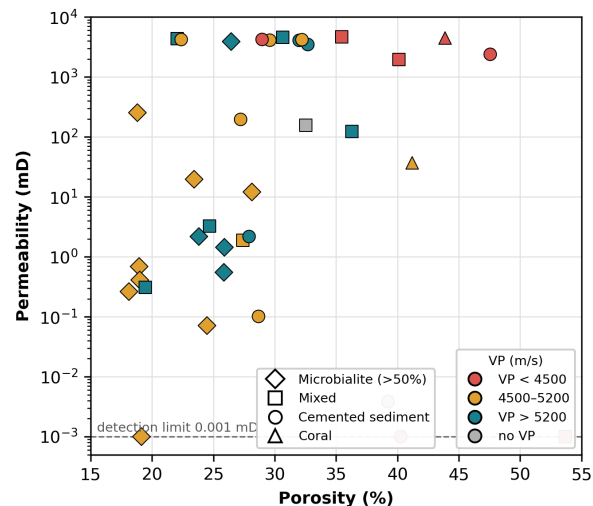


Figure 1: Permeability versus porosity, colored by wet compressional velocity at 10 MPa. Diamonds: microbialites; squares: mixed microbialite-sediment; circles: cemented skeletal sediments; triangles: pure corals. Porosity axis cut at 55% (MZB_11, 71%, not shown); dashed line: 0.001 mD detection limit.

dissolution, and burial modification generate heterogeneous pore networks. We therefore compare trends by facies and explicitly distinguish intact, visibly broken, and likely internally damaged plugs.

METHODS

Porosity and permeability were measured on all 37 plugs. Acoustic velocity and electrical resistivity were measured on brine-saturated samples following general CSL carbonate-core procedures (for details see Weger et al., 2023). Compressional and shear velocities were recorded during loading over a range of effective pressures. Electrical measurements include formation factor and resistivity at 720 Hz. For direct comparison, wet VP, resistivity, and formation factor are evaluated at 10 MPa effective pressure; duplicate measurements at the same condition were averaged. Permeabilities of 0.001 mD represent the instrument detection limit. These filters provide VP for 35 plugs, electrical properties for 29–30 plugs, and a common set of 27 plugs with permeability, porosity, VP, resistivity, and m.

The cementation exponent was calculated as $m = -\ln(F)/\ln(\phi)$, where F is formation factor, ϕ is fractional porosity, and Archie coefficient $a = 1$. The resulting m combines effects of pore geometry, connectivity, and tortuosity; because porosity enters the calculation directly, correlations between m and porosity require caution. Plugs were grouped into four classes: microbialite (>50% microbialite; 12 plugs), mixed microbialite–sediment (10), cemented skeletal sediment (12), and pure coral (3; MZB_08, MZB_11, and MZB_16). A bad acoustic signal was classified as likely internal breakage; “broke below 5 MPa” records observed failure. Plugs with both flags provide the strongest evidence of failure. Sleeve failure and subsequent oil flooding also caused some missing velocity and/or resistivity measurements.

DATA SET

Porosity ranges from 18.12% to 71.01%, permeability from 0.001 to 4694.38 mD, wet VP at 10 MPa from 3399 to 5924 m/s, resistivity from 3.93 to 97.98, and calculated m from 2.38 to 6.43. Permeability is unevenly distributed, with a low-to-moderate population and a separate high-permeability population of approximately 1956–4694 mD. The high-permeability population (13 plugs) is dominated by cemented skeletal sediments (7) and mixed plugs (4) and includes one coral and one microbialite. Facies representation is uneven: 12 microbialites, 10 mixed plugs, 12 cemented sediments, and only three pure coral plugs; coral trends are therefore preliminary.

RESULTS

Porosity and Permeability

Porosity alone does not predict permeability. Permeability spans >6 orders of magnitude, while the rank correlation between porosity and permeability is only $\rho = 0.23$. Samples with porosities near 20–40% occur across almost the entire permeability range, indicating that connected pore-throat geometry, rather than total pore volume, exerts the primary control on flow. Microbialites have median

porosity of 23.63% and permeability of 1.06 mD; mixed plugs have 31.58% and 140.18 mD; cemented skeletal sediments have 30.80% and 2934.53 mD but span both low and high values. The three coral plugs are the most porous (41.20–71.01%), yet their median permeability is only 36.98 mD; only MZB_08 (4472.32 mD) is highly permeable, consistent with a well-connected framework, although $n = 3$ precludes a general relationship.

Velocity and Sample Stability

Wet VP at 10 MPa has a first-order inverse relationship with porosity (Pearson $r = -0.70$; $n = 35$), but VP differs by several hundred meters per second at comparable porosity. The scatter is consistent with variable pore geometry and frame stiffness and is also affected by plug integrity. Median VP is 5219 m/s for mixed plugs, 5097 m/s for microbialites, 4818 m/s for cemented sediments, and 4065 m/s for the three coral plugs. The microbialites therefore commonly combine a relatively stiff framework with low permeability, whereas cemented sediments and corals combine higher permeability or porosity with lower velocity.

Mechanical instability is a defining characteristic. Sixteen plugs generated a bad acoustic signal interpreted as likely internal breakage; seven visibly broke below 5 MPa, including five that also generated bad signals. Thus 18 unique plugs, or 49%, carry at least one failure indicator. The five with both indicators are MZB_07, MZB_09, MZB_10, MZB_14, and MZB_31. Fractures and crack-aspect-ratio changes can strongly affect elastic velocity (Sun and Goldberg, 1997); measurements after internal damage should therefore not be interpreted solely as depositional pore-structure signals.

Resistivity and Cementation Exponent

Electrical properties show broad scatter at overlapping porosity. At 10 MPa, resistivity ranges from 3.93 to 97.98 and m from 2.38 to 6.43 (Fig. 2). Formation factor and resistivity are closely related, but neither resistivity nor m is a simple permeability proxy; samples with similar m span several orders of magnitude in permeability. The only coral plug with electrical data (MZB_08) has the lowest resistivity (3.93) and an m of 3.48, consistent with an electrically connected

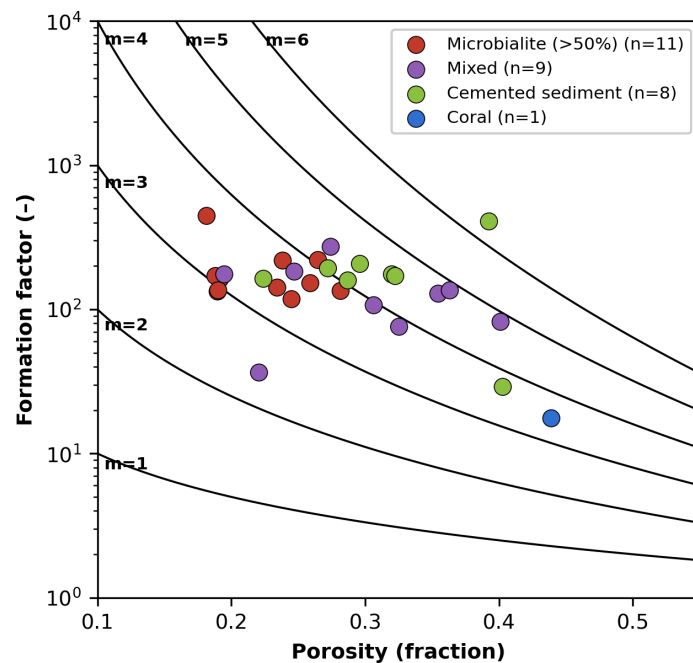


Figure 2: Formation factor versus porosity at 10 MPa, classified by facies, with Archie m contours ($m = 1-6$, $a = 1$) for reference. MZB_08, the only coral with electrical data, has the lowest resistivity, whereas cemented sediments display the highest m and the broadest electrical-property range.

pore network. Microbialites have median resistivity of 32.54 and the lowest median m (3.42), mixed plugs 28.16 and 3.95, whereas cemented sediments have median resistivity of 34.75 and the highest median m (4.22), with the widest electrical range; the maximum ($m = 6.43$) occurs in the low-permeability cemented sediment MZB_05. High m values indicate greater tortuosity or a larger proportion of poorly connected pore space. Pressurization-induced fractures may also alter the conductive network.

IMPLICATIONS AND CONCLUSIONS

The Mozambique plugs demonstrate that porosity is an incomplete predictor of carbonate reservoir properties. Permeability varies by more than six orders of magnitude and is weakly related to porosity, whereas VP has a stronger first-order relationship with porosity but substantial scatter from pore geometry, cement distribution, facies, and mechanical integrity. Resistivity and m further distinguish samples with similar porosity by highlighting differences in pore connectivity and tortuosity. Microbialites tend toward low porosity, low permeability, and higher velocity; cemented skeletal sediments dominate the high-permeability population; the pure corals are the most porous end members; and mixed plugs occupy the intermediate range.

Nearly half the plugs contain observed breakage or acoustic evidence interpreted as internal failure. This instability is itself a rock property of a weak, heterogeneous, or crack-sensitive framework, but once a plug breaks, velocity and resistivity may no longer represent the intact rock. Future analysis should retain break classifications, identify the pressure step at which signal degradation begins, and separate intact from damaged measurements before developing predictive transforms. The full petrophysical range is likely controlled jointly by facies, pore geometry, and pressure-dependent mechanical stability; because much of core ES-103 is unconsolidated sand, the plugs represent the lithified part of the reef.

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