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High-throughput visualization of dispersed quartz in sponge fossils: A novel tool for reef-type reservoir evaluation

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Dear Editor,

Marine petroleum represents one of the most important replacement frontiers for global energy reserve growth and production expansion. Sponge reef carbonates constitute a critical reservoir type for deep-marine hydrocarbon resources. The dispersed quartz grains within these carbonates are an important mineralogical factor governing compaction resistance of reef bodies and preservation of deep-burial pores. Their abundance and spatial distribution significantly affect reef-type reservoir quality and hydrocarbon enrichment potential.[1,2]

However, quantitative characterization of micron-scale quartz within sponge skeletons has long relied on low-throughput, partially destructive observation modes. High-throughput, fully non-destructive reservoir-scale evaluation remains rarely achieved, forming a technical bottleneck restricting precise exploration of reef-type hydrocarbon reservoirs.

In this study, we employ constant-temperature large-field equivalent blackbody temperature (EBT) imaging on aragonitic sponge fossil samples from the Cenozoic marine strata offshore Varadero, Cuba (Figure 1A). Samples were vacuum-impregnated with epoxy, cut into 30 micrometer thin sections, and polished. EBT imaging was conducted after 30 min of thermal equilibration, with a 2.5 cm field of view, 17 micrometer resolution, and approximately 5 min per acquisition. This technique enables non-destructive, high-throughput identification and quantification of quartz at the centimeter scale, providing a novel approach for rapid evaluation of reef-type reservoirs.

CONTROL OF QUARTZ ON DEEP-BURIAL PORE PRESERVATION IN REEF RESERVOIRS

The anomalously high porosity in deeply buried sponge reef reservoirs is a prominent research topic. Quartz has a significantly higher elastic modulus than aragonite and calcite. Rigid quartz grains dispersed in carbonates can markedly enhance compaction resistance, playing an important constructive role in pore preservation. Quartz grains hosted within aragonitic sponge skeletons form a synergistic support structure with the skeleton matrix.[2,3] Accordingly, quartz abundance and spatial distribution are closely related to reservoir pore evolution prediction and represent core evaluation parameters.

Bulk XRD results show aragonite accounts for 94.8 wt% and quartz 1.3 wt%, the important secondary phase affecting skeleton mechanical properties (Figure 1B). Limited by microscale characterization capabilities, researchers have long been unable to perform systematic non-destructive full-area detection of micron-scale quartz within sponge skeletons. The quartz-controlled reservoir mechanism thus lacks in-situ quantitative data support, hindering optimization of reservoir evaluation models.

INHERENT TECHNICAL LIMITATIONS OF CONVENTIONAL METHODS

Quartz identification in calcareous sponge fossils faces multi-dimensional shortcomings. Polarized light microscopy can achieve centimeter-scale scanning but quartz distinguishability is inherently limited and observer-dependent.[4] As shown in Figure 1C & D, quartz and aragonite skeletons have similar refractive indices, producing extremely weak grain-boundary contrast and making accurate full-area delineation nearly impossible through manual observation.

Microscale techniques such as EDS, EPMA, and micro-Raman can identify individual quartz grains but their field of view is generally tens to hundreds of micrometers.[5,6] Even automated systems such as TIMA require conductive coating, and centimeter-scale high-resolution acquisition takes hours to days. Bulk techniques such as XRD and infrared spectroscopy can measure average quartz content but effectively eliminate spatial information.[7,8] They cannot distinguish whether quartz occurs within skeletons, in pores, or in the surrounding matrix. Without spatial information, correlations between quartz content and reservoir quality cannot be established.

EBT IMAGING IDENTIFIES MINERAL PHASES VIA EMISSIVITY DIFFERENCES

EBT imaging utilizes intrinsic emissivity differences of mineral lattices in the long-wave infrared band, converting compositional differences into a visualized equivalent blackbody temperature distribution under isothermal equilibrium.[9,10] EBT is not the true thermodynamic temperature but the temperature of a blackbody producing the same radiant exitance. Under isothermal conditions, EBT spatial variations reflect mineral emissivity differences rather than actual temperature changes.

This method requires no coating or etching. Prepared thin sections can be directly loaded, and the process is non-destructive. The system supports a maximum imaging diameter of approximately 10 cm.

Quartz identification in the EBT map rests on three converging lines of evidence. First, quartz and aragonite differ fundamentally in crystal structure and phonon modes, producing systematic emissivity differences. Second, SEM-EDS point analysis of 10 representative bright-white particles shows Si as the overwhelmingly dominant element (77.5% of total counts), with Si/Al averaging 41.7 and Si/Ca averaging 46.2, far exceeding feldspar and clay ratios and excluding aragonite, calcite, and aluminosilicates. Third, the grains show sharp boundaries and homogeneous interiors consistent with authigenic quartz, unlike clay films or cryptocrystalline aggregates. Combined with bulk XRD showing 1.3 wt% quartz, these constraints robustly identify the high-signal phase as quartz.

Quantitative statistics target identifiable quartz grains with diameters >= 17 micrometers, covering the dominant population controlling reservoir-scale pore preservation.

SINGLE-MAP COVERAGE OF CENTIMETER-SCALE QUARTZ DISTRIBUTION

EBT imaging of the sponge fossil demonstrates outstanding phase discrimination (Figure 1E). The quartz phase appears as discrete high-EBT grains from bright white to light gray, with homogeneous interiors and sharp boundaries. The aragonite matrix appears as a continuous lower-EBT phase in red to orange-yellow tones, with spatial gradients reflecting lattice defect variations. Quartz grains can be identified based on EBT signal characteristics, elemental constraints, and morphological evidence. Combined with image processing, the method has the capability to output spatial distribution, grain size spectrum, and areal density in one step.

EBT variations in the aragonite matrix simultaneously reflect lattice defect degree changes. Both types of information are inherently registered in one image, effectively avoiding positioning deviations from multi-technique combination.

Figures 1F & G show two quartz occurrence modes. Pore-filling quartz occurs within skeleton-bounded pore spaces, showing subhedral to anhedral

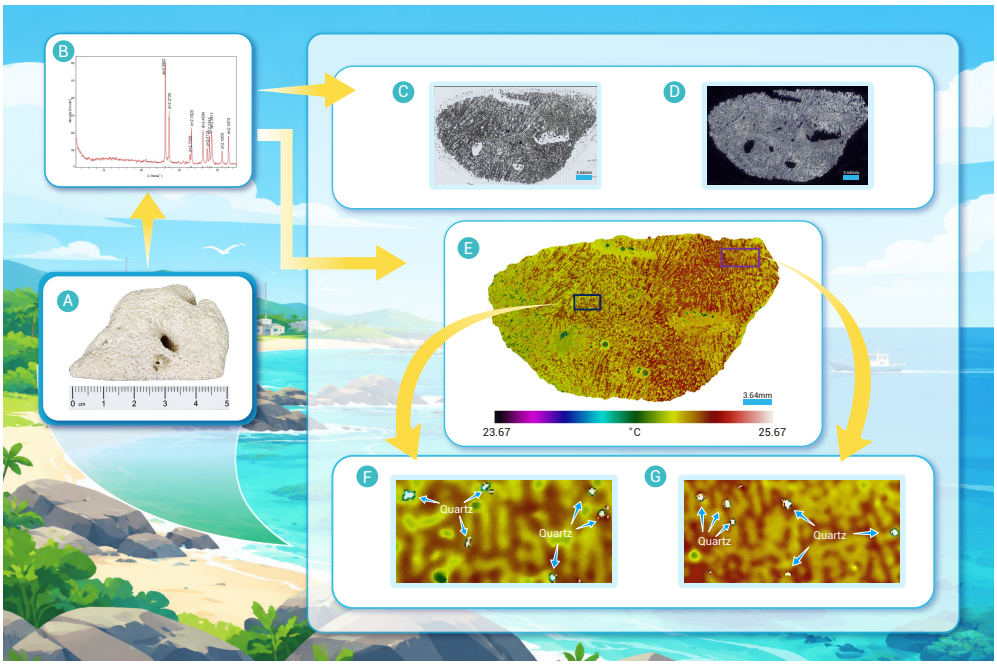


Figure 1. Multi-method integrated characterization of aragonitic sponge fossils from offshore Varadero, Cuba (A) Macroscopic photograph of the aragonitic sponge fossil sample used in this study; (B) Bulk X-ray diffraction quantitative analysis spectrum of the sample. Phase quantification shows aragonite accounts for 94.8 wt%, followed by clay minerals (2.6 wt%), quartz (1.3 wt%), halite (0.9 wt%), and calcite (0.4 wt%). (C) Large-field plane-polarized light micrograph of a thin section from the target sample. The signal contrast between quartz and aragonitic sponge spicules is weak, making effective manual distinction difficult; (D) The corresponding large-field cross-polarized light image. It can serve as supplementary evidence for quartz grain identification; (E) Full-area equivalent blackbody temperature distribution map of the sample. EBT detection efficiency is 1 to 2 orders of magnitude higher than existing microscale techniques. It achieves zero sample preparation, zero contact, and zero damage, with potential for batch evaluation of exploration samples. The color bar on the right corresponds to a temperature range of 23.67 to 25.67 degree Celsius; (F, G) Magnified details of the two framed regions in (E). Bright white grains in the thermal map represent quartz. Two occurrence modes of quartz are visible: pore-filling quartz and quartz intergrown with aragonitic sponge skeletons.

shapes constrained by pore boundaries and sharp contacts with the aragonite skeleton. Skeleton-intergrown quartz shows interlocking or embayed boundaries with the matrix, irregular shapes extending along spicule fiber directions, and partial enclosure by aragonite. Spatial location and boundary contact type distinguish the two modes in the EBT map. Both modes jointly affect compaction resistance through pore structure and skeleton rigidity pathways.

A NOVEL TOOL FOR REEF-TYPE RESERVOIR EVALUATION

This approach delivers value in two dimensions: quantitative capability and evaluation efficiency. It can provide quantitative evidence for the quartz-controlled reservoir mechanism and promote transition from qualitative inference to quantitative constraint. The anti-compaction effect of quartz is a widely reported geological understanding. This study provides a new technical means for its in-situ quantitative verification rather than directly proving the mechanism. Quantified quartz data can support establishment of correlations between quartz distribution and compaction resistance, revision of pore evolution models, and improvement of reservoir prediction accuracy.

Even 1.3 wt% dispersed quartz can influence reservoir evolution. Only full-area characterization can clarify the effect of such low-abundance rigid minerals. The high-throughput feature matches batch sample evaluation demand during exploration. EBT compresses characterization from hours to minutes, providing a high-throughput tool and showing promise for large-scale evaluation in reef-type hydrocarbon accumulation areas.

The accuracy and efficiency of reef reservoir evaluation are expected to improve systematically, providing technical support for energy exploration in reef-type hydrocarbon enrichment areas.

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DECLARATION OF INTERESTS

The authors declare no competing interests.