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Cryptic microscale heterogeneity in coral carbon retention warrants attention in carbonate carbon accounting

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The aragonite skeletons formed by coral biomineralization, if preserved over long timescales after sedimentary burial, can constitute a geological-scale carbonate carbon reservoir.[1] Coral reefs are among the most biologically productive and geochemically active ecosystems on Earth, and their carbonate production represents a significant flux in the global carbon cycle. It should be clarified that coral calcification itself is accompanied by CO_2 release, and the short-term net carbon sink effect of coral reefs primarily arises from the photosynthesis of symbiotic organisms.[2,3] We explicitly note that buried coral carbonate represents a long-term geological inorganic carbon reservoir, distinct from the organic blue carbon concept in ecosystem management and climate policy. The ultimately buried and preserved carbonate skeletons represent an important component of long-term geological carbon cycling, distinct from the short-term ecosystem-level carbon balance. While it is well established that coral skeletons exhibit microscale heterogeneity in geochemistry, density, and crystal orientation, we draw attention to a different, previously underappreciated dimension: subtle lattice damage that is invisible to conventional microscopy but may modulate long-term dissolution resistance. Subtle lattice damage within the skeleton can increase mineral dissolution rates during burial and reduce long-term carbon retention efficiency, and this overlooked microscale heterogeneity may introduce systematic biases into carbon cycle estimates. This article proposes a new perspective: using large-field-of-view macro infrared thermal imaging to perform full-field non-destructive characterization of apparently homogeneous coral skeletons, identify microscale spatial differences in their carbon retention potential, and propose a new hypothesis of microscale heterogeneity in coral carbon retention based on preliminary observations.

FROM THE HOMOGENEITY ASSUMPTION TO A NEW PATH FOR MICROSCALE CHARACTERIZATION

Traditional methods such as polarized light microscopy, X-ray diffraction, and scanning electron microscopy can only identify obvious alteration accompanied by phase transitions, and there remains a lack of full-field, non-destructive detection methods for early burial modification involving only subtle lattice damage. These conventional techniques typically require targeted sampling and provide only point-based or localized measurements, making it difficult to capture the spatial distribution of incipient alteration across an entire skeleton. Large-field-of-view macro infrared thermal imaging offers a new approach:[4] under constant temperature conditions, spatial differences in the equivalent blackbody radiation temperature of single-phase homogeneous minerals can reflect the relative distribution of lattice defect density, which is closely related to dissolution rates during burial. The physical basis lies in the relationship between lattice imperfections and infrared emissivity: defects and dislocations alter the vibrational modes and electronic structure of the mineral, which in turn modifies its radiative properties. To control for surface roughness and thickness effects, samples were prepared as uniformly polished thin sections of standardized thickness. The ~1% clay and 0.8% siderite accessory phases are too sparse and discretely distributed to account for the smooth continuous planar gradient observed, which is more consistent with a structural origin. Therefore, thermal imaging signals show promise as an indirect indicator of carbon retention potential, offering the advantage of rapid, full-field, and non-destructive measurement that conventional methods cannot provide.

This study examines a Holocene reef coral sample collected from Wuzhizhou Island, Sanya, in the South China Sea (Figure 1A). After rinsing with deionized water, the sample was prepared as a standard polished thin section, with its surface finely polished to minimize topographic effects. Routine characterization indicates that the sample is apparently homogeneous: XRD is dominated by primary aragonite peaks, with only approximately 1% clay minerals and 0.8% siderite, and no calcite was detected (Figure 1B). Both plane-polarized and cross-polarized light images show that the native skeletal framework is continuous and regular (Figures 1C & D). These conventional observations collectively suggest that the sample has not undergone significant diagenetic alteration, providing an ideal test case for evaluating whether more subtle microscale variations can be detected by thermal imaging.

Large-field-of-view macro-lens infrared thermal imaging was conducted in a temperature-controlled darkroom, using a unified emissivity setting to convert raw infrared radiation signals into equivalent blackbody radiation temperature. To reduce interference from absolute calibration errors, instrument bias, and environmental temperature drift, the measured temperatures can be normalized relative to the maximum temperature of the sample to construct a relative equivalent blackbody radiation temperature index for intra-sample comparison. This normalization approach is particularly suitable for comparing spatial variations within a single sample, as it removes the influence of absolute temperature offsets while preserving relative differences across the field of view. The instrument noise floor is ±0.03°C, well below the gradient amplitude reported below.

STABLE PLANAR THERMAL GRADIENT FEATURES UNDER THREE AMBIENT TEMPERATURES

Observations show that even in a sample judged homogeneous by routine characterization, significant and stable spatial differences in equivalent blackbody temperature exist within the skeleton (Figure 1E-G). Qualitative image registration confirms that gradient direction and local features align across temperatures. The consistency across different thermal environments also suggests that the observed patterns reflect intrinsic properties of the sample rather than artifacts induced by a particular measurement condition.

The equivalent blackbody temperature exhibits a significant gradient across the sample plane, with a relatively well-defined direction of temperature change along which temperature transitions continuously from low to high, and the maximum temperature difference across the full field of view is approximately 0.6°C. The temperature distribution is simultaneously superimposed with local spatial heterogeneity, and temperature variations in different regions are controlled by the multifactorial coupling of internal skeletal structure, fluid seepage pathways, and local reaction conditions, which cannot be fully described by a simple one-dimensional diffusion model. Among these features, the systematic gradient from one side to the other has an amplitude of approximately 0.3°C. The presence of both a broad regional gradient and finer-scale local variations suggests that the processes governing carbon retention potential operate at multiple spatial scales within the skeleton. The concentric ring structures are artifacts caused by residual bubbles from thin-section preparation and were excluded from the analysis (Figure 1E-G).

LOGICAL LINK BETWEEN THERMAL SIGNALS AND CARBON RETEN-

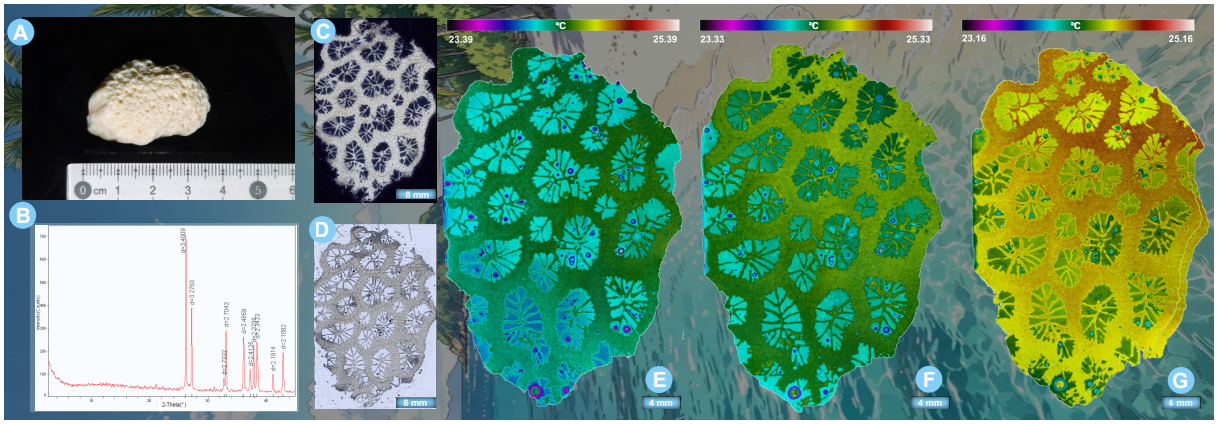


Figure 1. Multi-method characterization and equivalent blackbody radiation temperature distribution of a Holocene coral sample (A) photograph of the intact coral sample; (B) X-ray diffraction pattern of the sample, dominated by primary aragonite peaks with no calcite detected; (C) large-field-of-view cross-polarized light micrograph with generally uniform interference colors across the full field of view; (D) large-field-of-view plane-polarized light micrograph showing a continuous and uniform native skeletal framework; (E~G): large-field-of-view macro infrared thermal images under three different ambient temperature conditions, with equivalent blackbody radiation temperature ranges of 23.39 to 25.39°C (E), 23.33 to 25.33°C (F), and 23.16 to 25.16°C (G), respectively, with the color scale decreasing from red (high temperature) to purple (low temperature). The spatial patterns of thermal distribution are highly consistent across all three images, with a significant temperature gradient across the plane and a relatively well-defined direction of temperature change along which temperature transitions continuously. The concentric ring structures in the images are residual bubbles from thin section preparation, which are preparation artifacts and do not represent native skeletal structures.

TION POTENTIAL, AND A NEW HYPOTHESIS

The inference regarding carbon retention potential in this study is based on two independently verified findings. First, for single-phase homogeneous minerals under constant temperature, there exists a stable relationship between equivalent blackbody radiation temperature and lattice defect density: the higher the degree of structural modification and the greater the defect density, the lower the equivalent blackbody temperature. This relationship has been verified in systems such as silicates and aluminosilicates,[4] providing a solid physical foundation for extending the approach to carbonate minerals such as aragonite. Second, the higher the lattice defect density in aragonite, the faster the dissolution rate during burial and the lower the long-term carbon retention efficiency.[3,5] Lattice defects serve as preferential sites for mineral dissolution, as they represent zones of higher free energy and greater chemical reactivity compared with perfect crystal lattices.

Based on these two foundations, a logical relationship can be established: the higher the equivalent blackbody temperature, the lower the lattice defect density, the lower the dissolution risk during burial, and the higher the relative long-term carbon retention potential. We explicitly frame the normalized thermal signal as a candidate relative indicator, which is a testable hypothesis pending calibration via Raman mapping, micro-XRD, and dissolution experiments. Accordingly, the normalized thermal signal can serve as a potential indicator of the relative long-term carbon retention potential of coral aragonite, and intra-sample comparisons do not require additional geochemical calibration, whereas cross-sample comparisons require further standardization. It is important to note that this indicator provides relative rather than absolute assessments of carbon retention potential, and its quantitative relationship with actual dissolution rates remains to be calibrated through independent geochemical measurements. We recognize that natural sediment dissolution rates are governed primarily by pore-water chemistry, with microscale structural variation modulating local susceptibility rather than dominating bulk budgets.

These preliminary observations offer a new perspective: the long-term carbon retention capacity of coral skeletons is not homogeneous but exhibits significant microscale spatial heterogeneity across the plane, and carbon retention potential may vary systematically among different regions. If confirmed across multiple samples and methods, this cryptic microscale heterogeneity warrants attention in the accounting of long-term coral carbonate carbon burial, which is a geological inorganic carbon reservoir distinct from ecosystem-level blue carbon. We present this as a preliminary observation raising a testable hypothesis rather than a finalized challenge to existing accounting frameworks. If validated by multiple samples and methods, this hypothesis would revise the homogeneity assumption in traditional carbon storage accounting and advance coral carbonate carbon cycle research from macroscale average estimation toward microscale precise characterization. Future work will expand coral samples from different ocean regions, species, and geological ages, and combine independent microscale techniques such as Raman spectroscopy and micro-XRD to verify the structural origin of the thermal signals, clarifying the applicability and quantitative precision of the method. Beyond coral reef systems, the proposed approach may also be applicable to other carbonate-bearing environments such as carbonate platforms, shell beds, and microbialites, where microscale heterogeneity in mineral preservation similarly affects long-term carbon burial estimates. The non-destructive nature of the method makes it suitable for analyzing precious or rare samples, and its full-field capability enables screening of large sample sets that would be impractical with conventional point-based techniques.

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DECLARATION OF INTERESTS

The authors declare no competing interests.