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Early detection of coral reef acidification micro-hotspots driven by offshore energy development

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Dear Editor,

Offshore energy development is a key measure to safeguard global energy security. At present, offshore oil and gas, wind power, tidal power and other offshore energy industries are expanding rapidly worldwide. However, large-scale energy activities have become a non-negligible driver of coastal ocean acidification. Carbon emissions generated throughout the full lifecycle of energy facilities locally alter seawater chemistry. This triggers ocean acidification of varying degrees and accelerates the corrosion and degradation of surrounding coral reefs.[1,2,3] If population-averaged datasets are adopted to conduct environmental assessments of ocean acidification impacts, it will inevitably fail to identify fine-scale ecological risks to coral reefs induced by energy-related activities.[4,5] Undoubtedly, this will become one of the critical bottlenecks restricting the green and sustainable development of offshore energy.

This study targets corals from the South China Sea. We adopt large-view macro-lens infrared thermal imaging. The technique reveals inherent microscale heterogeneity in coral skeletal corrosion susceptibility. The findings provide new technical references for ecological impact assessment, layout optimization and environmental risk control of offshore energy facilities. It also helps promote coordinated development between offshore energy exploitation and marine ecological conservation.

HIGH-PURITY PRIMARY ARAGONITE SKELETON OF GONIOPORA FROM THE SOUTH CHINA SEA

The coral sample used in this study was collected from Wuzhizhou Island, Sanya, South China Sea (Figure 1A). Whole-rock X-ray diffraction (XRD) analysis shows that aragonite is the dominant mineral phase, with a content of 88.5%. This matches the typical mineral composition of pristine coral skeletons. Minor impurities including halite (2.3%), clay minerals (2.3%), dolomite (1.9%), quartz (1.2%), K-feldspar (1.1%), calcite (1.1%), plagioclase (0.9%), and gypsum (0.7%) are also detected in the sample (Figure 1B). Plane-polarized and cross-polarized light micrographs show that the images display regular skeletal frameworks and unevenly distributed pore networks, which lay a structural basis for the spatial differentiation of lattice defects (Figure 1C & D).

Multiple techniques are available to evaluate coral corrosion susceptibility at the microscale, such as scanning electron microscopy (SEM), Energy Dispersive Spectroscopy (EDS) and Electron Backscatter Diffraction (EBSD). These methods obtain surface morphology, lattice characteristics, elemental distribution and mineral composition to predict corrosion patterns, which can be further verified by acid corrosion tests.[6,7] Nevertheless, these conventional characterization methods have obvious drawbacks. They are costly and complicated to operate. Most of them require vacuum coating on sample surfaces to improve testing efficiency and success rate. Although coating causes no severe damage to coral compositions and can be partially removed via chemical methods, such pre-treatment changes the original physical and chemical properties of samples. It interferes with subsequent acid corrosion tests and makes it hard to distinguish multiple influencing factors.

Therefore, developing a fully non-destructive, efficient and low-cost method for early assessment of coral corrosion susceptibility is critical to realize refined coordination between offshore energy development and marine ecological protection.

PHYSICOCHEMICAL MECHANISM OF EQUIVALENT BLACKBODY TEMPERATURE AS AN INDICATOR OF CORAL CORROSION SUSCEPTIBILITY

Intact coral skeleton slices were placed in a constant-temperature environment for over one hour to reach complete thermal equilibrium. Large-view macro-lens infrared thermal imaging was then performed. This technique requires no sample pre-treatment. It completes full-area scanning and stitching of centimeter-scale samples within minutes, while fully preserving the original skeletal structure.

Test results (Figure 1E) reveal significant spatial heterogeneity of Equivalent Blackbody Temperature (EBT) within a single coral colony. The EBT ranges from 23.60 °C to 25.60 °C. The overall temperature difference far exceeds the instrument detection precision of 0.03 °C. Clear temperature gradients exist between adjacent skeletal growth units.

All tests were conducted under conditions consistent with our previous studies.[8,9] In this case, EBT is solely governed by the infrared emissivity of materials. The two parameters show a distinct negative correlation: higher local infrared emissivity corresponds to lower EBT.

Our previous studies on silicate minerals have proven a universal rule. Higher diagenetic alteration and weathering lead to denser lattice defects, stronger infrared emission capacity and lower EBT.[8,9] Geochemical acidification is essentially a typical chemical weathering process. Thus, the above rule is applicable to aragonite coral skeletons. More lattice defects in aragonite enhance its infrared absorption and emission, resulting in lower EBT. Meanwhile, lattice defects act as preferred active sites for the acid corrosion of calcium carbonate. Higher defect density reduces the corrosion activation energy of aragonite and makes it more vulnerable to corrosion in acidified seawater. A complete logical chain is established: lower local EBT corresponds to denser lattice defects and higher corrosion susceptibility.

Thanks to the non-destructive nature of thermal imaging, samples can be preserved for long-term tracking and verification after imaging. This forms a complete research workflow: predicting vulnerable zones via non-contact detection first, and then conducting targeted follow-up monitoring.

MICROSCALE HETEROGENEITY IN CORAL CORROSION SUSCEPTIBILITY BASED ON THERMAL IMAGING

Based on a full set of multi-modal images, we conclude that corrosion susceptibility is not uniformly distributed across coral skeletons. It presents patchy and gradient variations along skeletal growth structures.

Large-view plane-polarized and cross-polarized light micrographs (Figure 1C & D) show well-organized coral skeletons. Pore networks form zones of varying density along growth directions. These features control the occurrence and flow of diagenetic fluids, as well as fluid-rock interactions. They lay a structural foundation for the spatial differentiation of lattice defects.

The large-view macro-lens infrared thermal image shows distinct zoning features: Bright warm-colored regions with high EBT (near 25.60 °C) are mainly distributed in the lower half and upper margins of the sample. These areas feature well-ordered aragonite crystals and low-density lattice defects. Their weak infrared emissivity leads to low corrosion susceptibility. They are less likely to dissolve first under local offshore acidification (Figure 1E).

In contrast, cool green regions with low EBT (near 23.60 °C) are concentrated in the upper half of the sample.. These zones contain abundant lattice

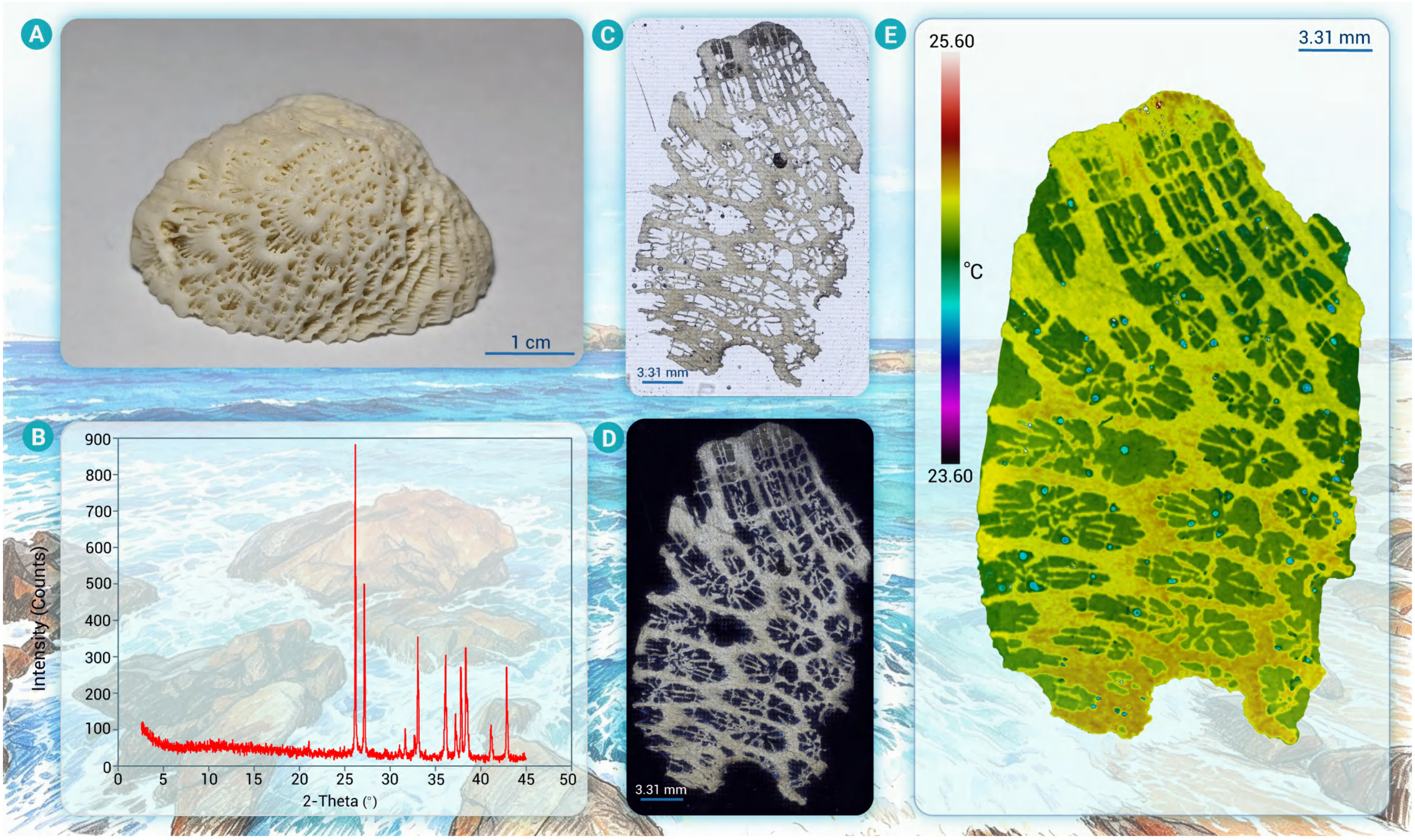

Figure 1. Early detection of coral reef acidification micro-hotspots driven by offshore energy development. (A) Photograph of the intact coral sample collected from the South China Sea; (B) X-ray diffraction pattern, showing dominant primary aragonite with a content of 88.5%, and some minor impurities; (C, D) Plane-polarized and cross-polarized light micrographs; (E) Large-view macro-lens infrared thermal image, with a measured temperature range of 23.60~25.60 °C. The color changes from red for high EBT to purple for low EBT. Dark green areas correspond to the coral pore system, including large corallite cavities, dendritic connected pores and scattered micro-pores. Orange areas represent skeletal matrix with high EBT, which features weak corrosion susceptibility. Bright yellow and light green areas represent matrix with low EBT, acting as acidification micro-hotspots with strong corrosion susceptibility. Sporadic blue spots are residual bubbles formed during thin section preparation, not native skeletal structures.

defects and high infrared emissivity, together with low EBT. They are the micro-hotspots with the highest corrosion susceptibility in the whole colony. Once offshore wind farms and other energy facilities trigger a slight decline in seawater pH, these zones are expected to undergo dissolution first.

INTRASKELETAL HETEROGENEITY AGGRAVATES ECOLOGICAL RISKS FROM OFFSHORE ENERGY DEVELOPMENT

The core contribution of this study is verifying prominent spatial heterogeneity of corrosion susceptibility within individual coral colonies via non-destructive thermal imaging. Coral reef acidification is not a uniform process across the whole reef area. We emphasize the diversity and complexity of ecological risks posed by ocean acidification induced by offshore energy activities.

In environmental impact assessments of energy projects, it is undoubtedly unreasonable to assume that acidification leads to synchronous and homogeneous degradation of entire coral communities. This view is inaccurate. Slight seawater pH decline caused by energy facilities first affects numerous high-susceptibility micro-zones with low EBT. Corrosion gradually spreads and connects along pore networks. It weakens the overall mechanical stability of skeletons and eventually leads to colony mortality. The structural heterogeneity of corals greatly amplifies the destructive effects of local acidification.

Tropical coastal waters host dense offshore oil, gas and wind energy projects. Local corals are already stressed by global background ocean acidification. Superimposed local acidification from carbon emissions, construction disturbance and pile foundation corrosion accelerates corrosion in high-susceptibility micro-zones of coral reefs. It shortens the degradation cycle of coral reef communities.[10]

Coral reef degradation results in biodiversity loss. It also weakens the coastal wave dissipation capacity, and further threatens the economic and ecological sustainability of coastal communities.

NON-DESTRUCTIVE SCREENING TECHNIQUE SUPPORTS GREEN DEVELOPMENT OF OFFSHORE ENERGY

Wide-field macro-lens infrared thermal imaging provides an effective solution to assess ecological impacts of offshore energy development. This technique is non-destructive, rapid, low-cost and easy to popularize.

Full-area detection of a single coral sample takes only several minutes. We can scan a large number of representative coral samples around energy facilities. The proportions of corals with high, medium and low acidification risks in different sea areas can be quantified to evaluate regional acidification levels. Samples after testing can be used for long-term monitoring, in-situ acid corrosion experiments and other follow-up studies.

Based on this method, we propose a new ecological risk management system for offshore energy development to support its green and sustainable progress.

In the site selection phase, thermal imaging surveys are carried out across candidate sea areas. We draw distribution maps of coral acidification vulnerability and avoid areas with highly vulnerable corals. This reduces ecological impacts at the source.

During construction and operation, regular sampling and testing are conducted on surrounding coral reefs. Early damage induced by acidification can be detected in a timely manner. Operators can adjust parameters of energy facilities and adopt targeted ecological protection measures.

Supported by multi-modal characterization, especially large-view infrared thermal imaging, this study confirms obvious microscale heterogeneity in coral skeletal corrosion susceptibility. Based on thermal radiation and crystal corrosion theories, we demonstrate that EBT can serve as a reliable alternative indicator for acidification vulnerability.

This research enriches the theoretical framework for ecological risk assessment of ocean acidification. It provides a potential technical route for site selection optimization and full-cycle ecological supervision of offshore energy projects.

Large-view macro-lens infrared thermal imaging is expected to become an effective tool in the environmental monitoring network for offshore energy development. It facilitates the coordinated achievement of global carbon neutrality goals and coral reef conservation.

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DECLARATION OF INTERESTS

The authors declare no competing interests.