PROJECT NUMBER 231 - AIOLI

AIOLI PhD Research and Training proposal

1. EXCELLENCE

1.1. Pre-proposal's context, positioning and objective(s)

The Humboldt Current System (HCS) in the Southeast Pacific, is one of the most productive marine ecosystems worldwide, accounting for approximately 10–15% of global fish catches while covering less than 0.1% of the ocean surface (FAO 2020). As an eastern boundary current system, it provides a key natural laboratory for examining how long-term warming and deoxygenation influence marine ecosystems and fish-community structure, but may be particularly sensitive to regional climate change. Comparable climate-driven pressures also affect other oceanic regions, notably semi-enclosed basins such as the Mediterranean Sea, where past warm periods were associated with changes in oxygen content, productivity, and ecosystem organization, such as during the sapropel events. In this comparative context, the HCS offers a reference framework for assessing whether ecological responses to warming reflect basin-specific dynamics or more general processes operating across highly contrasting circulation regimes. Within this framework, the **AIOLI project (Ancient Ichthyology & Oceanic LInkages)** investigates climate-driven fish-community reorganization using sedimentary archives.

Despite its high modern productivity, the HCS is currently under strong pressure from both intensive exploitation and ongoing climate change. The anchovy (*Engraulis ringens*), which sustains regional fisheries in Chile and Peru (~25% of the catches) and supports millions of livelihoods, is considered overexploited in several sectors of the system (Carlson et al. 2018; Díaz Vega and Flores Arévalo 2021; Canales and Cubillos 2021). Climate projections indicate that, by the end of the 21st century, the HCS is likely to experience surface warming of up to ~2 °C, accompanied by subsurface oxygen depletion. Such changes are expected to alter fish-community structure, trophic interactions, and the sustainability of fisheries-dependent socio-economic systems.

Understanding how fish communities respond to sustained warming in the HCS remains challenging. Modern observational records are limited in duration to the last decades and strongly confounded by fishing pressure, which complicates the isolation of pure climate-driven signals. The analysis of the last decades has shown the influence of changes in environmental conditions, namely El Niño events and Pacific Decadal oscillations, on the fish catches (Chavez et al. 2003). Sedimentary archives therefore provide a critical alternative for investigating ecosystem responses over timescales encompassing major climate transitions. The Last Interglacial period (LIG; ~130–116 ka) represents a particularly relevant analogue for future warming, as global temperatures during this interval were approximately 1–2 °C higher than present-day values, comparable to projections for the late 21st century under high-emission scenarios (Intergovernmental Panel on Climate Change (IPCC) 2023). However, sedimentary records from the Chilean sector of the HCS remain poorly characterized across most time intervals, including the Holocene, earlier interglacials, and glacial–interglacial transitions.

Recent work on the Peruvian margin demonstrated that LIG warming was associated with a pronounced reorganization of fish communities under warm and oxygen-poor conditions (Salvatteci et al. 2022). During this period, anchovies were nearly absent and were replaced by smaller goby-like and mesopelagic taxa, implying a substantial reduction in the efficiency of energy transfer to higher trophic levels. These findings suggest that continued warming could fundamentally alter the current anchovy-dominated ecosystem. It has been proposed that anchovies may respond to warming by shifting poleward to satisfy their oxygen requirements; however, this hypothesis remains untested due to the absence of LIG fish-community reconstructions from the southern (Chilean) portion of the HCS.

Addressing this question requires overcoming a methodological bottleneck. Traditional ichthyolith analysis relies on manual identification of fish bones and scales under stereomicroscopes, a process that is time-consuming and dependent on specialized taxonomic expertise (Salvatteci et al. 2012), thereby limiting sample throughput and reproducibility. The AIOLI project addresses both the geographic and methodological limitations by adapting automated imaging and classification approaches to ichthyolith analysis. It builds on the SASHIMI (System for Automated Scanning and High-resolution Imaging of MIcrofossils) platform developed at CEREGE for micropaleontological applications (Marchant et al. 2020) extending its use to fish remains. It will be based on a solid taxonomical framework provided by our Chilean biologist colleague from Univ. of Valparaiso, Prof. M. Landaeta who will validate the annotated image dataset produced by the PhD candidate.

By combining automated imaging with artificial intelligence-based classification, the proposed workflow substantially increases analytical throughput while reducing operator dependent subjectivity through quantitative and repeatable morphometric criteria. This approach enables the generation of large, reproducible datasets and allows taxonomic expertise to be focused on ecological interpretation rather than routine identification. In parallel, the project reconstructs past environmental conditions in the Chilean HCS by integrating planktonic foraminiferal assemblages and geochemical proxies, including Mg/Ca thermometry (Chalk et al. 2017), I/Ca as a proxy for dissolved oxygen (Lu et al. 2010; Hess et al. 2025), and δ^{11}B-based carbonate chemistry reconstructions (Chalk et al. 2025). These reconstructions will span the last ~150 kyr, with a primary focus on the LIG.

The main objective of the AIOLI project is to determine whether anchovy populations were sensitive to LIG warming and deoxygenation, and to establish whether this sensitivity resulted in a latitudinal redistribution within the HCS or a system-wide population collapse. Two alternative scenarios are evaluated: (i) a poleward displacement of anchovy populations during LIG warming, leading to higher anchovy abundances in southern (Chilean) margin sediments compared to contemporaneous Peruvian records, or (ii) a collapse of anchovy populations across the system, with fish communities dominated by smaller goby-like and mesopelagic taxa throughout the HCS (Figure 1). These scenarios are tested by comparing fish-community composition derived from ichthyolith assemblages with independently reconstructed environmental parameters.

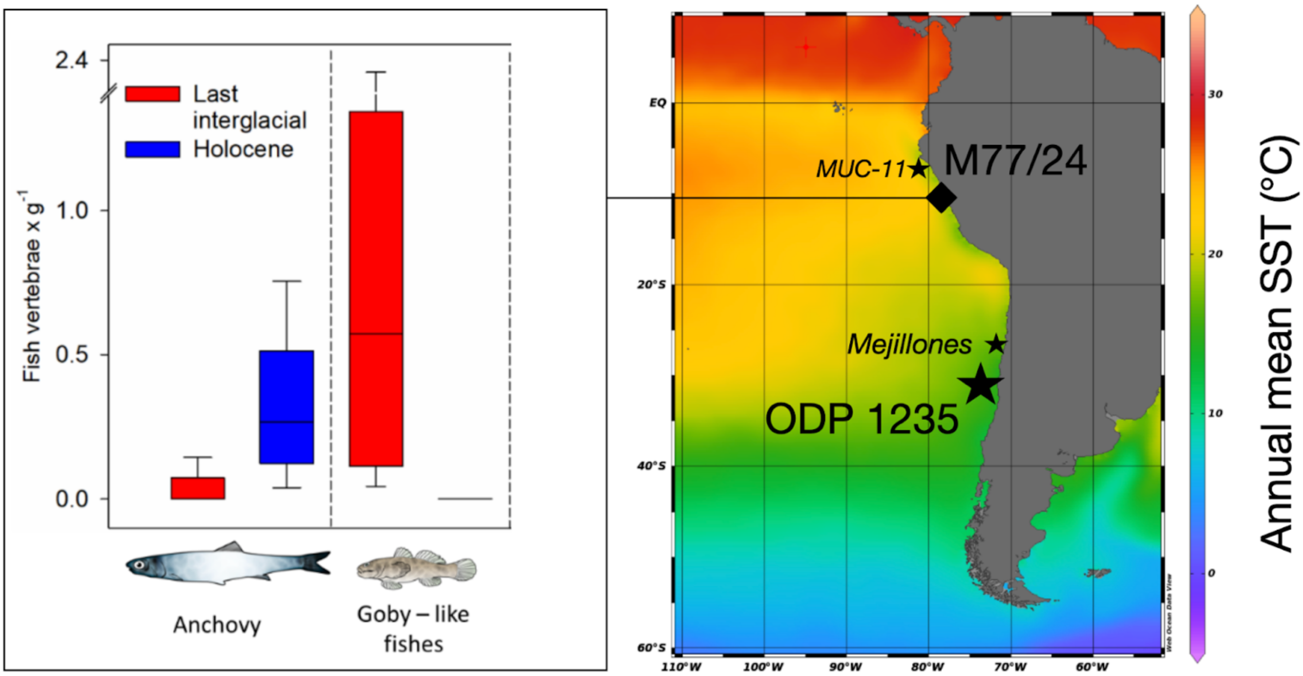

Figure 1 : (left) Estimates of fish vertebrae abundances on the Peruvian margin from the core M77/24 for two groups (anchovies and smaller goby-like fishes), during the Holocene (blue) and during the last interglacial (red) from (Salvatteci et al. 2022); (right) Location of the main deep-sea cores published (M77/24) ; and of interest for the AIOLI PhD proposal (MUC-11 ; Mejillones bay ; and the main site ODP 1235, 1000m deep).

Beyond its primary focus on the HCS, the methodological framework developed in this project is explicitly designed to be transferable. An exploratory application to sediment cores from the north-western Mediterranean Sea is therefore included as a proof-of-concept. This Mediterranean extension does not aim to test anchovy-specific biogeographic responses, but rather to assess whether climate-driven changes in oxygenation and productivity are consistently reflected in ichthyolith-based reconstructions of fish-community structure across contrasting oceanographic regimes. We envision this proof-of-concept study on a sediment core in the Western Mediterranean Sea as a Master 2 project supervised by the doctoral student, to ensure consistent and high quality approaches and to advance their supervision skills. By situating species-specific responses within a broader process-based framework, the project contributes to a more general understanding of how marine ecosystems reorganize under sustained climate forcing.

Overall, the project integrates automated imaging, artificial intelligence, paleoceanographic proxy development, and fish-community reconstruction to provide a quantitative test of climate-driven ecological responses in anchovy-dominated systems during a warm interglacial period. By combining methodological innovation with hypothesis-driven paleoecological analysis, the AIOLI project establishes robust long-term baselines relevant for assessing future fisheries vulnerability under ongoing climate change.

1.2. Interdisciplinary dimension of the project

The AIOLI project is inherently interdisciplinary and relies on the integration of paleoceanography, geochemistry, marine biology, automated imaging, and science communication to address climate-driven reorganization of marine ecosystems. Reconstructing fish-community responses to past warming requires the combined analysis of environmental drivers and biological assemblages preserved in sedimentary archives, an objective that cannot be achieved within a single disciplinary framework (Salvatteci et al. 2022).

Paleoceanography and geochemistry will provide the environmental context necessary to interpret changes in fish-community composition. Past variations in sea-surface temperature, oxygenation, carbonate chemistry, and thermocline structure are constrained using planktonic foraminiferal assemblages (de Garidel-Thoron et al. 2007) and established geochemical proxies, including Mg/Ca thermometry (Chalk et al. 2017), I/Ca as a proxy for dissolved oxygen (Lu et al. 2010; Hess et al. 2025), and δ^{11}B-based reconstructions of seawater carbonate chemistry (Chalk et al. 2025). These quantitative reconstructions are essential for distinguishing climate-driven ecological change from local depositional or taphonomic effects.

Marine biology and ichthyology skills are required to identify fish remains, reconstruct community composition, and relate fossil assemblages to modern ecosystem functioning. Accurate identification of ichthyoliths and fish scales relies on detailed knowledge of fish anatomy and regional species assemblages, particularly in highly productive systems such as the Humboldt Current System, where small pelagic fishes dominate trophic transfer (Salvatteci et al. 2022).

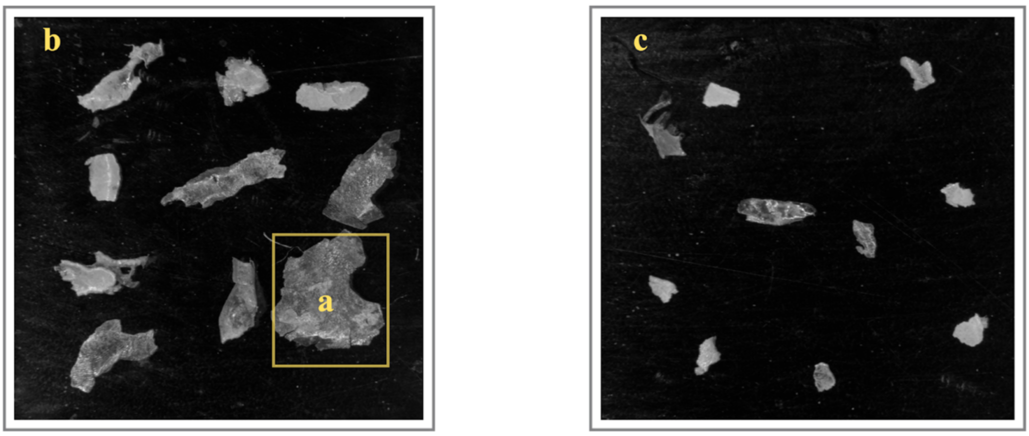

Figure 2 : Images of fish-scales (b) and fish-scales fragments (b) from the sediment core MUC-11 offshore Peru, acquired on the platform MANTA using the same optical setup as the one proposed to be fully automated during the PhD using the SASHIMI automaton (each element is about 300 µm long in b). Images from Alizée Dale M1 internal report.

A central methodological innovation of the AIOLI project lies in the integration of automated imaging and artificial intelligence–based classification with traditional paleoecological approaches. As a proof of concept, a short record of fish scales has been analyzed manually at CEREGE, in a short undated sediment core from the Peruvian margin as part of the Master 1 internship of Alizée Dale (Figure 2). The adaptation of the SASHIMI automated imaging workflow to ichthyolith analysis builds on recent advances in automated micropaleontology, where convolutional neural networks have demonstrated robust performance for microfossil detection and classification (Marchant et al. 2020; Godbillot et al. 2024). Extending these approaches to fish remains enables standardized, high-throughput data acquisition and reduces operator-dependent subjectivity, thereby overcoming a long-standing bottleneck of paleofish research.

The project also includes an intersectoral dimension through targeted science communication and outreach activities. Paleoecological results are translated into accessible formats, such as educational material, stakeholder-oriented briefs, and public presentations, aimed at non-specialist audiences and coastal actors. This approach facilitates the transfer of long-term scientific knowledge beyond academia and supports informed discussion of climate-related risks to marine ecosystems and fisheries sustainability (FAO 2020). This will be led in collaboration with the Parc National des Calanques, through the collaboration with Patrick Bonhomme.

While the primary scientific objectives focus on the Humboldt Current System, the interdisciplinary framework developed in the AIOLI project is explicitly designed to be transferable. The exploratory application to Mediterranean sedimentary archives provides a proof-of-concept for extending ichthyolith-based reconstructions to contrasting oceanographic regimes, where long sedimentary records exist but paleofish community data remain scarce (Pallacks et al. 2025). This transferability promotes integration between research communities and resource management working on different basins and contributes to a broader understanding of climate–ecosystem interactions across spatial and temporal scales.

2. IMPACT (2 pages max)

2.1. Expected impact of the project on the candidate's career

This doctoral project will provide advanced interdisciplinary training at the interface of paleoceanography, marine biology, and automated data analysis, thereby fostering the development of a scientific profile capable of addressing complex climate–ecosystem interactions. By combining expertise in fish-community reconstruction, geochemical proxy development, and artificial intelligence–based imaging workflows, the project supports the acquisition of a rare and highly transferable skill set relevant to both academic research and applied environmental science (e.g. for biomonitoring studies).

Training in paleoceanographic geochemistry and proxy-based climate reconstruction constitutes a central component of the project, and will be led at CEREGE. The analysis and interpretation of proxies such as Mg/Ca, I/Ca, and $\delta^{11}B$ require specialized methodological knowledge and access to advanced analytical facilities. Competence in these techniques enables independent reconstruction of past oceanographic conditions and provides a strong foundation for future research on climate variability and its marine biogeochemistry interactions. This expertise is complementary to training in biology, including ichthyology and ecosystem dynamics, in collaboration with Univ. of Valparaiso, which will allow environmental drivers and biological responses to be interpreted within a coherent analytical framework.

The project further strengthens methodological expertise through the development and application of automated imaging and artificial intelligence–based classification tools, as developed on the MANTA platform at CEREGE. Experience with high-throughput image acquisition, neural-network training and machine-learning techniques, and large dataset management is becoming essential in environmental sciences and related disciplines. By applying these tools to ichthyolith analysis, the project contributes to methodological innovation while providing training in reproducible, transferable research practices.

In addition to technical and analytical skills, the project promotes the development of scientific autonomy and project management competencies. The integration of multiple work packages, international collaboration, and the coordination of analytical, computational, and interpretative tasks contribute to the acquisition of skills essential for independent research careers. These include the ability to design hypothesis-driven studies, manage complex datasets, and synthesize results across disciplinary boundaries, and the supervision of a master student(s).

The project also contributes to the development of communication skills tailored to diverse audiences. By translating long-term paleoecological results into formats accessible to non-specialist stakeholders, including educators and coastal actors, the project supports the ability to communicate scientific findings beyond academic contexts. Such skills are increasingly valued in research environments that emphasize societal relevance, policy making, stakeholder engagement, and interdisciplinary collaboration.

Overall, the AIOLI project is expected to have a lasting impact on the researcher's career by establishing a strong interdisciplinary foundation, methodological versatility, and the capacity to engage with both scientific and societal dimensions of climate-change research. These attributes position the researcher competitively for subsequent postdoctoral research, integration into international research networks, and long-term contributions to the study of climate-driven marine ecosystem change.

2.2. Expected impact for the thematic axis

The AIOLI project primarily addresses the SCHADOC thematic axis **Climate Change and Environmental Challenges** by providing long-term empirical constraints on how marine ecosystems respond to sustained warming and associated changes in oxygenation and acidity. By reconstructing fish-community composition and environmental conditions during a past warm interglacial period, the project contributes to a deeper understanding of climate-driven ecosystem reorganization far beyond the limits of instrumental observations and outside of the impact of anthropogenic biases. This long-term perspective is essential for contextualizing present-day changes and for distinguishing anthropogenic trends from natural climate variability, as most observational and modeling efforts focus on the last ~150 years (e.g. FishMIP : (Blanchard et al. 2024)). A secondary contribution of the project relates to the thematic axis **Artificial Intelligence**, through the adaptation of automated imaging and machine-learning techniques to ichthyolith analysis. While artificial intelligence is not the primary objective, the project builds on the careful application of established classification methods to increase analytical throughput and reproducibility. The resulting image libraries and classified datasets will contribute to methodological development in automated paleoecology and will support future applications in related fields requiring large-scale, standardized image analysis.

From a societal perspective, the project generates knowledge relevant to regions where fisheries sustainability and food security are closely linked to climate variability. By providing long-term baselines for ecosystem response to warming, the project informs discussions on the vulnerability of fisheries-dependent systems under future climate scenarios. Although the project does not aim to produce operational management tools, its results will contribute to the scientific foundation required for evidence-based dialogue and policy on climate adaptation, marine resource use, and ecosystem resilience. More broadly, the project supports cross-cutting objectives aligned with international sustainability frameworks, particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 17 (Partnerships for the Goals).

2.3. Dissemination, exploitation and communication activities planned

Dissemination and communication activities are designed to ensure that the scientific results of the AIOLI project reach both the academic community and non-specialist audiences, while remaining consistent with the exploratory and research-oriented nature of the project. Scientific dissemination will include open-access peer-reviewed publications in international journals (one planned per WP1 to 3), presentations at international conferences (Ocean Science Meeting) ; and the deposition of datasets and image libraries in open-access repositories following FAIR principles (e.g. SeaNoe repository), thereby ensuring transparency, reproducibility, and long-term reuse by the research community.

In addition to academic dissemination, the project includes targeted communication activities aimed at the general public, with a particular focus on the long-term history of fish communities in the Mediterranean Sea and their relationship to past climate variability, in collaboration with the Parc National des Calanques. The Mediterranean proof-of-concept component provides a concrete framework for translating paleoecological results into accessible narratives on how marine ecosystems have responded to climate change over millennial timescales (1000s of years). These activities will emphasize changes in fish fauna composition, ecosystem reorganization, and the relevance of long-term perspectives for understanding current and future environmental change.

A central element of this outreach strategy involves collaboration with the Parc national des Calanques, and in particular with its visitor and interpretation facilities (Maison du Parc), where a new exhibition will provide an opportunity to showcase the approach and framework of the PhD project. Communication actions will include public talks (e.g. Pint of Science), illustrated displays and short format educational materials, and participatory events designed to engage a broad audience, including residents, visitors, and school groups. By linking deep-time sedimentary archives to a contemporary and well-known marine protected area, these activities aim to enhance public awareness of climate-driven ecosystem change and to situate present-day conservation challenges within their changing environmental context.

3. IMPLEMENTATION (2 pages max)

3.1. Work plan

The project is structured over a 36-month period and organized into four interconnected work packages (WPs), designed to ensure a logical progression from methodological development to paleoenvironmental reconstruction, fish-community analysis, and dissemination. Methodological development (WP1) precedes large-scale application, while paleoenvironmental reconstruction and fish-community analysis partially overlap to enable continuous integration of environmental and biological data. An exploratory western Mediterranean component is incorporated as a proof-of-concept, due to the lack of identified sedimentary sequence suitable for high resolution study across the LIG to the Holocene.

3.2. Work packages and tasks

WP1 – Automated ichthyolith imaging and classification framework (Months 1–8)
WP1 focuses on adapting and validating the automated imaging workflow for ichthyolith analysis. Imaging parameters are optimized for fish remains, and a reference image library is constructed using modern and fossil material. Classification algorithms are trained and validated against expert identifications to assess accuracy and reproducibility.
Main tasks: (i) Adaptation of the SASHIMI imaging workflow to ichthyolith size and morphology (preprocessing, background, lighting) (ii) Construction of a curated reference image library (iii) Training and validation of automated classification models (CNN, ViT) (iv) Comparison with manual expert-based identification
Milestone M1 : Validated automated workflow for ichthyolith imaging and classification.

WP2 – Paleoenvironmental reconstruction of the Humboldt Current System (Months 6–20)
WP2 reconstructs past environmental conditions in the Chilean sector of the Humboldt Current System over the last 300 kyrs, with a focus on the Last Interglacial period. Planktonic foraminiferal assemblages and geochemical proxies are analyzed to constrain sea-surface temperature, oxygenation, carbonate chemistry, and thermocline structure.
Main tasks: (i) Foraminiferal assemblage analysis (ii) Geochemical proxy measurements (Mg/Ca, I/Ca, $\delta^{11}B$, stable isotopes) (iii) Reconstruction of paleoenvironmental parameters
Milestone M2 : Completed paleoenvironmental dataset for targeted intervals.

WP3 – Fish-community reconstruction and hypothesis testing (Months 16–28)
WP3 applies the validated automated workflow to reconstruct fish-community composition from ichthyolith assemblages. Community metrics are quantified and compared with environmental reconstructions to test competing hypotheses of latitudinal redistribution versus system-wide collapse of anchovy populations during the Last Interglacial.
Main tasks: (i) Extraction and imaging of ichthyoliths (ii) Automated classification and quality control (iii) Quantification of fish-community composition (iv) Statistical comparison with Peruvian reference records (v) Integration with environmental proxies
Milestone M3 (Month 28): Completed fish-community reconstruction and hypothesis testing.

WP4 – Synthesis, dissemination, and exploratory Mediterranean application (Months 24–36)
WP4 integrates results from previous work packages and focuses on synthesis, dissemination, and communication. An exploratory application of the workflow to Mediterranean sediment cores is conducted as a proof-of-concept, without expanding the scope of the core scientific objectives.
Main tasks: (i) Integrated synthesis of environmental and biological datasets (ii) Preparation of peer-reviewed publications (iii) Exploratory application to Mediterranean sediment archives (Master 2, Institut Ocean funding to be requested) (iv) Development of communication and outreach materials in collaboration with Parc National des Calanques.
Milestone M4 (Month 36): Submission of publications, full PhD manuscript and completion of dissemination activities.

3.3. Training activities

Training is embedded throughout the project and spans analytical, computational, and transferable skills. Methodological training includes geochemical proxy analysis, foraminiferal taxonomy, automated imaging, and

machine-learning–based classification. These activities are complemented by training in scientific writing, data management, and interdisciplinary research practices.
Participation in workshops, seminars, and advanced training modules in paleoceanography, artificial intelligence applied to Earth sciences, and science communication further supports professional development. The combination of hands-on laboratory work and computational training ensures the acquisition of a balanced and transferable skill set.

3.4. Risk management
Several potential risks have been identified and mitigation strategies defined:

- **Delayed access to sediment cores:** Early coordination with core repositories (IODP) and collaborators (Univ. Valparaiso, M. Landaeta Chile ; IMARPE, D. Gutierrez and Univ. Lima Peru ; IRD representative, A. Siffeddine) reduces the likelihood of delays; alternative cores are identified (collab. G. Vargas, Univ. Santiago).
- **Performance limitations of automated classification:** Manual identification protocols provide a fallback option, ensuring continuity of fish-community reconstruction (considered very unlikely).
- **Analytical delays in geochemical measurements:** Parallelization of tasks across work packages minimizes the impact of temporary delays if machines fail simultaneously.

Overall, the modular structure of the work plan ensures that progress can continue even if individual tasks require adjustment.

3.5. Feasibility
The project is feasible within the proposed timeframe for several reasons. The automated imaging platform is already operational and requires adaptation rather than development from scratch. All geochemical proxies employed are well established, with existing analytical protocols in place. The exploratory Mediterranean component is deliberately limited in scope, ensuring that it does not compromise the primary objectives. Finally, the structured work plan, combined with clearly defined milestones and risk mitigation strategies, ensures that the research objectives can be achieved within the duration of the doctoral project.

4. ETHICS SELF-ASSEMENT

This project involves analysis of marine sediment cores and does not involve human subjects or personal data; clinical trials; live animals; human embryos or cells; genetically modified organisms; dual-use research; or third-country research with ethical implications.
Core material will be sourced from French and international repositories ((I)ODP) governed by standard sample request protocols, and Chilean repositories where, according to Chilean law, sediment core sampling for scientific research does not require special ethical permits.

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