Geoconservation of fossiliferous sites in periglacial areas:
the Tyndall Ichthyosaurs study case in Torres del Paine National Park (Chile)

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Geoconservation of fossiliferous sites in periglacial areas: the Tyndall Ichthyosaurs study case in Torres del Paine National Park (Chile)

ABSTRACT

Fossils are fragile and non-renewable, which should be reflected in their management strategies due to its scientific and educational relevance. A wide range of natural physical, chemical and biological processes, together with human access and activities, can threaten the stability of *in situ* paleontological resources, with weathering and erosion generally being the main natural processes affecting the stability of *in situ* fossils, contributing to their destruction. Therefore, it is of vital importance to ensure their preservation over time using geoconservation strategies that are best adapted to the conditions of the fossil site.

This study proposes methods of conservation and monitoring for the Tyndall Glacier fossiliferous site (Chile), which contains almost one hundred ichthyosaur skeletons found to date, articulated and practically complete. Given its very high scientific potential, geoconservation of this fossil locality is essential. However, this site, located in a periglacial area, presents numerous logistical challenges due to its geological, geographical and climatic characteristics, as well as its remoteness, which makes the protection of these fossils extremely difficult. To establish the most appropriate conservation and monitoring methods, the following aspects were analysed: (1) the action of the glacier on the fossils, whose retreat has contributed to the exposure of the ichthyosaurs in the last 80 years; (2) the deterioration factors, divided into four types: climatic (temperature, precipitation, relative humidity, wind and UV radiation), geological (gelifraction, deformation, mineralization and glacial erosion), biological (lichen and mosses), and anthropogenic; (3) the percentage of exposure of the ichthyosaurs; and (4) their state of preservation and damage, in order to determine which present greater risk of destruction and therefore require greater protection. Each of these proposed methods of conservation and monitoring aims to facilitate logistical aspects given the characteristics of this site. In addition, their application depends on the specific conditions of each fossil according to its state of deterioration and its location in the fossil site. The results obtained in this study are crucial to lay the basis for the development of a proper geoconservation strategy.for the Tyndall ichthyosaurs that will ensure their preservation for science, education and future generations.

Key words: conservation, geoconservation, ichthyosaurs, monitoring, paleontological resource.

Geoconservação de sítios fossilíferos em áreas periglaciárias: o caso do estudo dos ictiossauros Tyndall no Parque Nacional Torres del Paine (Chile)

RESUMO

Os fósseis são frágeis e não renováveis, o que se deve refletir nas respetivas estratégias de gestão devido à sua relevância científica e educativa. Um vasto leque de processos naturais físicos, químicos e biológicos, juntamente com o acesso e as actividades humanas, podem ameaçar a estabilidade dos recursos paleontológicos *in situ*, sendo geralmente a meteorização e a erosão os principais processos naturais que afectam a estabilidade dos fósseis *in situ*, contribuindo para a sua destruição. Por conseguinte, é de importância vital assegurar a sua preservação ao longo do tempo, utilizando estratégias de geoconservação que melhor se adaptem às condições das jazidas fossilíferas.

Este estudo propõe métodos de conservação e de monitorização para o sítio fossilífero do glaciar Tyndall (Chile), que contém quase uma centena de esqueletos de ictiossauros, articulados e praticamente completos. Dado o seu muito elevado potencial científico, a geoconservação desta jazida é essencial. No entanto, sua localização numa região periglaciar, apresenta inúmeros desafios logísticos devido às suas caraterísticas geológicas, geográficas e climáticas, bem como ao seu isolamento, o que torna a proteção destes fósseis muito difícil. Para estabelecer métodos de conservação e monitorização mais adequados, foram analisados os seguintes aspectos: (1) a ação do glaciar sobre os fósseis, cujo recuo contribuiu para a exposição dos ictiossauros durante os últimos 80 anos; (2) os factores de deterioração, divididos em quatro tipos: climáticos (temperatura, precipitação, humidade relativa, vento e radiação UV), geológicos (gelifracção, deformação, mineralização e erosão glaciar), biológicos (líquenes e musgos), e antropogénicos; (3) a percentagem de exposição dos ictiossauros, e (4) o seu estado de conservação e de dano. Estes aspetos permitiram determinar quais os fósseis que apresentam maior risco de destruição e que, por isso, necessitam de maior proteção. Cada um dos métodos tem como objetivo facilitar os aspectos logísticos, dadas as caraterísticas deste sítio, sendo que a sua aplicação depende das condições específicas de cada fóssil em função do seu estado de deterioração e da sua localização no sítio fossilífero. Os resultados obtidos neste estudo são fundamentais para lançar as bases de uma estratégia adequada de geoconservação dos ictiossauros de Tyndall que garanta a sua preservação para a ciência, a educação e as gerações futuras.

Palavras-chave: conservação, geoconservação, ictiossauros, monitorização, recurso paleontológico.

Geoconservación de sitios fosilíferos en áreas periglaciares: caso de estudio de los ictiosaurios de Tyndall en el Parque Nacional Torres del Paine (Chile)

RESUMEN

Los fósiles son frágiles y no renovables, lo que debe reflejarse en sus estrategias de gestión debido a su relevancia científica y educativa. Una amplia gama de procesos físicos, químicos y biológicos naturales, junto con el acceso y las actividades humanas, pueden amenazar la estabilidad de los recursos paleontológicos *in situ*, siendo la meteorización y la erosión generalmente los principales procesos naturales que afectan la estabilidad de las fósiles *in situ*, contribuyendo a su destrucción gradual o catastrófica. De acuerdo con ello, resulta de vital importancia asegurar su preservación a través del tiempo utilizando las estrategias de geoconservación que mejor se adapten a las condiciones del sitio fosilífero.

En este trabajo se proponen métodos de conservación y monitoreo para el sitio fosilífero del glaciar Tyndall (Chile), que alberga casi cien esqueletos de ictiosaurios hasta la fecha, articulados y prácticamente completos. Dado su elevado potencial científico, la geoconservación de esta localidad fósil es esencial. Sin embargo, este yacimiento, ubicado en un área periglacial, presenta numerosos desafíos logísticos debido a sus características geológicas, geográficas y climáticas, además de su lejanía, lo que dificulta la protección de estos fósiles. Para establecer los métodos de conservación y monitoreo más adecuados se analizaron los siguientes aspectos: (1) la acción del glaciar sobre los fósiles, cuyo deshielo ha contribuido a la exposición de los ictiosaurios en los últimos 80 años; (2) los factores de deterioro, divididos en cuatro tipos: climáticos (temperatura, precipitaciones, humedad relativa, viento y radiación UV), geológicos (gelifracción, deformación, mineralización y erosión glaciar), biológicos (liquen y musgos), y antrópicos; (3) el porcentaje de exposición de los ictiosaurios; y (4) su estado de preservación y daño, a fin de determinar cuáles presentan mayor riesgo de destrucción y por ende requieren de mayor protección. Cada uno de los métodos propuestos busca facilitar los aspectos logísticos dada las características del sitio fosilífero. Además, su aplicación depende de las condiciones específicas de cada fósil de acuerdo con su estado de deterioro y su ubicación dentro del yacimiento. Los resultados obtenidos en este trabajo resultan cruciales para sentar las bases del desarrollo de una buena estrategia de geoconservación en los ictiosaurios del Tyndall que aseguren su preservación para la ciencia, la educación y las futuras generaciones.

Palabras clave: conservación, geoconservación, ictiosaurios, monitoreo, recurso paleontológico.

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I. INTRODUCTION

1.1. General background

1.1.1. Paleontological heritage and its protection

Fossils provide us with direct and tangible links to the prehistoric past (Hardes, 2014), so those sites that possess paleontological treasures, whether local, national, or international, are essential for preserving and understanding the history of life on Earth and providing materials for current and future scientific research (Lipps, 2009). Unfortunately, paleontological resources are fragile and non-renewable, which should be reflected in their management and conservation strategies (Santucci et al., 2009). A wide range of natural physical, chemical, and biological processes, along with human access and activities, can threaten the stability of *in situ* paleontological resources. Erosion and weathering are generally the main natural processes affecting the stability of *in situ* fossils, contributing to their gradual or catastrophic destruction (Santucci et al., 2009; Peng et al., 2020). This diminishes their scientific and educational value, and is irreplaceable (DeBlieux et al., 2012). Therefore, it is vitally important to ensure their physical protection through conservation techniques that help to slow down or diminish the effect of these natural processes on fossils. However, the preservation of fossil material can be complex, especially when preserved *in situ*. Fossilized bones are usually excavated and removed from the site for conservation in laboratories and storage or display in museums. However, there are cases where there is no alternative to displaying them *in situ*, such as when the size of the site or the large number of identical species makes the extraction of almost all the remains too costly and unnecessary (Agnew & Demas, 2016). It is then necessary to ensure their preservation over time, using geoconservation strategies that are best suited to the conditions of the fossiliferous site.

1.1.2. Geoconservation

Geoconservation is a discipline that emerged from the need to protect the elements of geodiversity that are affected by various types of threats (Wignall, 2002), where geodiversity corresponds to the variety of elements of geological origin (rocks, minerals, fossils, sediments, geological features and soils), together with the natural processes that form and alter them (Wignall, 2022). When elements of geodiversity are important for conservation, they are referred to as geoheritage (Gray, 2013). Consequently, geoconservation seeks to ensure the conservation of geoheritage. It encompasses the stages of selection, characterization, quantification, protection (legal or *in situ*), valuation, dissemination and monitoring of geoheritage (Brilha

2005; Henriques et al., 2011), as well as the recording and rescue of data or specimens of features and sites threatened with loss or damage (Larwood et al., 2013).

1.1.3. Geoconservation in Chile

In accordance with a study by Benado et al. (2019), despite the fact that Chile has comparative advantages in terms of geodiversity due to its geological characteristics, it presents significant delays in geoconservation matters compared to European and even South American countries. In fact, the dimension and relevance of the national geological heritage is still unknown (Benado et al., 2019). Possible causes for this underdevelopment are: the lack of public policies in geoconservation, the scarce collaboration between institutions, and the limited knowledge of the academic and professional world in Earth Sciences about what to conserve and how to conserve (Benado et al., 2019). Thus, it is necessary to start implementing measures to ensure the geoconservation of our national heritage for science, education, tourism, and future generations.

1.1.4. Ichthyosaurs from the Tyndall locality

Since 2004, paleontological expeditions to the Tyndall Glacier, in Torres del Paine National Park, Magallanes and Chilean Antarctica Region, have resulted in the discovery of almost one hundred ichthyosaur skeletons to date, articulated and practically complete (Pardo-Pérez et al., 2022). The ichthyosaurs are exposed in the rocks as a consequence of the continuous melting of the Tyndall glacier, caused by climate change (Pardo-Pérez et al., 2022). Due to its climatic characteristics, the area can be considered a periglacial zone. Periglacial environments are those found in a cold climate, typically near glaciated regions, and which are subject to intense cycles of freezing and thawing of surface sediments (Davis, 2023). The rocks in this area have been assigned to the Zapata Formation, of Upper Jurassic (Titonian) to Lower Cretaceous (Berriasian to Albian) age, a unit that in turn is part of the Rocas Verdes Basin (Stinnesbeck et al., 2014; Pardo-Pérez, 2015). In addition to the ichthyosaurs found at the locality, the associated fauna includes ammonites, belemnites, inoceramids and numerous ganoid teleost fishes and actinopterygians (Pardo-Pérez, 2015). Given its incredible scientific potential, geoconservation of this fossil locality through conservation and monitoring methods is essential. However, this location presents numerous logistical challenges due to its geological, geographical and climatic characteristics (intense rainfall, temperature changes and winds that can exceed 100 km/h), in addition to the size of the site and its remoteness, which makes it extremely difficult to protect these fossils.

1.1.5. General characteristics of ichthyosaurs

Ichthyosaurs, belonging to the order Ichthyosauria, were a group of aquatic reptiles that inhabited the Mesozoic seas, between the Lower Triassic and Lower Upper Cretaceous (90-250 million years ago), as evidenced by their distribution and fossil record (McGowan & Motani, 2003; Motani, 2009; Pardo-Pérez, 2015). Ichthyosaurs are known in rocks from Europe, North America, South America, Asia and Australia (McGowan & Motani 2003). However, the ichthyosaur record in the southern hemisphere is sparse compared to the northern hemisphere (Pardo-Pérez, 2015). This comes mainly from Late Jurassic and Early to Late Cretaceous localities in Australia, Argentina, Colombia, Madagascar and Chile (Pardo-Pérez et al., 2012; Stinnesbeck et al., 2014; Pardo-Pérez, 2015), including an isolated ichthyosaur tooth in Antarctica (Hikuroa, 2009).

Ichthyosaurs can be easily distinguished from other Mesozoic marine reptiles by their elongated jaw bones and morphology, similar to the body shape of a dolphin or whale (McGowan & Motani 2003). Ichthyosaurs possessed a fusiform body, two pairs of fin-like limbs, a dorsal fin for stabilization and a caudal fin for thrust generation (Pardo-Pérez, 2015). Their eyeballs were larger relative to the orbital part of the skull than those of any other vertebrate, indicating very sensitive vision in low-light environments and at great depth (Motani et al., 1999). Like reptiles, they needed to emerge to breathe atmospheric air (Pardo-Pérez, 2015). They were viviparous, as the construction of their locomotor apparatus made terrestrial locomotion impossible and, therefore, laying eggs on land was not an option (Seeley, 1878; Motani, 2005). Ichthyosaurs may have been able to dive to depths greater than 600 meters (Motani et al., 1999). From the gut contents identified in some specimens, ichthyosaurs fed on fish, belemnites and bivalves (Pardo-Pérez, 2015), but pterosaur bones and turtles have also been detected within some specimens (Fischer et al., 2011a; Stinnesbeck et al., 2014), indicating opportunistic feeding behaviour (Fischer et al., 2011b). According to Bardet (1992), ichthyosaurs are considered one of the reptiles best adapted to open marine life during the Jurassic and Cretaceous.

1.2. Problem statement

In general, there is a lack of information on methods of *in situ* physical protection of paleontological heritage to ensure its geoconservation, but given its importance there are scientific, intellectual and legal reasons to conserve and monitor fossils (Santucci et al., 2009). According to authors such as DeBlieux et al. (2012), the most common methods of fossil protection are 1) shelter construction and 2) excavation. However, neither of these techniques is completely feasible in this paleontological locality due to the previously mentioned characteristics.

Since 2010, five specimens have been excavated at the Tyndall fossil locality, the most recent and important being specimen MHNRS-Pa-1, excavated at the edge of the glacier during March and April 2022 and corresponding to the first complete ichthyosaur excavated in Chile (Pardo-Pérez et al., 2025). The importance of this specimen lies in the fact that it preserves its gastrointestinal contents and is the only Hauterivian (131 Ma) ichthyosaur documented to date that contains the articulated skeleton of a preserved foetus (Pardo-Pérez et al., 2025). However, despite numerous efforts to protect this paleontological heritage for science and education, there are still numerous ichthyosaur fossils in the locality exposed to constant erosion and weathering (Pardo-Pérez et al., 2025), as not all of them can be excavated to ensure their protection, because the task would be extremely complex and costly. For this reason, this work aims to propose methods of conservation and monitoring of paleontological sites that fit the conditions of this fossiliferous site, essential processes to ensure the development of a proper geoconservation strategy. These methods are aimed at mitigating the effects of erosion and weathering on the ichthyosaurs of the Tyndall locality, in order to slow down their deterioration and protect them, as well as to evaluate the stability and condition of the fossils *in situ* over time. It is also important to emphasize that these methods seek to facilitate logistical aspects in terms of transportation and, specially, must be environmentally friendly, given that the Tyndall locality is located in the protected area of the Torres del Paine National Park. To this end, this work analyses the degree of exposure of the ichthyosaurs and their state of preservation, in order to determine the level of damage to the specimens, associated with the processes of erosion and weathering to which they have been exposed since the melting of the glacier. This, together with the analysis of various deterioration factors (climatic, geological, biological and anthropogenic), will help us determine a geoconservation strategy to preserve these paleontological resources.

1.3. Objectives

1.3.1. Main objective

To propose geoconservation measures for the ichthyosaurs of the Tyndall fossil site in Chile, involving their conservation and monitoring, considering the deterioration factors that affect them, their degree of exposure and preservation state, as well as the logistical difficulties presented by the study area, analysing their advantages and disadvantages.

1.3.2. Specific objectives

- Analyse how the retreat of the Tyndall glacier has contributed to the exposure of the ichthyosaurs and estimate the time it takes for the fossil to be destroyed since glacial retreat.

- Identify and analyse the main deterioration factors caused by erosion and weathering affecting the ichthyosaurs from the Tyndall fossil locality.
- Analyse the percentage of exposure of each ichthyosaur specimen from the Tyndall fossil locality to determine which present the greatest risk of destruction.
- Analyse the state of preservation of the Tyndall ichthyosaurs to determine which specimens require greater protection.
- Propose methods of *in situ* conservation and monitoring of paleontological sites that allow the development of a proper geoconservation strategy in the study area.

II. MATERIALS AND METHODS

The development of this research project was divided into a stage of bibliographic compilation and cabinet work using the available material.

This material corresponds to data such as geographic coordinates, photographs, photogrammetry, drawings, and anatomical information of the 87 ichthyosaur skeletons found during field campaigns from 2004 to 2024. Of these, we officially worked with 60 specimens, corresponding to those with the most detailed anatomical information and best photographs, including the specimen MHNRS-Pa-1 excavated in 2022. The last one was used as an anatomical reference as it presents the most completely exposed skeleton in the area.

2.1. Characterization of the study area

2.1.1. Location and access

The study area corresponds to the locality of the Tyndall Glacier, which covers an area of approximately 7.5 km^2. It is located in the Torres del Paine National Park (Figure 1), Province of Última Esperanza, Region of Magallanes and Chilean Antarctica, specifically in the Andes Mountains in Southern Patagonia (between 51°58 "S and 72°57" W), 60 km from the city of Puerto Natales and 301 km from the city of Punta Arenas.

The transportation to the park is by bus or car from Puerto Natales, following route 9. Once at the park entrance, there is a 27 km hike (~ 8 hours) to the camping area. Then, from there it is necessary to climb a rock wall and walk for another hour to the fossil site.

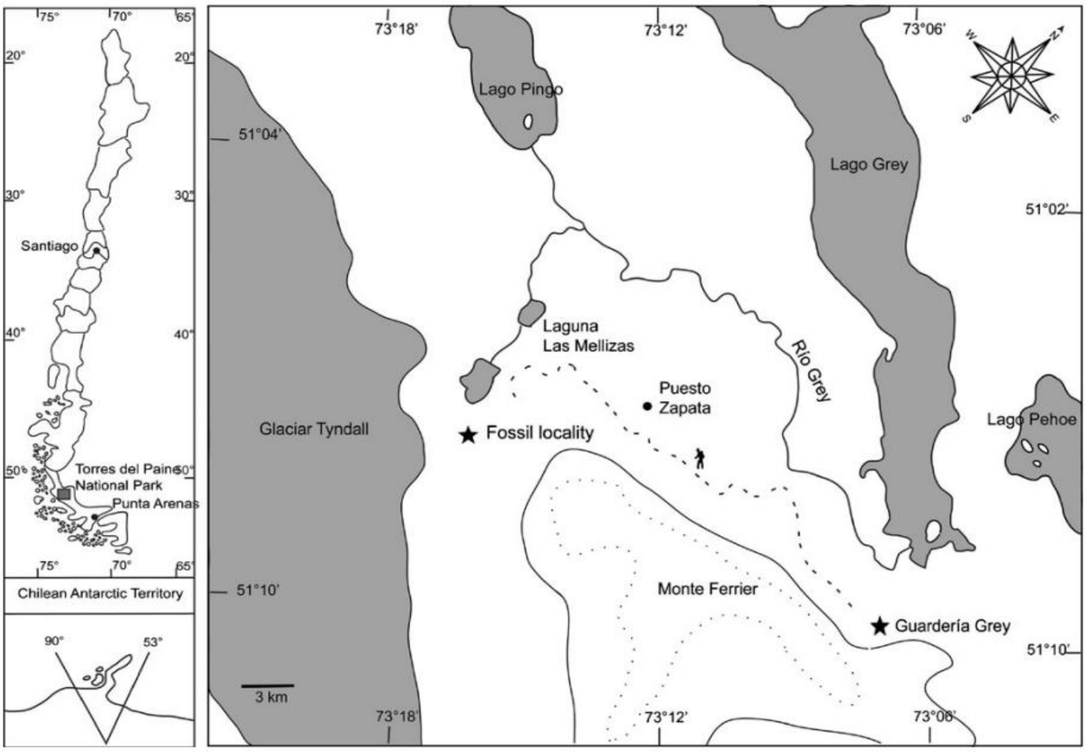

Figure 1. Map with the location of the fossil locality in Torres del Paine National Park, Chile. Extracted from Pardo-Pérez et al. (2012).

2.1.2. Geology of the area

According to Fildani & Hessler (2005), the Mesozoic evolution of the Andean margin in Southern Patagonia is recorded in two formations: the Zapata Formation and the Punta Barrosa Formation, which are now part of the fold-thrust belt (Figure 2).

In the Upper Jurassic an extension process began that affected the Última Esperanza Province, resulting in the deposition of the Tobifera Formation of marine volcanoclastic origin and the eventual formation of the Rocas Verdes Basin, of oceanic origin (Fildani & Hessler, 2005). This basin would represent an extreme case of extension (rifting) that progressed to the rupture of the continental crust associated with the intense magmatism experienced by the Andean margin (Mpodozis & Ramos, 2008). The floor of this basin corresponds to the predominantly mafic igneous complex Sarmiento Ophiolite, which includes pillow basalts and mafic dykes (Allen, 1982; 1983). The rifting phase that gave rise to the Rocas Verdes basin culminated in a stage of thermal subsidence and a marine transgression on the Andean margin in the Upper Jurassic to Lower Cretaceous (Mpodozis & Ramos, 2008).

The rocks in the study area have been assigned to the Zapata Formation, of Upper Jurassic (Tithonian) - Early Cretaceous (Berriasian to Aptian-Albian) age (Stinnesbeck et al., 2014; Pardo-Pérez, 2015). The Zapata Formation was deposited in the Rocas Verdes Basin, during the thermal subsidence stage, in an inferred shallow marine environment (Wilson, 1991). The formation is composed mainly of gray to black shales, with disseminated pyrite, and interbedded thin sandstone layers. This sequence represents a hemipelagic and low-oxygen depositional environment in water at least 2500 m deep, in a slope environment and probably associated with an active submarine canyon (Stinnesbeck et al., 2014). The fossiliferous unit with ichthyosaurs is at least 80 meters thick (Stinnesbeck et al., 2014).

Subsequently, towards the Middle Cretaceous, the regime changes from extension to contraction. The onset of Andean contraction causes a series of changes in depositional regimes and sediment dispersal patterns, which give rise to the formation of the Magellanic foreland basin, represented by the sediments of the Punta Barrosa Formation, of Upper Cretaceous age. This formation records the evolution of a belt of folds and thrusts, and indicates that towards the end of the Mesozoic the Andean margin experienced a remarkable crustal shortening (Fildani & Hessler, 2005).

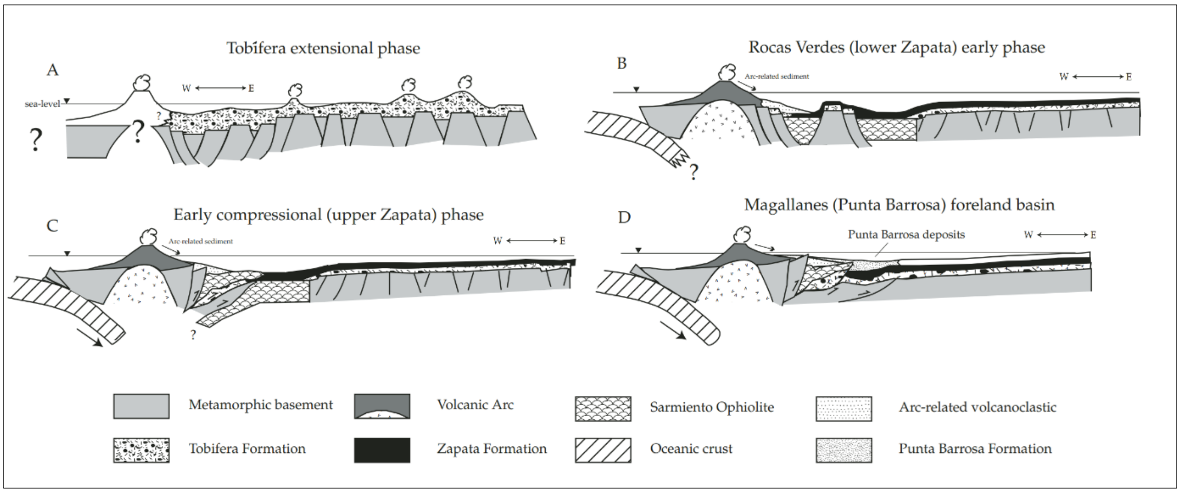

Figure 2. Evolution of the Rocas Verdes-Magallanes basin geometry scheme. (A) Tobiferous phase (Upper Jurassic) with extensional phase and crustal stretching. (B) Emplacement of oceanic crust and formation of structurally controlled rift sub-basins. (C) Early inversion of the basin. (D) Final formation of the Magellanic foreland basin. Extracted and edited from Fildani & Hessler (2005), modified from Wilson (1991).

2.2. Methods

2.2.1. Tyndall glacier melt curves maps

In order to know when the ichthyosaur fossils were exposed on the surface and therefore susceptible to erosion and weathering, a map was created with the melting curves of the Tyndall glacier, which includes the 87 ichthyosaur skeletons found to date, including those that have been excavated. To make the map, satellite images from Google Earth, from the years 1970 (01 January), 1985 (31 December), 2013 (20

November), 2016 (02 March), 2018 (18 October) and 2024 (12 December 2024), were used to delimit the curves of the glacier front. To obtain the 1945 glacial curve, the work of Rivera & Casassa (2004) was used as a reference, which was obtained after georeferencing a map of the authors. QGIS software was used to process the data and prepare the map. It should be noted that the months in which the satellite images were captured correspond to the spring and summer seasons, so the position of the glacier in those periods may have been affected.

2.2.2. Deterioration factors

The extrinsic factors that constantly contribute to the weathering and erosion of the rock and fossil material of the Tyndall locality have been divided into four types: climatic, geological, biological and anthropic. This analysis was performed using the data and bibliographic information available for the area, and field observations recorded in different annotations and photographs taken between the years 2004-2024. In addition, the 10 Deterioration Factors (ABC Method) proposed by the Canadian Conservation Institute in collaboration with the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM, 2016), which can be extrapolated to paleontological sites, were taken into account. These factors are: Physical Forces, Theft and Vandalism, Fire, Water, Pests, Infrared (IF) and Ultraviolet (UV) Light, Inadequate Temperature, Inadequate Humidity, Dissociation, and Contaminants.

- Climatic factors: were determined from meteorological data extracted from the DGA (Dirección General de Aguas) and DGAC (Dirección General de Aeronáutica Civil), from the Tyndall and Teniente Gallardo stations respectively, for the period 2010-2024, covering a period of 14 years, although depending on the parameter analysed, the period may vary. It should be noted that the years analysed correspond to those with the most complete meteorological data. The NomadSeason website, which has meteorological information worldwide, was also reviewed. The parameters reviewed correspond to: Temperature (daily and monthly average), Accumulated Precipitation (daily and monthly), Relative Air Humidity (monthly and annual average), Wind Speed (annual) and UV Radiation (general trend based on monthly and annual averages).
- Geological factors: were determined based on field observations and available bibliographic information on the geology of the site. The works of Fildani & Hessler (2005) and Stinnesbeck et al. (2014) stand out. The geological factors analysed based on the characteristics of the area and the fossils are: Gelifraction, Deformation, Glacial Erosion and Mineralization (the latter, in the case of the presence of pyrite, corresponds to the only intrinsic deterioration factor considered in this work).

- **Biological factors:** were determined from field observations and available bibliographic information. These biological factors of deterioration are: lichen and moss. Regarding these, the works of Huereca et al. (2018) and Velandia (2019), which present information on both factors, stand out.
- **Anthropic factors:** determined based on the geographic conditions in which the locality is located, its access and a series of regulations imposed in accordance with Law No. 17,288 for the protection of National Monuments and Law No. 21,600 of the Biodiversity and Protected Areas Service and the National System of Protected Areas, with emphasis on prohibitions and use of Protected Areas.

With the information and data obtained, a list was created that summarizes the main deterioration factors that have contributed to the deterioration and loss of the fossil material of the locality over the years.

2.2.3. Exposure percentage calculation

The calculation of the percentage of exposure of the 60 ichthyosaurs used for the study was performed based on their exposed anatomical elements, using as reference the most complete specimen MHNRS-Pa-1, and the reference literature by: Pardo-Perez et al. (2018, 2018a, 2025), Cleary et al. (2015) and Beardmore et al. (2012). This was done to determine which fossils present the greatest risk of destruction, considering that those with the highest degree of exposure are those most susceptible to destruction by natural action.

To calculate the percentage of exposure of each ichthyosaur found at the Tyndall locality, the analysis of Beardmore et al. (2012) was modified, in which the skeleton of a complete ichthyosaur model was divided into six sections: (1) Skull, (2) Pectoral elements (including forelimbs), (3) Pelvic elements (including hind limbs), (4) Ribs, (5) Anterior vertebral column and (6) Posterior vertebral column. However, for this study the anatomical units were defined according to Pardo-Pérez et al. (2018a), and the gastralia unit was included separately from the ribs, considering that specimen MHNRS-Pa-1 has good preservation of this unit. In addition, an eighth unit was added for those ichthyosaur vertebrae that could not be categorized with certainty within the anterior or posterior section of the vertebral column, being called "Uncertain vertebrae". So the division used in this study is the following: (1) Skull; (2) Forelimb and pectoral girdle; (3) Hind fin and pelvic girdle; (4) Ribs; (5) Gastralia; (6) Anterior vertebral column; (7) Posterior vertebral column, and (8) Uncertain vertebrae.

Figure 3 corresponds to an ichthyosaur model divided into the 8 units defined for this work.

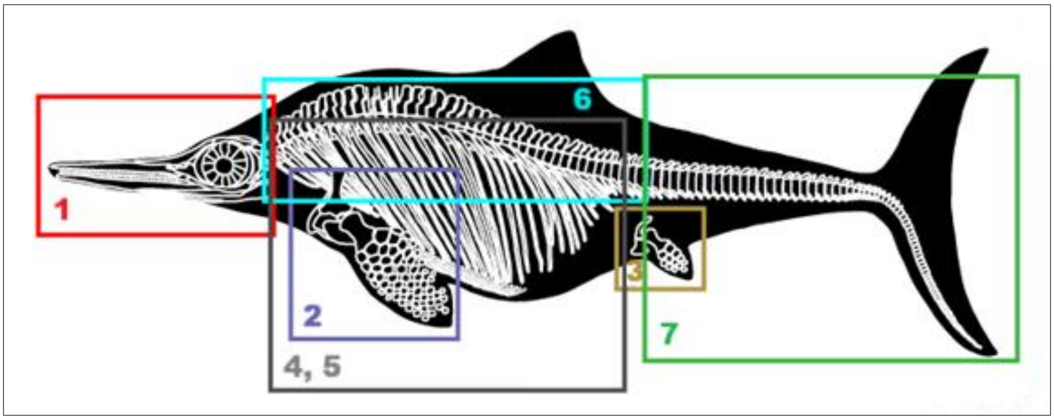

Figure 3. Divisions assigned in the skeleton of a complete ichthyosaur model. For representation, each division was coloured with a number and a square of the same colour. 1: Skull, 2: Forelimb and pectoral girdle, 3: Hind fin and pelvic girdle, 4: Ribs, 5: Gastralia, 6: Anterior vertebral column, and 7: Posterior vertebral column. Unit 8 (Uncertain vertebrae) is not included in the figure but encompasses sections 6 and 7. Modified from Beardmore et al. (2012).

Based on the previous, Tables 1-8 were created, taking as references the anatomical units of Cleary et al. (2015), Pardo-Pérez et al. (2018, 2018a) and of the specimen MHNRS-Pa-1 (Pardo-Pérez et al., 2025).

Each table presents a score from 0 to 4, with a value in percent assigned. In this way, each ichthyosaur was assigned a score and, therefore, a percentage according to its exposed anatomical elements present. The final exposure percentage corresponds to the average percentage obtained from each section.

Unit 1: Skull		
Score	Exposition (%)	Criteria
4	100%	Complete. All elements observed
3	75%	Good exposition (only 1-3 elements not exposed)
2	50%	Moderate exposition (≈1/2 elements observed)
1	25%	Limited exposition (only 1-3 elements exposed)
0	0%	No exposed skull elements

Table 1. Unit 1: Skull. Based on the criteria of Cleary et al. (2015) and Pardo-Pérez et al. (2018).

Unit 2: Forelimb and pectoral girdle		
Score	Exposition (%)	Criteria
4	100%	5 elements exposed (coracoids, clavicle, scapula, humerus, forefin elements)
3	75%	4 of the 5 elements exposed
2	50%	3 of the 5 elements exposed
1	25%	1-2 of the 5 elements exposed
0	0%	No exposed pectoral elements

Table 2. Unit 2: Forelimb and pectoral girdle. Based on the anatomical unit definition criteria of Pardo-Pérez et al. (2018a).

Unit 3: Hind fin and pelvic girdle		
Score	Exposition (%)	Criteria
4	100%	5 elements exposed (ilium, ischium, pubis, femur, hindfin elements)
3	75%	4 of the 5 elements exposed
2	50%	3 of the 5 elements exposed
1	25%	1-2 of the 5 elements exposed
0	0%	No exposed pelvic elements

Table 3. Unit 3: Hind fin and pelvic girdle. Based on the anatomical unit definition criteria of Pardo-Pérez et al. (2018a).

Unit 4: Ribs		
Score	Exposition (%)	Criteria
4	75-100%	51-66 of the 66 exposed ribs
3	50-75%	34-50 of the 66 exposed ribs
2	25-50%	18-33 of the 66 exposed ribs
1	10-25%	8-17 of the 66 exposed ribs
0	0-10%	0-7 of the 66 exposed ribs

Table 4. Unit 4: Ribs. Based on the number of exposed ribs of specimen MHNRS-Pa-1 and the criteria for definition of anatomical units in Pardo-Pérez et al. (2018a).

Unit 5: Gastralia		
Score	Exposition (%)	Criteria
4	75-100%	28-36 of the 36 exposed gastralia
3	50-75%	19-27 of the 36 exposed gastralia
2	25-50%	10-18 of the 36 exposed gastralia
1	10-25%	5-9 of the 36 exposed gastralia
0	0-10%	0-4 of the 36 exposed gastralia

Table 5. Unit 5: Gastralia. Based in the maximum account of exposed gastralia observed in MHNRS-Pa-1. This unit has been included as an additional one for this study.

Unit 6: Anterior vertebral column		
Score	Exposition (%)	Criteria
4	75-100%	36-46 of the 46 vertebrae
3	50-75%	24-35 of the 46 vertebrae
2	25-50%	13-23 of the 46 vertebrae
1	10-25%	6-12 of the 46 vertebrae
0	0-10%	0-5 of the 46 vertebrae

Table 6. Unit 6: Anterior vertebral column. Based on the number of presacral vertebrae exposed in MHNRS-Pa-1 and the criteria for anatomical unit classification of Pardo-Pérez et al. (2018a).

Unit 7: Posterior vertebral column		
Score	Exposition (%)	Criteria
4	75-100%	71-93 of the 93 vertebrae
3	50-75%	48-70 of the 93 vertebrae
2	25-50%	24-47 of the 93 vertebrae
1	10-25%	10-23 of the 93 vertebrae
0	0-10%	0-9 of the 93 vertebrae

Table 7. Unit 7: Posterior vertebral column. Based on the number of caudal section vertebrae exposed in MHNRS-Pa-1 and the citeria for anatomical unit classification of Pardo-Pérez et al. (2018a).

Unit 8: Uncertain vertebrae		
Score	Exposition (%)	Criteria
4	75-100%	105-139 of the vertebrae
3	50-75%	71-104 of the vertebrae
2	25-50%	36-70 of the 139 vertebrae
1	10-25%	15-35 of the 139 vertebrae
0	0-10%	0-14 of the 139 vertebrae

Table 8. Unit 8: Uncertain vertebrae, for ichthyosaurs whose vertebrae cannot be classified as either presacral or caudal. Based on the total number of vertebrae of specimen MHNRS-Pa-1.

2.2.4. Fossil preservation state

In order to propose adequate geoconservation measures, it is necessary to know the state of preservation of the fossil material in the study area. For this purpose, an analysis table was prepared that includes a series of useful parameters to characterize the state of preservation of the ichthyosaurs. These parameters were selected from the photographs analysed and taking into account the deterioration factors defined above. The ICOMOS-ISCS Illustrated Glossary of stone deterioration forms was also used (Garcia de Miguel, 2011). These parameters are defined below:

- Cracks: correspond to fractures and fissures affecting the fossil material and the respective rock. This parameter was further subdivided into (1) empty cracks, and (2) filled cracks (generally filled with mineral, but can also be filled with sediment or biological material).
- Erosion: corresponds to abrasion, wear and exposure of the fossiliferous material. This parameter was subdivided into (1) detachment/lost (loss and/or detachment of the fossil material in the rock), (2) fossil erosion (corresponds to the erosion of the fossil layer by the action of glacial retreat, thanks to which we can see the fossil on the surface, together with the constant erosion associated with the climatic factors described previously), and (3) glacial striations (marks and grooves associated with the passage of the glacier over the rock).

- **Visible mineralization:** correspond to minerals that can be appreciated visibly through photographs and in the field (without chemical analysis), and that contribute to the deterioration of the fossil material. These are (1) oxides, (2) carbonates, (3) pyrite, and (4) others (for those minerals that have been difficult to identify from visual analysis).
- **Biological colonization:** are those biological elements that have proliferated both in the rock and in the fossil, and that have contributed to its deterioration. These are mainly (1) lichen and (2) moss.

Once the parameters to be analysed were defined, a point system was created to assign a value to each of these parameters. The point system is as follows: 0 (not present), 1 (stable) and 2 (unstable). It should be noted that this is a qualitative and subjective analysis, which does not represent quantity, but depends on the general state of the fossil material. For example, if the rock containing the fossil presents fractures that are visibly affecting the paleontological material, it is classified as "unstable" and therefore has 2 points. On the other hand, if the rock presents a couple of fractures that do not seem to cause considerable damage to the paleontological material, it is classified as "stable" and has 1 point. In the same way, if the rock does not present visible fractures, it is catalogued as "not present" and has 0 points. The same criterion applies for each of the parameters. Figure 4 below represents the previous example.

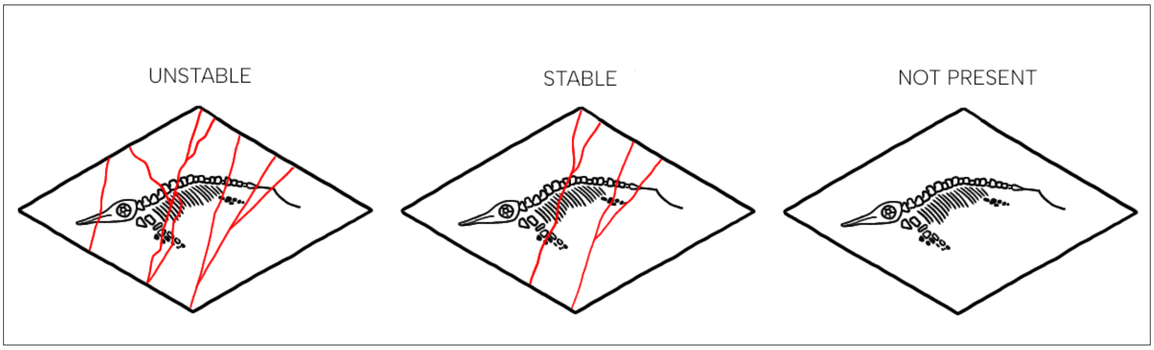

Figure 4. Representation of the scoring system of the State of Preservation table, using as an example the parameter "cracks", where "unstable" corresponds to value 2, "stable" corresponds to value 1, and "does not present" corresponds to value 0. Author's own elaboration.

2.2.5. Damage maps elaboration

Based on the percentage of exposure of the ichthyosaurs and their state of preservation, damage maps were made to locate the elements that are contributing to their deterioration. The parameters analysed for the maps are: presence of cracks, fossil erosion, loss of fossil material, presence of glacial striae, mineralization and biological material present (described in the previous section: Fossil preservation state). This information allows us to have an idea of the damage suffered by the ichthyosaurs.

For the realization of the damage maps, 21 ichthyosaurs were selected, those with a degree of exposure greater than or equal to the general average (13% of exposure) and a deteriorated preservation status (poor to regular), with a value greater than or equal to the general average (7 points). Accordingly, the ichthyosaurs that meet these two conditions are those that present a higher level of damage and, given their exposure, are more susceptible to deterioration by erosion and weathering. However, of these 21 selected ichthyosaurs, only 10 were used to make the maps, since they have better photographs, which are of paramount importance when designing the maps, since they are subject to the quality of the image.

Photographs provided by Dr. Judith Pardo-Pérez taken during field campaigns from 2004-2024, together with Clip Studio Paint PRO illustration software, were used to produce the maps.

2.2.6. Conservation and monitoring methods

The previous parameters (glacial melt, deterioration factors, exposure percentage, and preservation state) were analysed to support physical protection and monitoring proposals for Tyndall ichthyosaurs.

The physical protection proposals correspond to conservation methods inspired by measures or actions applied to the safeguard of tangible cultural heritage, ensuring its accessibility to present and future generations (ICOMCC, 2008). Conservation comprises: (1) Preventive Conservation, which are indirect techniques that do not interfere with the materials or modify their appearance; (2) Curative Conservation, which correspond to all those actions applied directly on a fossil and that can modify the appearance of the property; and (3) Restoration (ICOMCC, 2008). The methods proposed in this work include preventive and curative actions, i.e., indirect and direct.

In order to develop conservation proposals for the Tyndall fossil locality, we discussed with paleontologists from different parts of the world (e.g. from the National and Kapodistrian University of Athens, Greece, and from the University of Alaska Fairbanks, USA), and reviewed different online catalogues for the sale of materials used in construction of buildings, looking for those that could be suitable to the conditions of the locality, in relation to the deterioration factors previously discussed.

On the other hand, the guidelines proposed by Santucci et al. (2009; 2024) based on several study cases in U.S. national parks were reviewed in order to define the most convenient monitoring methods for this fossil locality, taking into account the deterioration factors previously discussed, together with the geography of the area, remoteness and logistic costs.

III. RESULTS

3.1. Glacier Tyndall retreat

The melt curves of the Tyndall Glacier from 1945 to 2024 (Figure 5) allow us to understand the process of ichthyosaur exposure over the last 80 years associated with glacier retreat.

It is possible to observe that the highest density of exposed ichthyosaurs is located between the melting curves of 1945 and 1970.

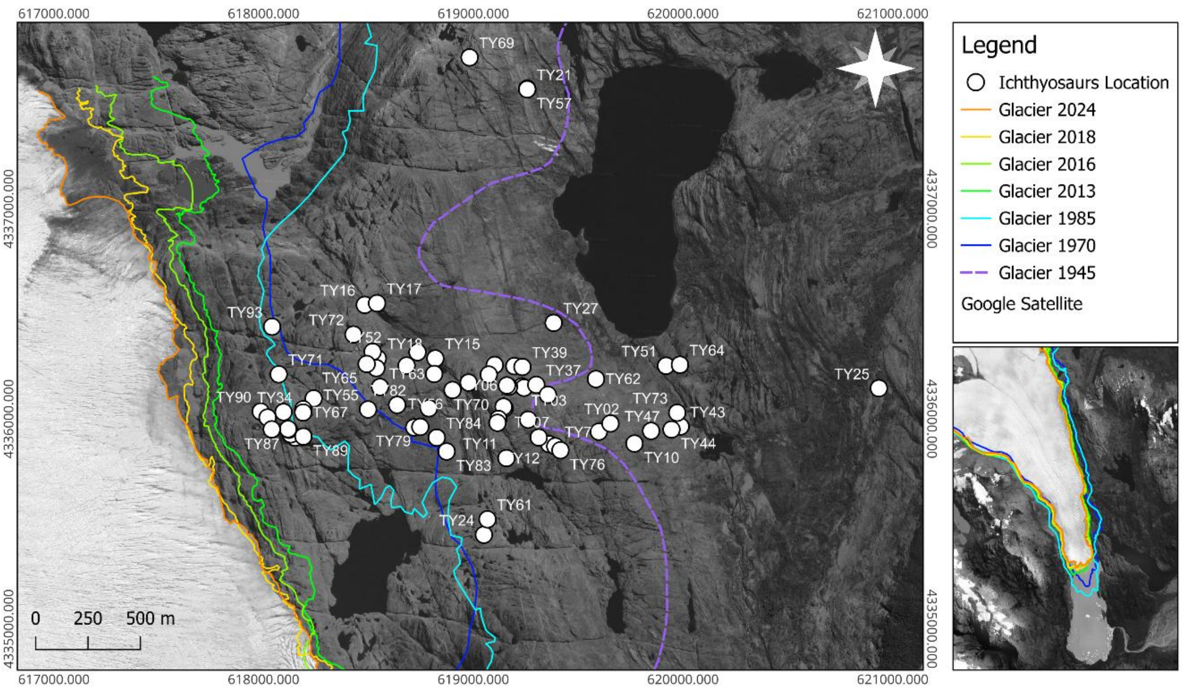

Figure 5. Tyndall glacier Melt Curves map (years: 1945, 1970, 1985, 2013, 2016, 2018 and 2024) and location of the 87 ichthyosaur skeletons discovered in the fossil locality. Author's own elaboration.

3.2. Deterioration factors

3.2.1. Climatic factors

The climatic factors affecting the locality are mainly responsible for the weathering and erosion of the rock and, therefore, for the fossil's decay. The ichthyosaurs fossils, once exposed on the surface due to the melting of the Tyndall glacier, are affected by: (i) temperature changes, ranging between -10°C and 20°C; (ii) intense precipitation, accumulating a monthly average up to 300 mm in the rainy months; (iii) humidity of the air, which can reach monthly over 80%; (iv) strong winds, over 100 km/h; and (v) UV radiation in the summer months causing the heating of the rock surface.

Meteorological data collected from the Tyndall station (DGA: 12288000) located near the Tyndall glacier, and from the Teniente Gallardo station (510005) located in the town of Puerto Natales (∼60 km from Torres del Paine National Park) are shown in Figures 6–13 and Table 9. This data show the climatic conditions to which the fossils are exposed at this site.

- **Temperature**

According to the graph in Figure 6, between the years 2012-2020, daily temperatures at Tyndall fossil site fluctuate between -10 and 20 °C. Meanwhile, Figure 7 shows that the lowest average monthly temperatures occur in the winter months (June, July and August), while the highest average monthly temperatures occur in the summer months (December, January and February).

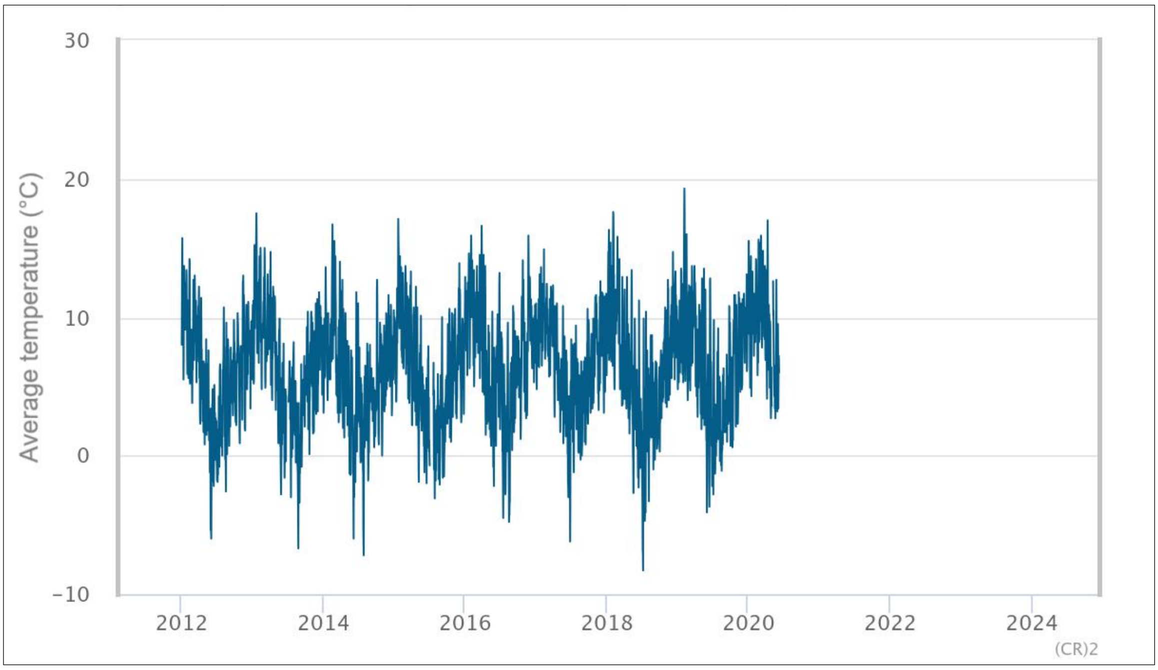

Figure 6. Variation of the daily average air temperature (°C) between 2012-2020 at the Tyndall station (DGA: 12288000). Graph modified from DGA (Dirección General de Aguas), Explorador Climático Cr[2].

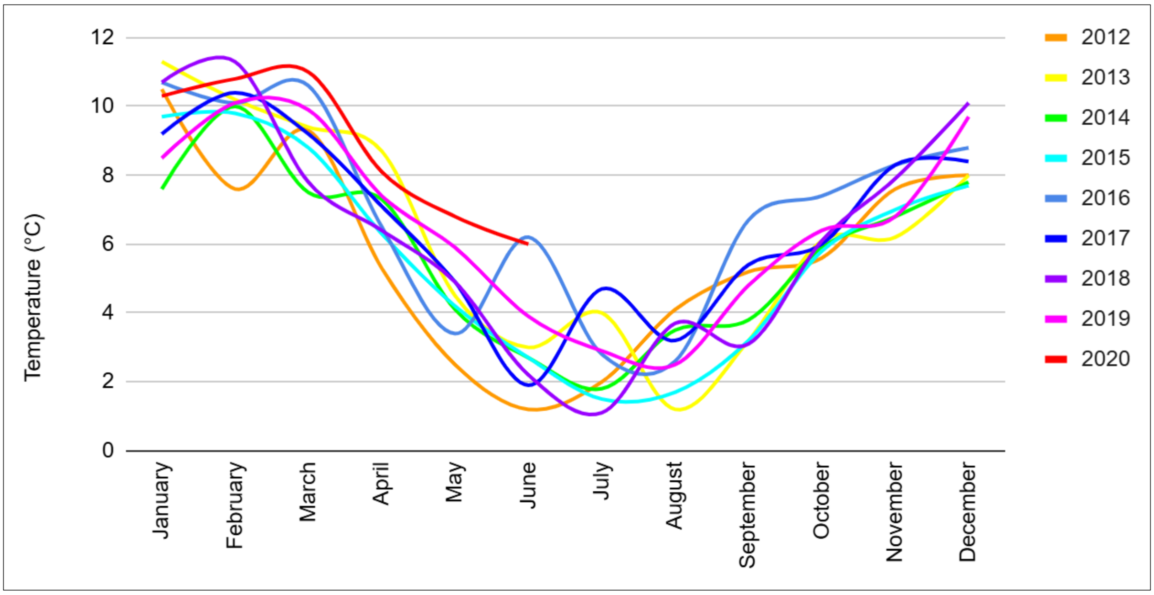

Figure 7. Variation of the monthly average air temperature (°C) between 2012-2020 at the Tyndall station (DGA: 12288000). Data source: DGA (Dirección General de Aguas), Climate Explorer Cr[2].

- **Precipitation**

According to Figure 8, the accumulated daily precipitation in the site fluctuates between 5-40 mm, and can even exceed 60 mm during the day. It is important to note that this graph has information gaps in the period 2013-2014, and in some months of the years 2015, 2016, 2021 and 2023. Meanwhile, according to the variation of the monthly accumulated precipitation graph (Figure 9), it is possible to see that the rainiest months are March, April and May (autumn), which can exceed 300 mm of accumulated monthly precipitation.

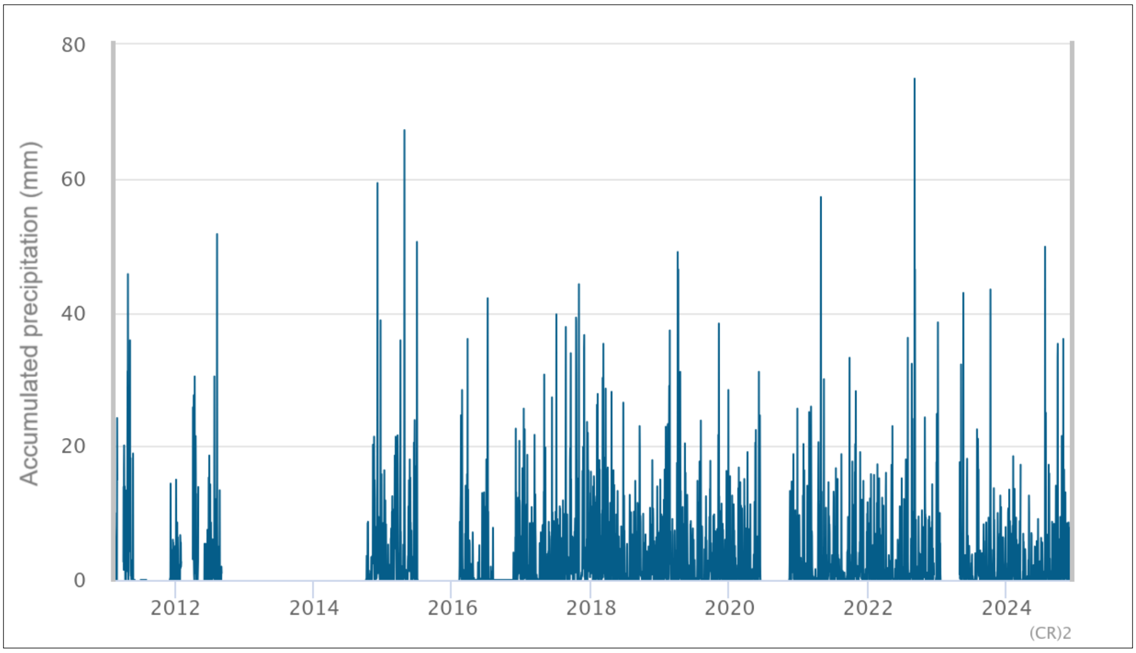

Figure 8. Variation of the accumulated daily precipitation (mm) between 2011-2024 at the Tyndall station (DGA: 12288000). Graph modified from DGA (Dirección General de Aguas), Explorador Climático Cr[2].

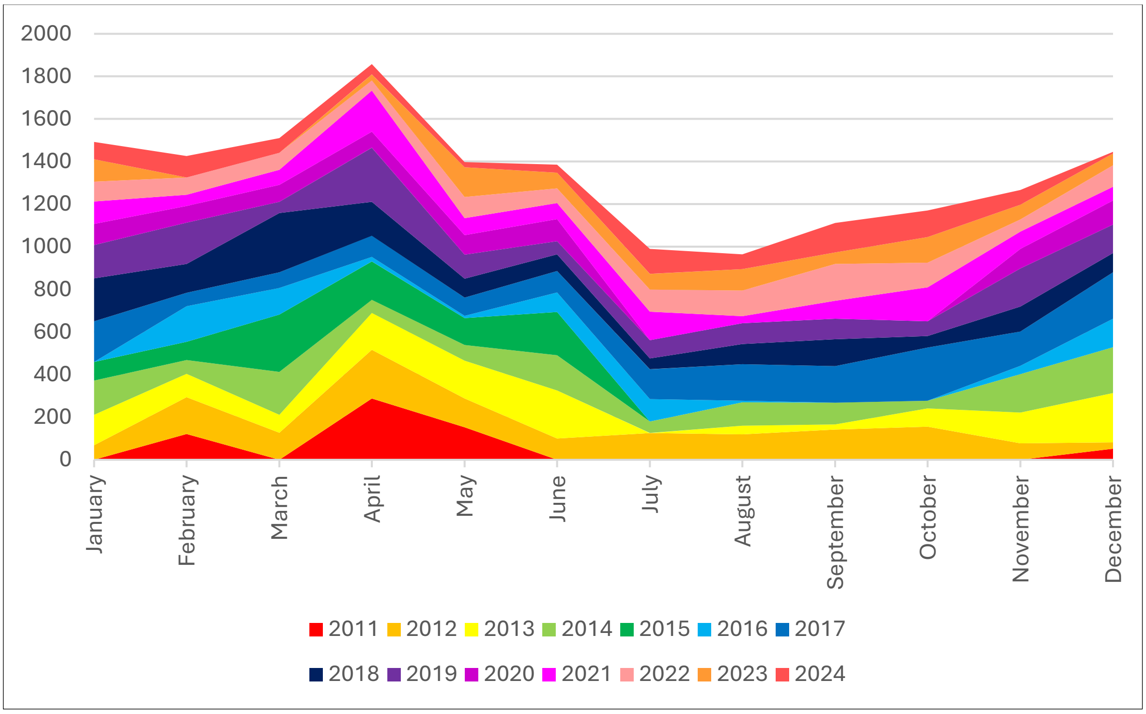

Figure 9. Variation of the monthly accumulated precipitation (mm) between 2011-2024 at the Tyndall station (DGA: 12288000). Data source: DGA (Dirección General de Aguas), Climate Explorer Cr2.

➢ Relative humidity

Based on the graph in Figure 10, the most humid months of the year are the winter months (June, July and August), including May (autumn), when the relative humidity can exceed 80%. Moreover, according to Figure 11, it is possible to observe that annually these values remain above 60% humidity on average, except in 2014, where humidity reached lower values compared to the general trend.

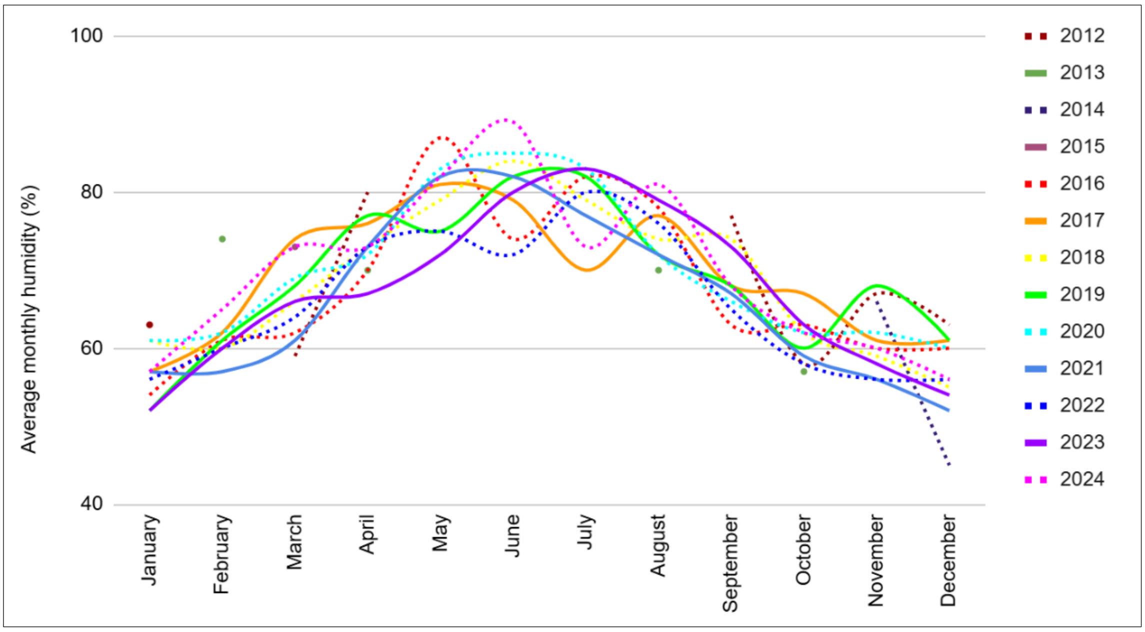

Figure 10. Variation of the monthly relative air humidity (%) between 2012-2024 at Teniente Gallardo station (510005). Data source: DGAC (Dirección General de Aeronáutica Civil).

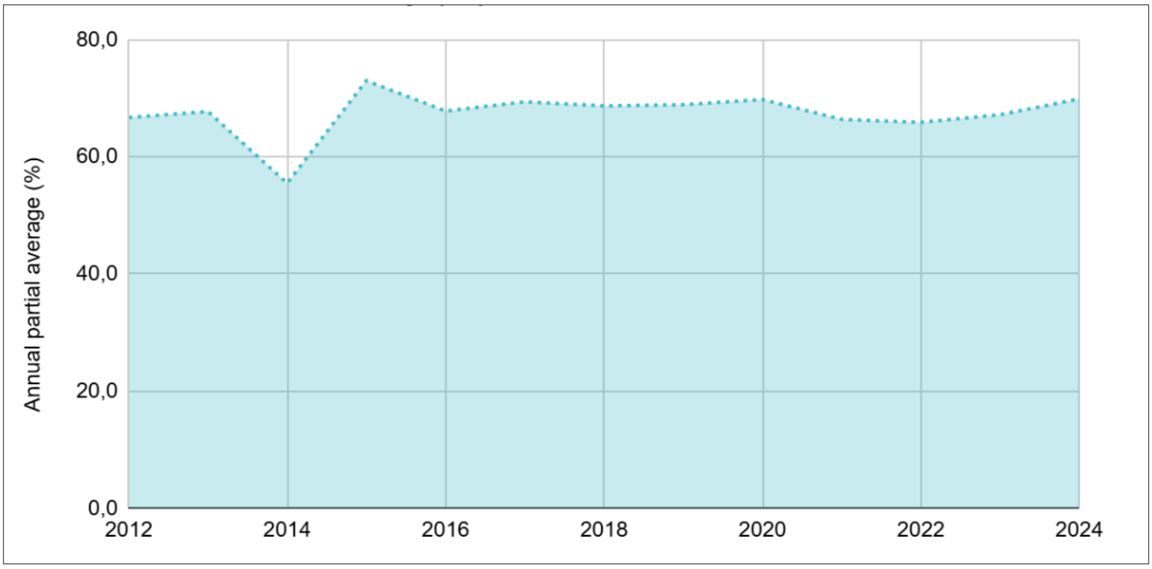

Figure 11. Variation of the annual relative air humidity (%) between 2012-2024 at Teniente Gallardo station (510005). Data source: DGAC (Dirección General de Aeronáutica Civil).

- **Wind**

Table 9 shows the annual behaviour of the wind speeds that can affect the locality, with an annual average of 30 km/h. Based on this data, the graphic in Figure 12 was created, which shows the maximum annual wind intensity in an average of ten minutes, with average values of 80 km/h, even exceeding 100 km/h.

	Predominant annual wind			Maximum intensity (average 10 mnts)		
	Kt	Km/h	Direction	Kt	Km/h	Direction
2010	19	35	W	54	100	NW
2011	18	33	W	40	74	W
2012	17	31	W	38	70	W
2013	16	30	W	38	70	NW
2014	17	31	W	38	70	W
2015	16	30	W	39	72	NW
2016	14	26	W	40	74	NW
2017	15	28	W	40	74	NW
2018	15	28	W	40	74	SW
2019	14	26	W	40	74	NW
2020	15	28	W	35	65	W
2021	15	28	W	41	76	NW
2022	16	30	W	45	83	W
2023	16	30	W	91	169	W
2024	14	26	NW	40	74	W
Average	16	30		44	80	

Table 9. Annual prevailing wind directions and maximum wind intensity recorded in a 10-minute average, in kt (knots) and km/h, between 2010-2024 at Teniente Gallardo station (510005). Data source: DGAC (Dirección General de Aeronáutica Civil). It is worth mentioning that 1 kt is equivalent to 1,852 km/h.

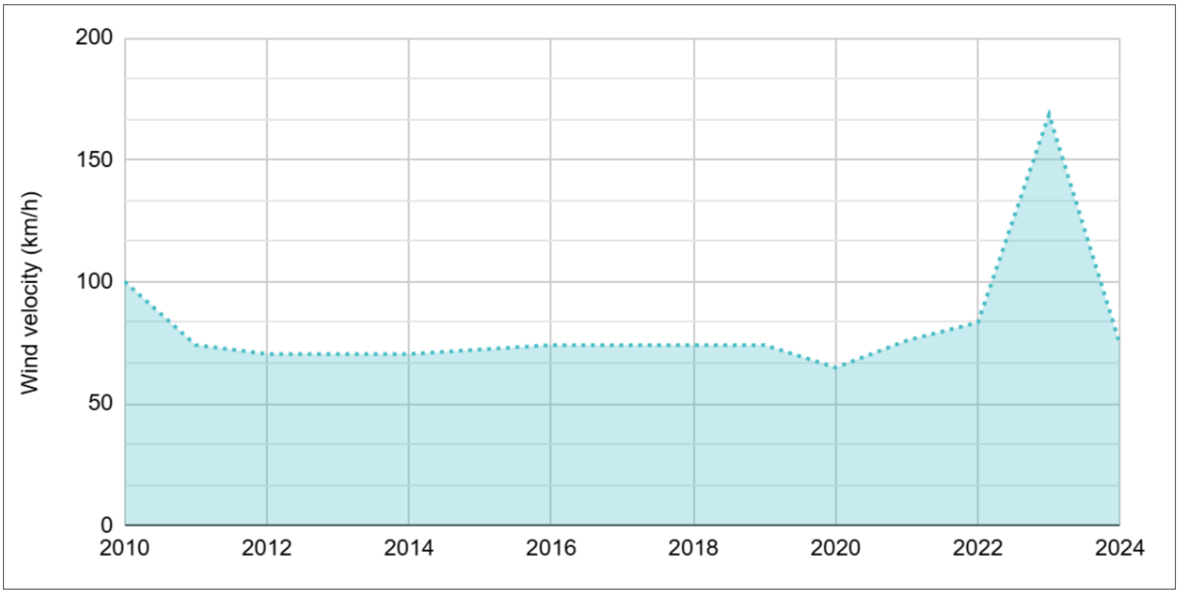

Figure 12. Variation of the maximum annual wind intensity, in a 10-minute average, between 2010-2024 at Teniente Gallardo station (510005). Data source: DGAC (Dirección General de Aeronáutica Civil).

➢ UV radiation

According to Figure 13, the months with the lowest UV indices are the winter months, with low to moderate values, while the months with the highest UV indices are the summer months, including November (spring), with very high to extreme values.

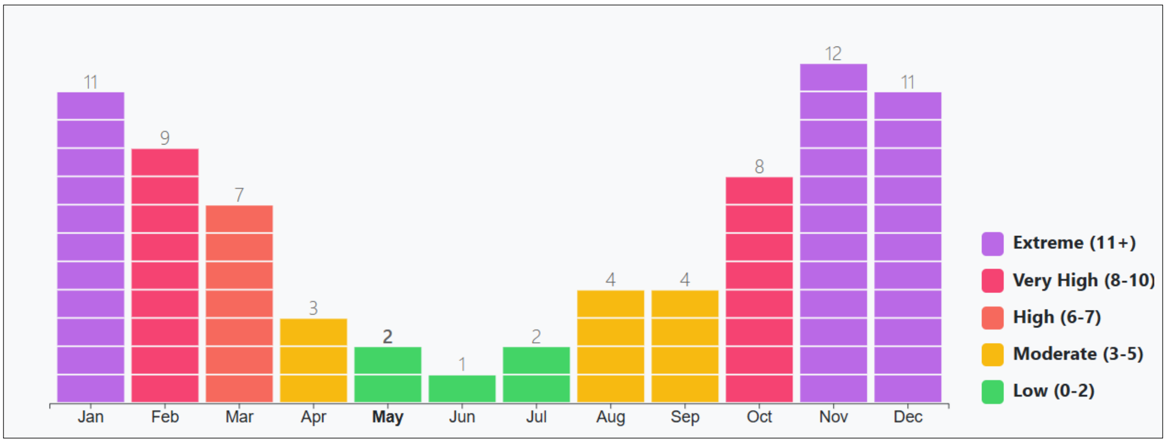

Figure 13. Variation of the maximum monthly UV Index in Puerto Natales. Data source: Copernicus Climate Change Service. Graph modified from NomadSeason.

3.2.2. Geological factors

- **Gelifraction**

One of the mechanical processes that have contributed to the deterioration of Tyndall's fossils is gelifraction. This process occurs when temperatures fluctuate above and below the freezing point (0°C), resulting in the expansion and contraction of water in rock fractures, which contributes to erosion and weathering of soil, rocks, and fossils (Santucci et al., 2009).

- **Deformation**

The Zapata formation was affected by deformation (Fildani & Hessler, 2005), causing the formation of folds and fracures, some of which with preferential directions. These structures, tend to weaken the rock and to allow the infiltration of water, and infillings by secondary minerals and vegetation, thus accelerating the rock decay and, therefore, fossil content. In addition, these zones of weakness also favour physical weathering processes (e.g. gelifraction, biological weathering).

- **Mineralization**

The rocks of the locality have disseminated pyrite, which is associated with a low oxygen environment at the time of their formation (Fildani & Hessler, 2005; Stinnesbeck et al., 2014). Pyrite, when in contact with oxygen and water, produces a physicochemical oxidation reaction that generates ferrous sulphate ($FeSO_4$), sulphur dioxide (SO_2) and sulfuric acid (H_2SO_4) (Larkin, 2011). Although in this case we are referring to small quantities, these types of compounds can negatively affect the fossil material.

Other minerals such as Fe oxides, carbonates and other minerals not identifiable to the naked eye (requires further studies) can also be found. These minerals are found in the rock, around the fossil and in some cases in the fossil bones. In the case of carbonates, they are filling small fractures (veinlets). Even though they do not have the corrosive power of pyrite, these minerals also contribute to the deterioration of fossils.

- **Glacial erosion**

Glacial erosion is perhaps one of the determining factors in the locality. The melting of the Tyndall glacier over the years (Figure 5) has left the fossils exposed on the surface and subject to the processes of erosion and weathering. In addition, the movement of the glacier also generates wear and abrasion on the rock and fossil bones, in addition to glacial striations which in the future may become areas of weakness and accelerate physical weathering processes, contributing to fossil deterioration. However, it should be noted that it is thanks to glacial retreat that today we can see and study these fossils.

Figure 14 illustrates the deterioration caused in fossils and rocks by the geological factors previously mentioned.

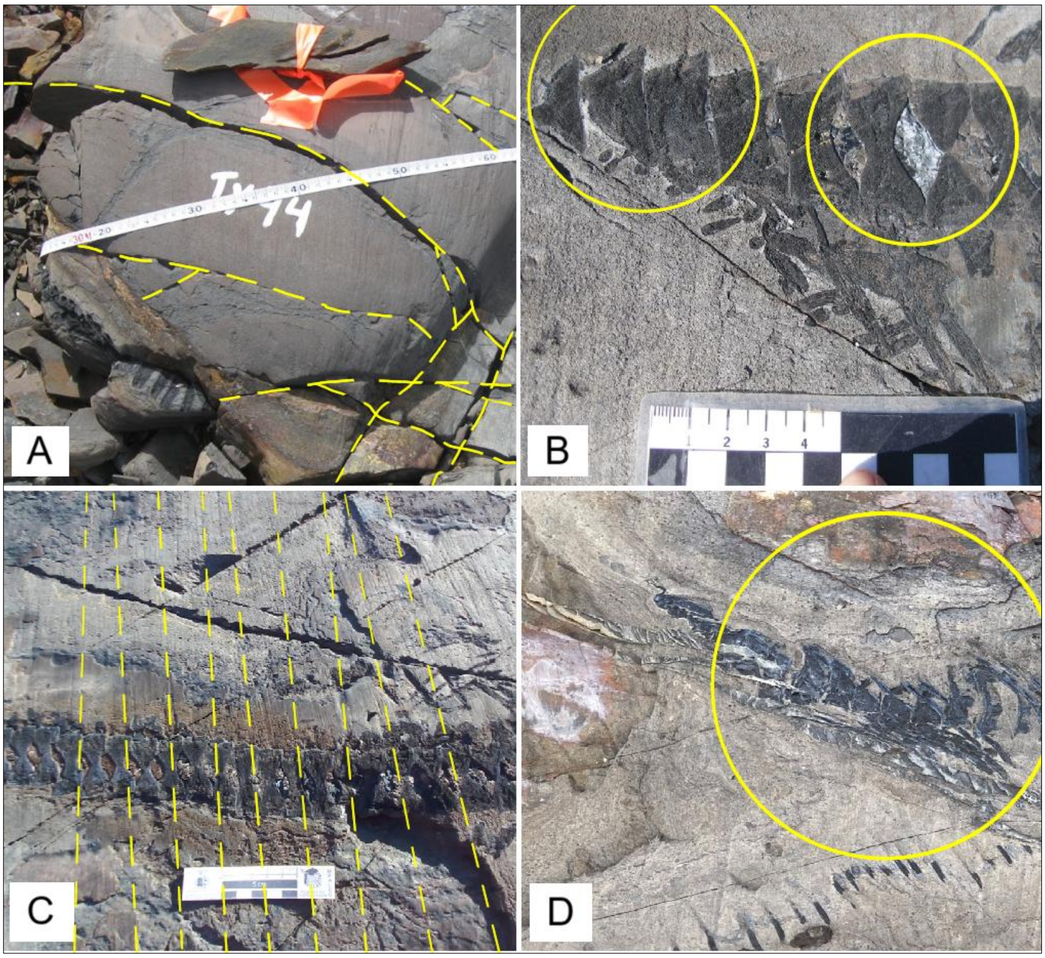

Figure 14. Examples of geological factors causing deterioration in Tyndall ichthyosaurs. A: cracks (due to gelifraction or deformation) in specimen TY-44. B: carbonate mineralization in the interstices of the vertebrae of specimen TY-54. C: preferential direction of glacial striations in specimen TY-54. D: Carbonate mineralization in fossil and rock of specimen TY-09. Photographs by Judith Pardo-Pérez.

3.2.3. Biological factors

- **Lichen**

One of the biological factors that can damage Tyndall fossils is lichen (Figure 15), which can cause fragmentation of the rock through a biological weathering process. This fragmentation can occur physically and chemically, through the segregation of substances by the lichen that affects the rock. Lichens are traditionally considered a symbiotic association between a fungus or several algae (Huereca et al., 2018), whose diversity is due to an adaptive radiation to almost all types of substrates, from soil, rocks, bark or turtle shells, to man-made structures (Huereca et al., 2018). The lichen present at the locality is distributed over rock and fossils, without showing a preferential distribution. According to the analysed photographs and observed field campaigns, the lichen present on the rocks and fossil ichthyosaurs of Tyndall could be of the crustose type. The so-called crustose type is the one that grows strongly attached to the substrate, to the point that it is impossible to separate them from it without destroying it (Huereca et al., 2018). The characteristics of this type of lichen allow them to survive in very extreme environments and on exposed rock surfaces (Huereca et al., 2018).

- **Moss**

It is also possible to find moss distributed on Tyndall rocky substrate, on the fossil material, and also infilling small fractures (Figure 15). Mosses are small-sized terrestrial plants, which remain fixed on the substrate (Velandia, 2019). They live in sectors with high humidity levels, as they need water for reproduction. Despite the fact that these organisms have multiple benefits (e.g. soil protectors and stabilizers, contribute to the accumulation of nutrients, nitrogen fixation in the soil, and absorption of pollutants from the atmosphere) their presence favours the accumulation of organic matter in the substrate (Velandia, 2019), which contributes to the destruction of fossil material. As with lichen, the presence of moss causes biological weathering of the rock, which can be both physical and chemical, since moss also generates substances that can alter the rock and, therefore, the fossil material.

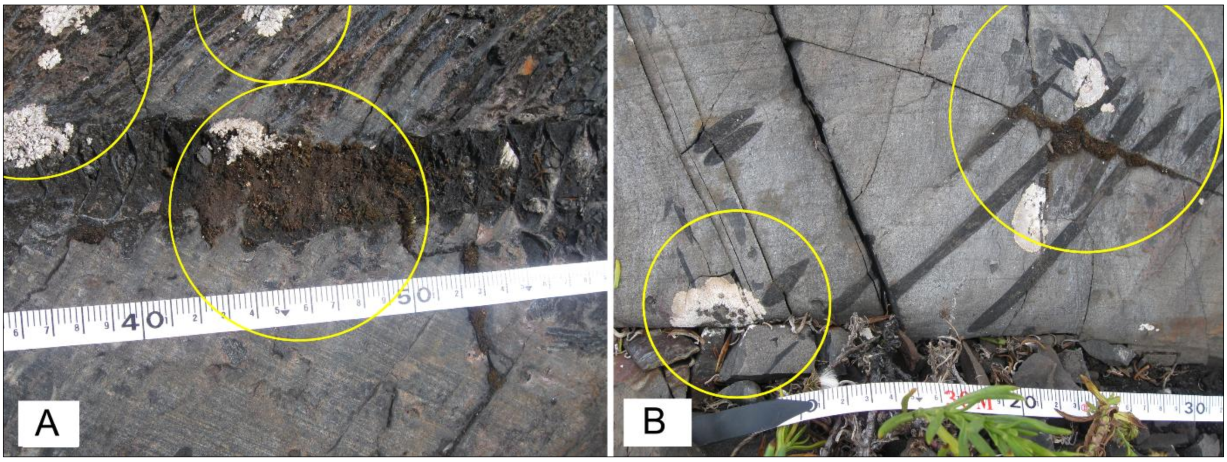

Figure 15. Presence of lichen and moss on Tyndall's ichthyosaurs. A: Section of specimen TY-38. B: Section of specimen TY-44. Photographs by Judith Pardo-Pérez.

3.2.4. Anthropic factors

Human disturbance can threaten the stability of the fossils and be contrary to their geoconservation objectives. Fortunately, the anthropogenic threat factors at the Tyndall fossil locality are low, as it is located more than 27 km from the entrance to Torres del Paine National Park, and the area can only be accessed on foot, or on horseback up to a certain distance. The locality is secured by the Chilean Biodiversity and Protected Areas Service (SABP), and is only visited by scientists, such as geologists, paleontologists, and glaciologists, with a research permit. The locality does not qualify as a tourist area because of its fragile ecosystems, lack of a management plan, and absence of trails and infrastructure.

The area is not under threat of theft of fossil material or vandalism, even so, in Chile there are laws that ensure its protection.

- National Monuments Law (Law No. 17,288)

This law protects National Monuments through the National Monuments Council, and the theft or destruction of their elements is punishable by law. According to this law national monuments are the places, ruins, constructions or objects of historical or artistic character; the burial grounds or cemeteries or other aboriginal remains, the anthropo-archeological, paleontological or natural formation pieces or objects, which exist under or on the surface of the national territory or in the submarine platform of its jurisdictional waters and whose conservation is of interest to history, art or science; sanctuaries of nature; monuments, statues, columns, pyramids, fountains, plaques, crowns, inscriptions and, in general, objects that are destined to remain in a public place, with commemorative character.

- Biodiversity and Protected Areas Service and the National System of Protected Areas (Law No. 21,600)

The purpose of this law is the conservation of biological diversity and the protection of the country's natural heritage, through the preservation, restoration and sustainable use of genes, species and ecosystems. In addition, according to this law there is a series of prohibitions imposed to ensure the protection and maintenance of Chile's protected areas (Table 10), including Tyndall area located inside Torres del Paine National Park.

1	Removing or extracting leaf soil, peat, firewood, rocks, sand or gravel.
2	Intimidating, feeding, hunting, fishing, capturing, extracting, mistreating, injuring or killing native fauna.
3	Destroying nests, places of settlement, reproduction or breeding or carrying out actions that interfere with or prevent the completion of the reproductive cycle of native species.
4	Cutting or uprooting specimens of plants, algae, fungi or lichens.
5	Collecting eggs, seeds, flowers or fruits.
6	Introducing specimens of native or exotic species and transgenic species, pollen, seeds or transgenic propagules.
7	Introducing livestock and other domestic animals. Among them, dogs.
8	Causing noise, light or atmospheric pollution.
9	Releasing, emptying or depositing dangerous substances in water systems or in the soil.
10	Altering the conditions of a protected area or its components by occupation, plowing, cutting, uprooting or other similar actions.
11	Altering, removing, scratching, destroying or extracting pieces or other elements with historical or archaeological significance.
12	Interrupting, blocking, altering or draining bodies or water courses, including wetlands.
13	Scratching, destroying or removing signage or infographics, and installing advertising posters.
14	Causing damage to the facilities or natural heritage existing in the area.
15	Using or carrying weapons.
16	Spending the night, eating, lighting fires, setting up camp, parking, anchoring or transiting in places or sites that are not enabled or authorized for this.
17	Entering protected areas without having paid the entry fee, if applicable.
18	Moving in motorized or non-motorized vehicles in places that are not established for these fines.
19	Flying drones.

Table 10. Prohibitions related to the use of protected areas in accordance with Law No. 21,600. This excludes people who have private permits or carry out projects or activities within the protected areas, with pre-established authorization by the Chilean Biodiversity and Protected Areas Service.

3.3. Tyndall ichthyosaurs exposure

According to the Exposure Table (Appendix 1), Tyndall's ichthyosaurs have an average exposure of 13%. The specimen MHNRS-Pa-1, with an anatomical exposure of 55%, is the ichthyosaur with the highest percentage of exposure in this locality.

Based on the general average, it was determined that those ichthyosaurs with ≥13% exposure have a high exposure, while those with <13% present a low exposure.

3.4. Tyndall ichthyosaurs preservation state

According to the Preservation State table (Appendix 2), the fossils have an average score of 7, with 14 being the highest value (specimens TY-43, TY-44 and TY-53).

Based on this, it was determined that fossils with a score ≥ 7 have a deteriorated state of preservation (poor to regular), while those with a score < 7 possess in general a good state of preservation.

3.5. Tyndall ichthyosaurs damage maps

The damage maps of the selected specimens according to the criteria of exposure and state of preservation described in the methodology are presented in Appendices 3-12.

The maps indicate the location of the main fractures and cracks, the presence of minerals and biological material (lichens and mosses) on the fossil and rock, the main direction of the glacial striations, if there is loss of fossil material or not, and the fossil erosion (which corresponds to the erosion that today allows us to observe the fossils).

3.6. Conservation methods

The conservation methods proposed for the Tyndall's ichthyosaur fossils are described in the following paragraphs.

These methods are intended to ensure the physical preservation of fossil material exposed to various agents of deterioration, protecting them from their direct action and attenuating their effect. These methods were designed for those fossils that present high levels of exposure and poor preservation, and therefore require greater care. It should be noted that, with the exception of excavation, none of these methods have yet been carried out at the fossil locality and their implementation is subject to various factors that will be detailed later in the discussion chapter. Along with the protection of the fossil, each one of these proposals aims to generate the least possible impact on the environment, as well as to ensure easy transport of material taking into account the climate, geography and remoteness of the fossil locality.

3.6.1. Multilayer Approach

Given the climatic and geological conditions of the locality (strong wind, low temperatures, high rainfall and hard rock), the Multilayer Approach appears to be an effective alternative. This approach consists of the use of a geotextile layer (buffer layer), a geomembrane layer (outer protective layer), and a sediment layer (natural stabilizing layer), in that order (Figure 16). This method provides both moisture control and physical protection, and also avoids direct contact between the fossils and the rougher outer material.

- **Geotextile:** corresponds to a permeable layer, which allows moisture and air exchange, which can be beneficial to prevent condensation that could eventually damage the fossils.
- **Geomembrane:** these are more robust in terms of complete waterproofing, which can be advantageous in rainy environments, especially if the fossils need to be protected from direct water infiltration.
- **Sediment:** the use of sediment (in this case available glacier moraine) on top of both layers could be convenient, as it corresponds to a natural stabilization technique and adds an additional layer of protection against climatic and physical disturbances.

The materials must be properly secured to prevent them from breaking or being blown away by the wind. Stakes or anchors with bolts can be used for this purpose, although it should be taken into account that the hardness of the rock could difficult the process. In this sense, the sediment layer is a good alternative if the use of anchors is to be avoided.

The costs of the materials required to carry out the Multilayer Approach method are presented in Table 11. It is important to mention that the type of geomembrane and geotextile required will depend on the protection needs of the fossil in particular. For example, if we are looking for greater mechanical resistance and durability, a heavier and thicker layer is a good option. On the other hand, if we want greater flexibility and better filtration, it is preferable to use lighter geotextiles and thinner geomembranes.

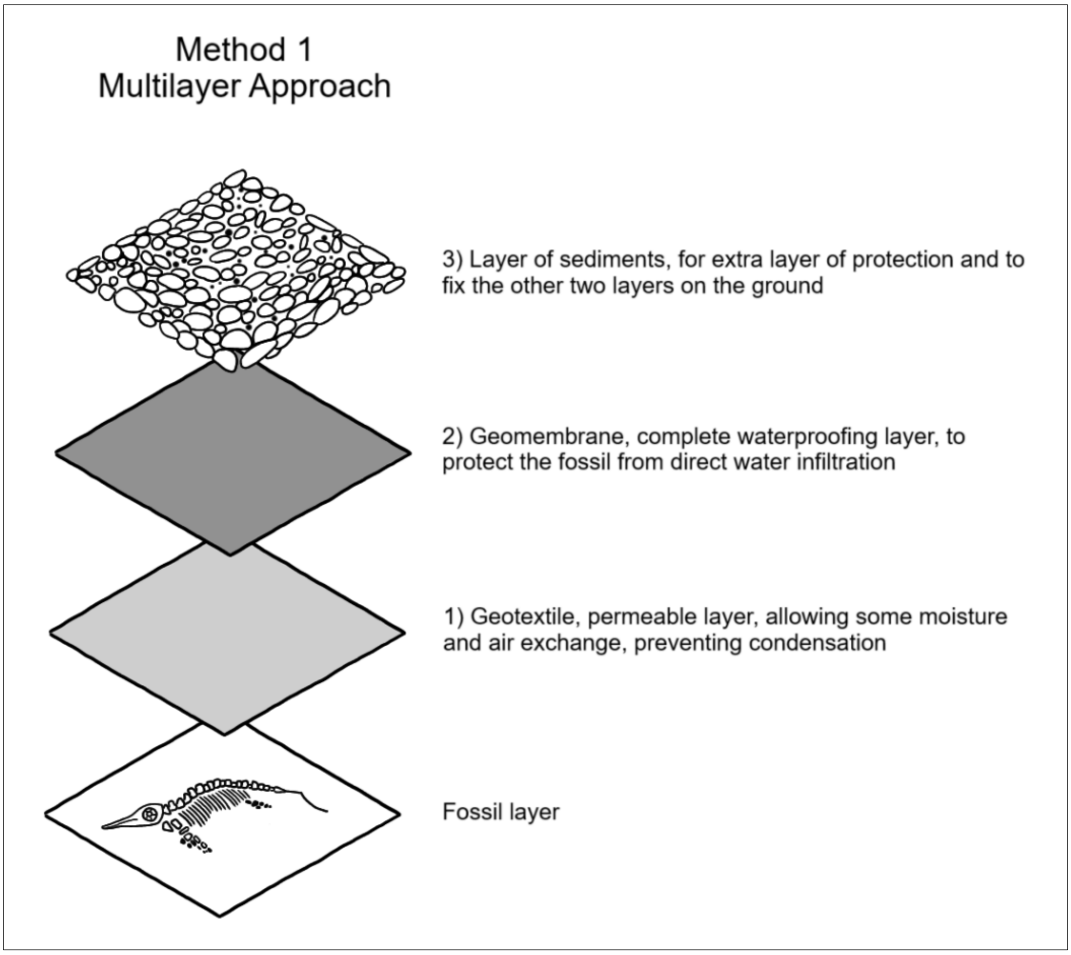

Figure 16. Possible models to protect Tyndall fossils: the Multilayer Approach.

Material	Type	Unit	CLP	EUR	Supplier
Geotextile	130 gr/m²	m²	900	~0.892	GEOTEX
Geotextile	150 gr/m²	m²	1000	~0.991	GEOTEX
Geotextile	200 gr/m²	m²	1250	~1.238	GEOTEX
Geomembrane	1 mm	m²	1640	~1.628	GEOTexaco
Geomembrane	1,5 mm	m²	2572	~2.554	GEOTexaco
Geomembrane	2,0 mm	m²	3588	~3.562	GEOTexaco
Glacier morrein	–	–	–	–	–

Table 11. Indicative cost per m² of the materials required for the multilayer approach, in Chilean pesos (CLP) and in Euros (EUR). The table compares three types of geotextiles according to weight per unit surface area, and three types of geomembranes according to their thickness. The glacial moraine available in the area has no extra cost.

3.6.2. Natural Layer Approach

This method consists of using a layer of sediment over the fossil layer (Figure 17), in this case, the glacial sediments present in the locality. This layer corresponds to a natural protective barrier that seeks to imitate the action of the glacial moraine prior to its removal. This method does not consider the use of materials foreign to the locality, so this proposal is environmentally friendly. Moraine is available in abundance within the area, so it does not imply extra costs, however, its behaviour against wind action requires continuous monitoring.

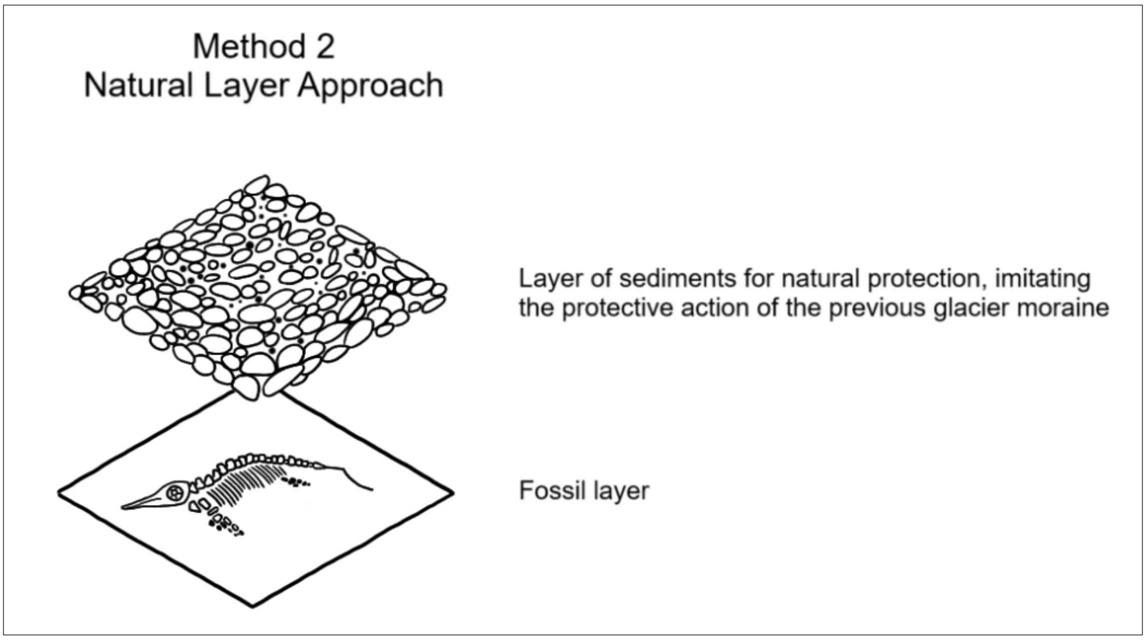

Figure 17. Possible models to protect Tyndall fossils: the Natural Layer Approach.

3.6.3. Retaining Wall Approach

This method consists of creating a retaining wall around the fossil from a mortar made of lime and sand (Figure 18). In simple terms, a mortar is a mixture of different inorganic components, which upon hardening provides physical and mechanical properties very similar to a concrete mixture. In this case, the inorganic materials are lime and sand. Lime is traditionally used as a plasticizing and binding material, which gives the mixture great workability. It can be aerial or hydraulic. Sand, on the other hand, is an inert material that prevents cracking and contraction of the mortar. The main idea of this proposal is to redirect rainwater (completely or partially), preventing it from flowing directly over the fossil material. It should be noted that the fossil layer should have a certain inclination, so that the water can drain away.

The costs of the materials required for the production of the Retaining Wall method are presented in Table 12.

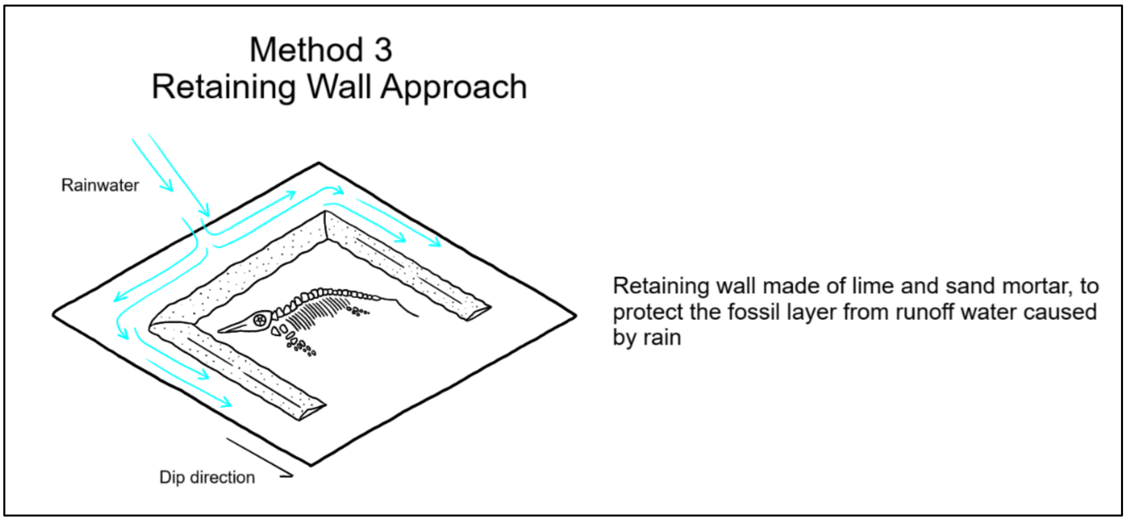

Figure 18. Possible models to protect Tyndall fossils: the Retaining Wall Approach.

Material	Unit	CLP	EUR	Supplier
Air lime	25 kg	7560	~7.536	SOPROCAL
Hydrauic lime	25 kg	8490	~8.463	SOPROCAL
Coarse sand	25 kg	1970	~1.964	Rio Maipo
Fine sand	25 kg	2210	~2.203	Rio Maipo

Table 12. Indicative cost of materials required for the retaining wall approach. The prices of aerial lime, hydraulic lime, coarse sand and fine sand are compared in Chilean pesos (CLP) and Euros (EUR). Each value corresponds to the cost of a 25 kg bag of material.

This method can be combined with the installation of a protective cover (shelter) at ground level, which could be beneficial to combat the incidence of UV radiation by generating shade protection and could also help to provide some degree of control and channelling of rainwater over the fossil.

3.6.4. Filling Cracks Approach

This method (Figure 19) is not part of preventive conservation, but corresponds to a curative conservation method, since it can modify the appearance of the fossil by acting directly on it, and therefore corresponds to the most invasive method here presented. It consists of filling existing cracks in the rock in order to stop processes such as the growth of minerals and vegetation (lichen, moss and other types of plants), as well as weathering processes associated with water infiltration and its freezing (gelifraction). So this method would help us to prevent or diminish effects associated with physical and chemical weathering. For its realization, first the rock and fossil surface must be cleaned, eliminating the vegetation in the cracks and removing loose fragments. Then, from the creation of a natural grout based on lime and sand, the cracks are filled. Subsequently, the broken fragments must be stabilized and the dusty areas consolidated with epoxy-based adhesives or polyurethane (of these two materials, polyurethane has a better durability, although both become friable with the passage of time, so their selection must be careful).

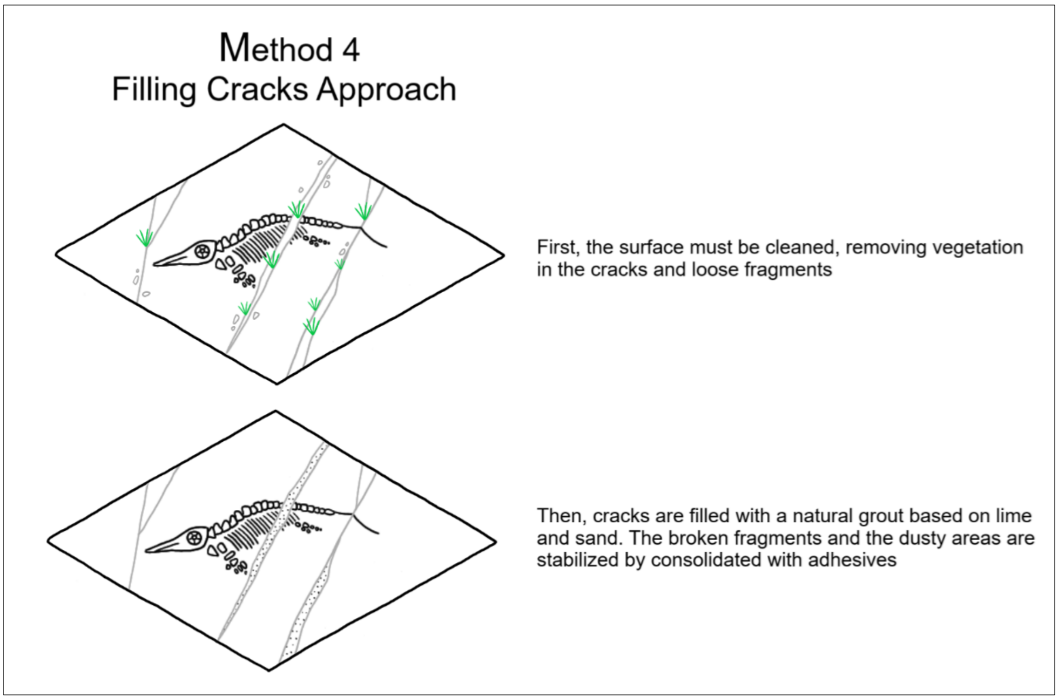

Figure 19. Possible models to protect Tyndall fossils: the Filling Cracks Approach.

Table 13 shows the costs of the adhesives to be used in the Crack Filling method. It is noted that the costs of the materials for the creation of the grout (lime and sand) are listed in the previous table.

Material	Unit	CLP	EUR	Supplier
Epoxy Resin	1 kg	25600	~23.60	PLASTICENTER
Polyurethane Resin	1 kg	28500	~26.28	PLASTICENTER

Table 13. The adhesive prices required for the filling cracks method, in Chilean pesos (CLP) and Euros (EUR).

3.6.5. Excavation

If none of the four methods previously described is viable for the protection of the Tyndall fossils and measures are urgently required to ensure its preservation, the best way to avoid fossils decay is through excavation, which corresponds to the complete or partial removal of the fossil. In this way, the fossil material can be conserved in laboratories, and stored and/or exhibited in museums. However, it is necessary to take into consideration that the excavation process can also cause deterioration of the fossil material, especially if the appropriate precautions are not taken. Fossil excavation, unlike the methods described previously, which are type of *in situ* conservation of the material, corresponds to a type of *ex situ* conservation.

The logistical cost of the 2022 field campaign, in which the specimen MHNRS-Pa-1 was excavated, was approximately 25 million Chilean pesos (~24,882,601 EUR). This includes: excavation materials (e.g. diamond saws, spare blades, wood, polyurethane foam, *chuzos*, hammers, chisels, among other various fungibles), dome tents for the excavation, tents for the camp, fuel for the excavation, gas for the camp, food for the team members and their respective salaries, horses for transporting material, vehicle rental to reach the park, payment for helicopter flight hours and the use of a boom truck (the latter was used to transport the blocks with the fossil contents from Tyndall fossil locality to the entrance of Torres del Paine National Park and from there to the Río Seco Natural Museum located 14 km from the city of Punta Arenas).

3.7. Monitoring methods

Monitoring is key to evaluating the progress of any conservation plan and is recognized as an important part of geoconservation management (Wignall, 2022). Paleontological monitoring consists of periodically assessing the stability and condition of *in situ* fossils to observe and document any factors (natural or anthropogenic) that may contribute to the deterioration or loss of fossil material (Santucci et al., 2024). Documenting long-term changes in paleontological resources represents an important step for their management, since it allows knowing the rate and degree of impact on the fossil material and thus establishes the scientific basis for future actions to ensure a good geoconservation strategy (DeBlieux et al., 2003).

Santucci et al. (2009) presented a comprehensive strategy for monitoring fossils, which included the identification of natural and anthropogenic stressors that affect them. The authors described five vital signs: (1) erosion (geologic factors); (2) erosion (climatic factors); (3) catastrophic geologic hazards; (4) hydrology/bathymetry; and (5) human access/public use.

The following is a description of the long-term paleontological monitoring methods best suited to the conditions at the Tyndall fossil locality, taking into consideration the factors previously mentioned, as well as remoteness and logistical costs.

3.7.1. Climatic Records

It is important to monitor changes in climatic factors in order to understand how they contribute to the deterioration of the fossil material and at what rate. For this, local weather data, especially precipitation and temperature records, should be collected and analysed according to Santucci et al. (2009) for at least a five-year period, although this may vary according to the needs of the site. It should be noted that fossil sites in areas with high annual precipitation should be evaluated more frequently than in areas with low annual precipitation (Santucci et al., 2009).

The Tyndall locality has a weather station (DGA: 12288000), which provides complete annual, monthly and daily information on precipitation and temperatures, advantageous for keeping a record of weather variations. These records can be easily accessed through the DGA's CR^2 Climate Explorer, with very complete data from 2010 onwards.

3.7.2. Photogrammetry

Photogrammetry is a technique used to obtain spatial information from images. This technique quantifies the dimensions and positions of the objects represented. The use of high-resolution photogrammetry for *in situ* monitoring of localities with paleontological material is a valuable and highly recommended technique (Santucci et al., 2009), as it allows archiving, analysing and visualizing samples that would otherwise be difficult or impossible to access (Heinrich & Wings, 2014).

The process involves taking a series of photographs of an object from different angles to computationally generate a 3D model by comparing the features of the photographs (Heinrich & Wings, 2014).

This technique has already been applied to some specimens at Tyndall site. However, in order to carry out a more effective monitoring strategy, photogrammetry should be done on as many specimens as possible, in order to have a more complete record, especially of those that present a greater risk of deterioration. This task should be carried out by properly trained personnel.

Photogrammetry requires a high resolution digital camera, a computer with a fast processor and graphics card, and suitable software. On the internet we can find the following free softwares: Meshroom and MeshLab, for 3D image reconstruction, modeling and processing. In addition, it is important that the photographs have a proper scale, since the scientific value of 3D data is much higher if the size of the object is known (Heinrich & Wings, 2014).

3.7.3. Repeat Photography

This monitoring technique is essential to evaluate differential rates of erosion of fossiliferous strata and the stability of *in situ* paleontological resources. To carry it out, it is necessary to establish photography points for large- and small-scale repeated photography, with consistent reference points and perspectives available over time (Santucci et al., 2009).

Ideally, photography points should be established at each specimen at the Tyndall locality and repeat photography should be conducted at least once a year. This task can be performed by either scientists or a trained park volunteer/staff. It does not require specialized equipment and has minimal cost. It is important that the photographs are scaled, labelled (with the time, day, month, and year the photograph was taken), and then archived. Photographs can be taken with any camera with good resolution.

3.7.4. Erosion Monitoring Stakes

The installation of multiple erosion stakes in a rock unit is a useful tool for evaluating differential rates of erosion in fossiliferous strata and the stability of *in situ* fossils. Stakes should be installed perpendicular to the surface, with the reference level marked directly on the monitoring stake at the point where it penetrates the ground surface (Santucci et al., 2009). During subsequent site visits, any changes in ground surface level with respect to the monitoring stake should be recorded. According to Santucci et al. (2009), during the first five years after installation, monitoring should be carried out at least once a year, although this could vary according to the needs of the locality. The recommended material for the stakes is galvanized steel.

Due to the hardness of the rock at Tyndall site, the installation of the stakes can be complex, so it is important that they are installed by trained personnel. However, monitoring (including taking photographs to record changes) can be done by a park volunteer/staff.

3.7.5. Crack Monitors

Crack monitors can be used to monitor the expansion of natural cracks in rock strata with fossil material. Crack monitors consist of two overlapping plates that are attached with epoxy to both sides of the crack. The crack expansion can be measured by permanently marking both sides of the crack and using calipers to measure the distance between them. The observed expansion should be documented by photographs (DeBlieux et al., 2003).

At the Tyndall fossil locality, the installation task should be carried out by trained personnel, but subsequent monitoring (including taking photographs to record changes) can be done by a park volunteer, at a minimum frequency of once a year.

3.7.6. Digital Elevation Model (DEM) and Geospatial Data

Digital elevation data and geospatial data from paleontological localities allow the creation of maps showing slopes and orientations of rock strata (Santucci et al., 2009). This information can be used to determine which areas would be susceptible to higher rates of erosion and which in turn would benefit from more frequent monitoring, since the factors that contribute to the deterioration of fossil resources will depend on topographic conditions and for each specimen is different (e.g. existence of light and shade, accumulations of water and moisture, and proliferation of biological material).

The Tyndall fossil locality has digital elevation models and geospatial data from information collected through airborne laser altimetry by the Chilean Air Force (Keller et al., 2007) and data taken by the Japanese ALOS satellite. However, this information has not been used for paleontological purposes, but only to study glacier variations. In addition, in order to have better data, these should be updated and include the use of drones in the area. This type of technology, by allowing a better understanding of the topography of the area, will help us to implement an effective monitoring strategy. These techniques are relatively expensive and require specialized personnel, however, these data can be accessed through the Chilean Geospatial Data Infrastructure (IDE Chile).

It is important to note that for each of the proposed monitoring methods it is important to have the collaboration not only of the scientists in charge of studying the area, but also of the park staff, who should be encouraged and trained to carry out the monitoring tasks at least once a year.

The following table summarizes the estimated costs of each monitoring method, as well as the type of equipment and expertise needed to carry it out (Table 14).

Monitoring Method	Estimated Cost*	Specialized Equipment	Expertise
Climatic Records	€	No	Trained volunteer
Photogrammetry	€	Yes	Trained volunteer
Repeat photography	€	No	Trained volunteer
Erosion Monitoring Stakes	€	No	Trained volunteer
Crack Monitors	€	No	Trained volunteer
DEM and Geoespatial Data	€€	Yes	Scientist

Table 14. Cost, equipment and expertise summary for each monitoring method proposed for the Tyndall fossil site. Estimated Cost* (in €) = € (<1000 euros); € (1000-10,000 euros). Based and modified on Santucci et al. (2009).

IV. DISCUSSIONS

According to Page (2017) there are scientific, educational, economic, recreational, ecological and cultural reasons to ensure the protection of fossil material. However management and conservation practices may represent one of the most complex aspects of paleontological heritage protection (Page, 2017), and so far, there is very limited research work on fossil conservation (Peng et al., 2020), which makes the task even more challenging. Furthermore, it must be kept in mind that in practice each fossil site is different and the fossils that each presents will dictate their own unique management regime if their qualities are to be adequately safeguarded for future generations (Page, 2017).

In order to implement a proper geoconservation strategy for *in situ* conservation of fossils, it is essential to establish an accurate assessment of the state of preservation and/or deterioration of fossils (Ortega et al., 2016). In addition, it is necessary to document whether fossils are being exposed and at what rate, in order to lay the scientific foundations for future measures involving their proper management (Amzil et al., 2024). In this sense, in the Tyndall fossil locality, it is of great importance to analyse the deterioration factors that have contributed to the weathering and erosion of the fossil material, among which are glacier melt and meteorological factors such as precipitation, temperature fluctuations, humidity, wind intensity and UV radiation, as well as geological, biological and even anthropogenic factors.

Based on the Melt Curves map (Figure 5), it can be seen that from 1945 to 2024, the Tyndall glacier has experienced a significant retreat. In the last 80 years it has retreated up to 2.5 km from the location of the ichthyosaurs. This means that the fossils at the locality have been exposed gradually over a period of at least 80 years and thus subject to the constant action of various erosion and weathering factors. It can also be observed that the highest density of ichthyosaur findings is located between the 1945 and 1970 curves, covering a period of 25 years of thawing and subsequent exposure.

With respect to the influence of the glacier on the fossils, we can say the following: as glaciers move over the terrain, they produce changes in the ground through weathering and erosion processes, which occur at the base and on the margins of the glacier (DGA, 2008). On the one hand, weathering processes occur mainly due to the freezing and melting of water at the base of the glacier, and variations in the ice load, leading to fracturing of the rock (DGA, 2008), while erosion processes are essentially abrasion, plucking and erosion of the rock by subglacial watercourses. This allows us to affirm that the destructive action of the glacier on the fossils begins even before the melting process. Although glacial erosion is more intense at the base and sides of the glacier, where the ice is in direct contact with the rocky substrate (Sugden & John, 1976; Cuffey & Paterson, 2010), those fossils that before the melting were just below the glacier front may have experienced more intense deterioration processes. This is because the glacier front corresponds to a very dynamic zone, in which the following processes occur: (1) ablation, which generates meltwater; (2) calving, i.e. the detachment of ice blocks; (3) sedimentation, associated with the formation of moraines; (4) the formation of proglacial lakes; and (5) periglacial and weathering processes, associated with gelifraction and mechanical weathering, both of which are the product of meltwater (Sugden & John, 1976). When the glacier retreats, along with the aforementioned phenomena, it leaves land exposed to colonization by mosses, lichens and microorganisms. This indicates that the glacier acts as a strong erosive and weathering agent on the fossils, especially during melting periods. However, it is thanks to this retreat that today we can have access to these fossils. And, as shown in Figure 5, more ichthyosaur fossils will continue to be discovered in the locality in the future, so it is necessary a proper management to ensure their geoconservation for future generations.

As mentioned before, paleontological resources can be very susceptible to the impacts of natural factors and human influences (DeBlieux et al., 2013; Santucci et al., 2009). Based on what was previously discussed, climatic, geological and biological factors are the main causes of destruction of the paleontological material in the study area, while the anthropogenic factor as a destructive agent is significantly lower, due to the non-existence of construction works and vandalism associated with the destruction of fossil material. This is because the fossil site is located within a protected area, 27 km from the park entrance and can only be accessed on foot after an approximately eight-hour hike.

Regarding climatic factors, temperature fluctuations (between -10°C and 20°C), precipitation (up to 300 mm in the rainy months) and humidity (average that can exceed 80%) are the main agents of weathering and erosion, while to a minor degree abrasion by wind action (which can reach speeds of over 100 km/h) and the heating of the rock by IR/UV radiation (which can be extreme in the summer months). Based on the graphs presented (Figures 6-13), it is possible to say that the highest temperatures reached in a year are in the summer months (December, January and February). At the same time, these are the months with the highest UV radiation indexes. Meanwhile, the lowest temperatures occur in the winter months (June, July and August), sometimes reaching values below freezing point (Appendix 13). These months, together with the month of May, are also the most humid months with the lowest incidence of solar radiation. The rainiest months correspond to autumn (March, April and May). This indicates that during half of the year the fossil ichthyosaurs are subject to intense rainfall, high humidity and temperature variations that can reach freezing point, while in summer the rock can become hot due to the extreme values of ultraviolet radiation indexes.

On the other hand, the factors of geological origin that cause destruction are associated with processes of gelifraction, mineralization and the action of glacial retreat, in addition to deformation that has generated areas of weakness and the subsequent formation of cracks. These cracks enhance processes of surface scaling, detachment, weathering and surface erosion of the reliefs because they allow the development of minerals, the accumulation of water and the growth of vegetation (Coster & Legal, 2021).

Biological material is an important factor of deterioration, being moss and lichen the main destructive agents, although there may also be more developed vegetation (e.g. plants with roots and grasses). The presence of lichen and mosses can cause both physical and chemical alterations in the rock, through the segregation of substances (Huereca et al., 2018; Velandia, 2019).

According to the results and a subsequent analysis, it was determined that all these factors mentioned are those that must be fought if we want to ensure the protection and conservation of the fossil material of the locality, since it presents a risk of natural degradation. In addition, combined with the constant erosion, we can state that the fossils are exposed to physical and chemical weathering, which adds another difficulty to establish adequate protection methods.

In this work an effort was made to estimate the time it takes for the fossil to be destroyed since its exposure, in order to know precisely the erosion rate, however, the results were not conclusive. It appears, in fact, that destruction does not occur for all fossils at the same rate, but varies according to each specimen as will be discussed later.

Based on the data presented in the Exposure table (Appendix 1) we can see that the percentage of exposure varies significantly according to each specimen, with 13% being the overall average. While with respect to the State of Preservation table (Appendix 2), we can say that more than half of the ichthyosaurs analysed present a more advanced state of deterioration (state of preservation from poor to regular) with respect to the general average. In turn, based on the damage maps, we can note that weathering and erosion factors are reflected in the presence of cracks, glacial striations, mineralization (mainly of carbonate type), loss of fossil material (which causes a significant loss of taphonomic information) and the presence of lichen and mosses, both in the rock and in the fossil bone.

In order to analyse the existence of a correlation between the percentage of fossil exposure and its state of preservation, a graph was plotted (Figure 20). However, there does not seem to be a clear correlation between both factors. There are fossils with low exposure and a high level of damage, as well as fossils with high exposure and a low level of damage. Although there seems to be a small trend with respect to those fossils with a percentage of exposure higher than 13% (general average), in which they do present a worse state of preservation.

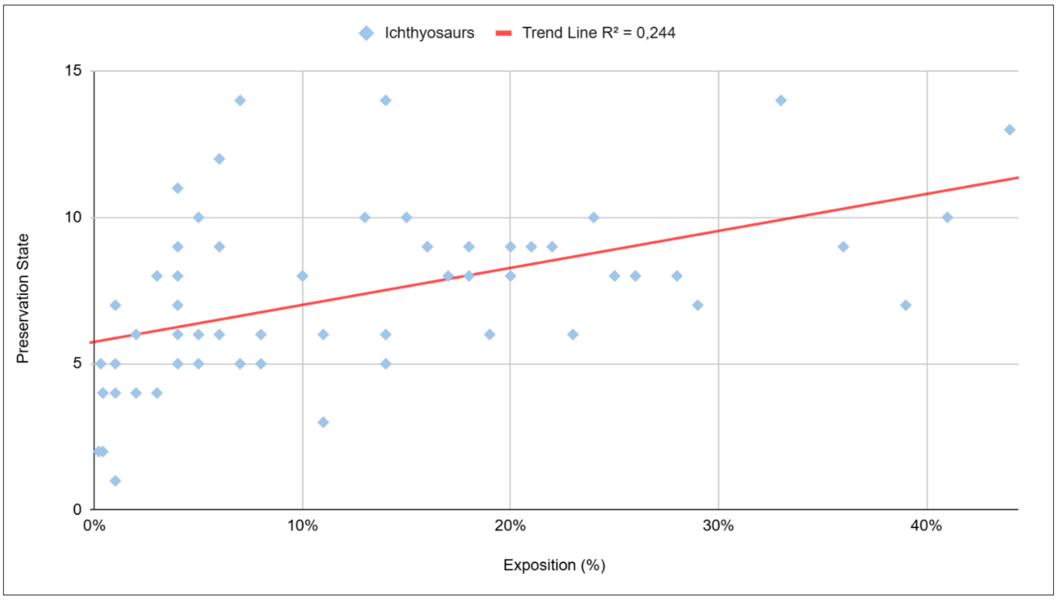

Figure 20. Preservation state vs. Percentage of exposure of the Tyndall Ichthyosaurs.

Based on the information discussed, erosion and weathering factors have a direct influence on the state of preservation of the fossils, which in turn seem to act at different levels on each specimen, being influenced by the topographic predisposition. This occurs because each fossil, with respect to its location in the site, presents its own microclimate and therefore the previously mentioned deterioration factors act with different intensity. Topography can generate substantial environmental variation at fine spatial scales (Quispe Huamán & Sotomayor Alzamora, 2022). Variability in elevation, surface slope and orientation of strata, as well as shadows projected by terrain features and radiation incidence, generate significant local gradients (Hofierka & Suri, 2002). In other words, topography will influence factors such as the presence of light and shade, as well as the accumulation of water from precipitation or glacial melt, and humidity, which is closely related to rock fracturing, loss of fossil material, occurrence of minerals and biological material. In this sense, it is of crucial importance to study in detail the topographic characteristics on which each specimen is found, in order to propose conservation and monitoring measures that best fit the local conditions. In this fossiliferous site, the use of Geographic Information Systems (GIS) and Remote Sensing are valuable tools that should be applied to have a better understanding of the microclimates (Quispe Huamán & Sotomayor Alzamora, 2022).

Generally, fossil protection options involve two different strategies: *in situ* conservation (sheltering) or *ex situ* conservation (excavation) (DeBlieux et al., 2012; Coster & Legal, 2021). However, for logistical reasons and due to the climatic and geographic conditions of the area, the creation of shelters and/or the excavation of as much fossil material as possible are difficult tasks. In addition, there is a general lack of published scientific literature and limited guidance on *in situ* fossil management methods (Santucci et al., 2024). Therefore, one of the main challenges presented by this fossil locality is to define those conservation methods that are viable for the protection of this paleontological heritage. It is necessary to mention that this type of treatments must not damage the integrity to the bone material of the fossil, since conservation aims to preserve taphonomic information, so the products applied must be compatible with the material, reversible and not interfere with future analyses (Ortega et al., 2016). In addition, conservation principles must be followed according to official requirements (ICOM-CC, 2008).

Regarding the conservation methods proposed in this study, as previously discussed, we cannot use the same method in a generalized way for all the fossils of the Tyndall locality. On the contrary, each fossil needs specific treatment. At this point, damage maps become important, as they help us to have a better understanding of what are the main threats to the fossil and how we could try to mitigate the damage and protect it. For example, for specimens TY-25, TY-38 and TY-44 (Appendix 7, 8 and 9 respectively) due to the considerable presence of biological material and cracks that enhance their growth, using the Multilayer Approach could be detrimental to the fossil material, because although the layers of geotextile and geomembrane seek to prevent condensation, if the placement is not adequate, it could generate a type of greenhouse effect and promote the proliferation of biological material. Similarly, the Natural Layer Approach could enhance the accumulation of water and moisture in the interstices of the sediments, also promoting the growth of lichen and mosses. In this sense, for these specimens, it would be better to apply the technique of Retaining Wall Approach or Filling Cracks Approach. Although, in the case of specimen TY-44, it seems to be much more convenient to excavate the material, a method that should only be applied if is strictly necessary (e.g. if the destruction of the fossil is imminent given its advanced deterioration, or if the fossil is of particular interest to science). It is important to mention that excavation at the Tyndall locality can cause deterioration of the fossil, especially if the necessary precautions are not taken. This is because given the specific conditions of the site (e.g. the hardness of the rock), the excavation process can lead to loss and breakage of the fossil material. The aforementioned techniques, Multilayer Approach and Natural Layer Approach could be much more efficient in those fossils free of biological material, without large cracks, with slopes that are not very steep and that are in surface strata without too many irregularities, e.g. specimens TY-17 and TY-54 (Appendix 5 and 10 respectively). Regarding the Natural Layer Approach, it is important to mention that the durability of the moraine will depend on the intensity of the wind and the topography in which the fossil is located (e.g. in an area more exposed to wind action or more protected). Its durability should be monitored.

The methods proposed here have not been tested at the Tyndall fossil locality yet, but some of them have been used in other paleontological sites with good results, although they present specific conditions, different from those of our locality.

The first two methods (Multilayer Approach and Natural Layer Approach) are completely reversible and do not directly affect the fossil, since they are preventive conservation methods, i.e. indirect, which can also be reversed if resources and technical requirements allow other options to be considered in the future (Coster & Legal, 2021). Both methods seek to bury the fossil under a protective cover, thereby protecting it from climatic action such as wind ablation, freeze-thaw cycles (Agnew & Demas, 2016; Coster & Legal, 2021) and the direct action of precipitation. In the fossiliferous sites of Pinilla del Valle (Spain), protective layers of geotextile and plastic have been applied to buffer climatic variations (Ortega et al., 2016).

The Retaining Wall Approach is not completely reversible, but it is not acting directly on the fossil, but on the surrounding rock, in order to protect the fossil from the direct action of rainwater runoff. No bibliography was found on sites where this method has been applied, so if it does not exist in other parts of the world, the Tyndall locality would be a pioneer. In the results, it is proposed to combine the Retaining Wall Approach with protective shelter at ground level. Keeping a site *in situ* under shelter protection is a commonly adopted and implemented response to the problem of archaeological and paleontological site conservation (Rodríguez Temiño, 2014; Agnew & Demas, 2016; Ordóñez Martín et al., 2022), however, the following aspects should be taken into account: the main purpose of a protective structure, or shelter, at a site should be to provide a beneficial environment for its conservation, however, these have variable performance as, of course, not all shelters are appropriate at all sites (Tringham & Stewart, 2008). Despite its multiple benefits, such as protection from natural forces, e.g. rain, insolation, climatic fluctuations (Ordóñez Martín et al, 2022), and providing an opportunity for interpretation and education (DeBlieux et al., 2003), assuming that a shelter will provide adequate protection is erroneous (Tringham & Stewart, 2008). In fact, a shelter may contribute to the degradation of fossil material and cause further deterioration, e.g. due to inadequate dispersal of rainwater (Tringham & Stewart, 2008). In the case of the Tyndall fossil locality, the creation of shelters for the protection of fossils is not feasible, due to the logistical costs involved, but also because of the difficulty of giving them adequate maintenance over time, due to the remoteness of the site and rough geography. In addition, its implementation is not justified, since this option is preferred especially in visited sites or in sites that seek to attract visitors (Agnew & Demas, 2016).

The Filling Cracks Approach been used in other paleontological sites giving good results, as in Mammal Tracks of the Luberon UNESCO Global Geopark (Coster & Legal, 2021). As mentioned before, this conservation treatment consists of removing vegetation and small fragments of dust and rocks, then filling the cracks with a lime and sand grout, and finally stabilizing the broken fragments with adhesives (Coster & Legal, 2021). Unlike the other methods, this one is not reversible and, depending on the location of the cracks, acts directly on the fossil, which is why this type of intervention requires a much more exhaustive documentation of the initial state of the fossil and the testing of materials in the laboratory and *in situ* in order to study its aging (e.g. testing the selected adhesives under extreme temperature conditions to observe their behavior).

It is important to mention that none of these methods was thought from an aesthetic perspective, since they do not seek to preserve the fossil material for tourism, but rather to ensure its long-term protection for science and education. Each of these conservation methods has its advantages and disadvantages, and their application will depend on the specific conditions of each fossil. In addition, after their application, these methods require constant monitoring to evaluate their effectiveness.

In order to conserve geoheritage values and their associated geological elements in protected areas, it is also essential to have a plan and practices for monitoring paleontological resources as an essential part of any geoconservation strategy (Santucci et al., 2009; Woo, 2019). This will help us to measure the preservation state of fossil elements and ongoing processes, as well as the threats they may present (Woo, 2019). Unfortunately, paleontological resource monitoring is not a practice traditionally performed by academic paleontologists and is not a topic that is normally presented to students as part of their education (Santucci et al., 2024). Monitoring tasks can be costly, so it is important to select only the most important parameters (Woo, 2019). It is critical to understand which indicators need to be monitored at a given location, so they should be selected based on the natural processes of a protected area and the visitor and infrastructure pressure on it (Woo, 2019). In the case of the Tyndall fossil locality, it is vitally important to keep a record of the climatic conditions of the area, as well as to record each of the appreciable physical and chemical changes in the fossils over time. Studying how the rock behaves is also important to understand the evolution of the deterioration of the fossil material. For this purpose, several monitoring techniques have been proposed in this work, taking into consideration all the characteristics of the locality previously mentioned. The monitoring methods discussed in this study are: Climatic Records, Photogrammetry, Repeat Photography, Erosion Monitoring Stakes, Crack Monitors and Geospatial Data.

The most effective methods in this locality correspond to Photogrammetry and Repeat Photography, since photographic monitoring, both past and present, provides a valuable record to measure observable short and long-term changes in these *in situ* resources (Santucci et al., 2009). It is worth mentioning that both tasks should be carried out by a paleontologist or trained volunteer from time to time (at least once a year in the case of repeated photography), since the climatic conditions and the topography of the area make it difficult to place stationary cameras in the site. In this sense, it is essential that Chile's Biodiversity and Protected Areas Service (SBAP) take part in the development of monitoring practices by including them in its management plan and by training park staff.

Given the difficulty of protecting and extracting all the fossil specimens in the area, those monitoring methods that involve the use of digital technologies not only allow the rapid collection of accurate, high-resolution data, but also allow taking advantage of these data for digital conservation and dissemination of knowledge to specialists and the general public (Heinrich & Wings, 2014; Amzil et al., 2024). In this regard, Photogrammetry and the use of Geospatial Data become very relevant, since they will allow us to generate 3D fossil models, and thus safeguard the information even if the fossil is destroyed by natural action (Amzil et al., 2024).

The Erosion Monitoring Stakes and Crack Monitors methods will allow us to have a notion of erosion rates and crack behavior affecting rock and fossil material, so their application is necessary.

The use of Geospatial Data and Digital Elevation Models (DEM) will provide us better knowledge of the topography of the site, since they allow us to create maps that show the slopes and orientations of the rock strata (Santucci et al., 2009) and, therefore, we can have a better understanding of the microclimates in which each fossil is found. Thus, it will be easier to know which conservation methods should be applied to a fossil according to its location in the site. It is of great importance to highlight that from a good paleontological monitoring strategy in the Tyndall fossil locality, we could get to know the erosion rate at which the fossils are being destroyed by analysing their short and long term evolution, as well as the natural processes and factors that operate there, especially because these have become more unpredictable due to recent climate changes caused by global warming (Woo, 2019).

V. CONCLUSIONS

It is important to emphasize that paleontological resources are fragile and non-renewable, which should be reflected in paleontological heritage management strategies, since there are several reasons that justify their protection (scientific, educational, economic, recreational, ecological and cultural). However, management practices can be one of the most complex aspects of paleontological heritage protection, especially if left *in situ*. As reflected in this study, this is compounded by the lack of published scientific literature and limited guidance on *in situ* fossil management methods, which makes the task even more difficult.

The two most common methods of fossil protection are 1) shelter construction and 2) excavation to remove the fossil. However, neither of these techniques is completely viable at the Tyndall fossil locality due to remoteness, rugged geography, climate, and logistical costs. As a result, conservation and monitoring methods adapted for this particular fossil site were established to initiate the development of a proper geoconservation strategy to ensure its preservation. In order to develop these methods, the following aspects were analysed:

- The glacier's action on the fossils, whose retreat has contributed to the ichthyosaurs exposure over the last 80 years. The glacier's retreat has left the fossils exposed to the surface, and it acts as a strong weathering and erosive agent, even before thawing.
- The deterioration factors affecting ichthyosaurs, divided into four categories: climatic (temperature, precipitation, relative humidity, wind and UV radiation); geological (gelifraction, deformation, mineralization and glacial erosion); biological (mainly associated with the presence of lichen and mosses); and anthropogenic (to a minor degree). The extent to which these factors affect the fossil material varies, causing weathering and erosion. Therefore, the action of each factor must be mitigated or controlled to ensure the preservation of the fossil material.
- The percentage of ichthyosaurs exposed was found to be an overall average of 13%, with those exposed to a greater degree requiring greater protection.
- The state of preservation and level of damage of the ichthyosaurs result in more than half of them being in a deteriorated state (from poor to regular), meaning they require greater protection.

The conservation methods proposed in this study cover both preventive and curative aspects. These methods are: the Multilayer Approach, the Natural Layer Approach, the Retention Wall Approach and the

Filling Cracks Approach. Each method has its own advantages and disadvantages, and the most suitable method will depend on the specific conditions of each fossil taking into account its state of deterioration and its location within the site. This is because the topographic conditions in which each specimen is found seem to be a key factor in its state of preservation.

In addition to conservation methods, it is also essential to implement monitoring practices, in order to safeguard the values of paleontological heritage. Monitoring is an essential component of any geoconservation strategy. The monitoring methods for paleontological sites proposed here are: Climatic Records, Photogrammetry, Repeat Photography, Erosion Monitoring Stakes, Crack Monitors and Geospatial Data. These methods will help us measure and record the state of preservation of fossil elements over time, as well as ongoing processes and potential threats. Furthermore, continuous monitoring at the site will facilitate the careful selection of the most suitable conservation method for each fossil.

It is important to mention that these actions, which include conservation and monitoring methods, aim to facilitate logistical aspects in terms of costs and transportation, given the characteristics of the fossil site mentioned earlier. These methods must also be environmental friendly, given that the Tyndall site is located in the Torres del Paine National Park. In addition, the cooperation of the Biodiversity and Protected Areas Service (SBAP) is essential for developing strategies to protect this area.

Finally, this study marks the beginning of continuous research into the factors affecting the deterioration of this fossil site. The results obtained here are crucial for developing a proper geoconservation strategy to ensure the preservation of the ichthyosaurs of the Tyndall fossil site for scientific research, education and future generations.

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VII. APPENDICES

Appendix 1. Exposure Table, indicating the percentage of anatomical exposure of ichthyosaurs from the Tyndall locality. The reference specimen MHNRS-Pa-1 is colored in light blue.

Specimen	Skull		Forelimb and pectoral girdle		Hind fin and pelvic girdle		Ribs		Gastralia		Anterior vertebral column		Posterior vertebral column		Uncertain vertebrae		Exposition
	Score	%	Score	%	Score	%	Score	%	Score	%	Score	%	Score	%	Score	%	
MHNRS-Pa-1	1	25%	2	50%	0	10%	2	50%	2	50%	4	100%	4	100%	-	-	55%
TY-01	1	25%	1	25%	0	0%	0	0%	0	0%	4	87%	0	0%	-	-	20%
TY-02	0	0%	0	0%	0	0%	1	12%	0	0%	-	-	-	-	0	8%	3%
TY-03	0	0%	0	0%	0	0%	1	18%	0	0%	3	54%	1	15%	-	-	13%
TY-04	0	0%	0	0%	0	0%	2	32%	1	14%	-	-	-	-	1	21%	11%
TY-05	0	0%	0	0%	2	50%	2	32%	0	0%	1	22%	3	63%	-	-	24%
TY-07	0	0%	0	0%	0	0%	0	3%	0	0%	0	0%	0	0%	-	-	0,4%
TY-08	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	-	-	0	1%	0,2%
TY-09	0	0%	0	0%	0	0%	2	44%	1	10%	4	80%	0	0%	-	-	19%
TY-10	0	0%	0	0%	0	0%	0	6%	0	0%	-	-	-	-	0	5%	2%
TY-11	1	25%	2	50%	0	0%	4	98%	0	0%	3	61%	1	19%	-	-	36%
TY-12	2	50%	0	0%	0	0%	2	32%	0	0%	1	15%	0	0%	-	-	14%
TY-13	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	-	-	1	15%	3%
TY-15	0	0%	1	25%	0	0%	1	21%	0	0%	1	24%	2	37%	-	-	15%
TY-16	1	25%	0	0%	0	0%	0	0%	0	0%	2	39%	0	0%	-	-	9%
TY-17	0	0%	0	0%	2	50%	2	35%	4	78%	3	57%	2	33%	-	-	36%
TY-18	1	25%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	4%
TY-20	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	1	11%	-	-	2%
TY-21	0	0%	0	0%	0	0%	1	21%	0	0%	-	-	-	-	0	4%	4%
TY-22	1	25%	0	0%	0	0%	1	24%	0	0%	2	48%	0	0%	-	-	16%
TY-23	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	4%	-	-	1%
TY-24	1	25%	1	25%	0	0%	2	27%	1	25%	2	33%	0	0%	-	-	19%
TY-25	0	0%	0	0%	1	25%	1	12%	0	0%	0	0%	3	53%	-	-	13%
TY-27	0	0%	0	0%	0	0%	0	3%	0	0%	0	0%	0	1%	-	-	1%
TY-29	0	0%	0	0%	0	0%	0	5%	0	0%	2	28%	0	0%	-	-	5%
TY-34	0	0%	0	0%	0	0%	0	10%	0	0%	-	-	-	-	0	9%	3%
TY-38	2	50%	1	25%	1	25%	3	58%	0	10%	4	93%	1	16%	-	-	40%
TY-43	0	0%	0	0%	0	0%	1	14%	0	0%	-	-	-	-	1	21%	6%
TY-44	0	0%	0	0%	0	0%	4	86%	1	25%	0	0%	0	0%	-	-	16%
TY-47	0	0%	0	0%	0	0%	0	4%	0	0%	0	0%	0	0%	-	-	0,7%
TY-48	2	50%	0	0%	1	25%	1	23%	0	0%	1	24%	0	0%	-	-	17%
TY-51	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	-	-	0	2%	0,4%
TY-52	0	0%	0	0%	1	25%	0	8%	0	0%	0	7%	0	0%	-	-	6%
TY-53	1	25%	2	50%	2	50%	2	29%	3	75%	1	22%	1	24%	-	-	39%
TY-54	0	0%	0	0%	1	25%	4	100%	0	0%	3	52%	2	42%	-	-	31%
TY-55	0	0%	1	25%	0	0%	1	23%	0	0%	2	33%	0	0%	-	-	12%
TY-57	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	8%	-	-	1%

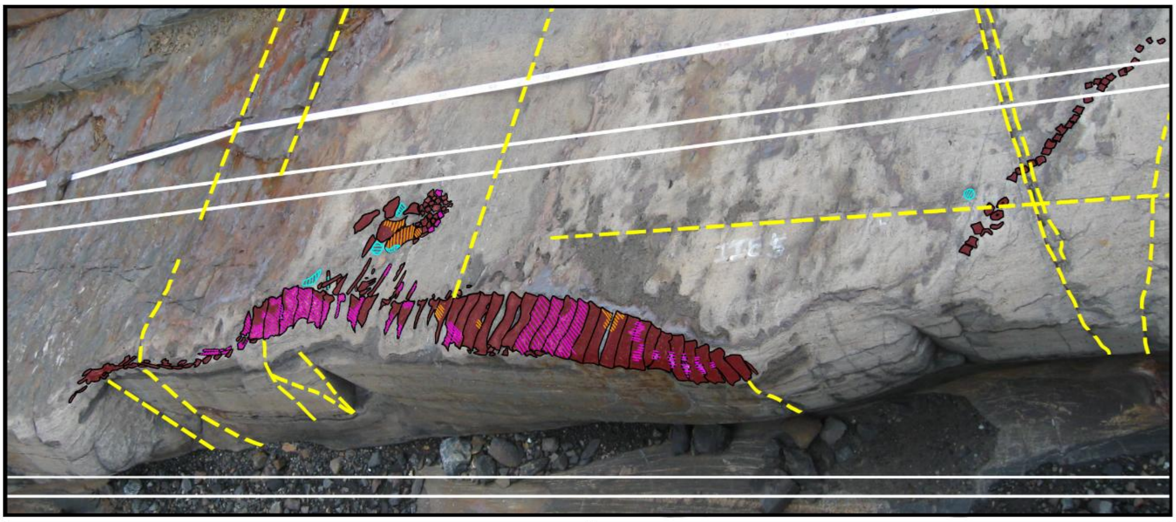
TY-61	2	50%	2	50%	0	0%	2	33%	0	0%	0	0%	1	23%	-	-	22%
TY-62	0	0%	0	0%	0	0%	1	15%	0	0%	1	15%	0	0	-	-	4%
TY-68	1	25%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	4%
TY-69	1	25%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	4%
TY-70	0	0%	1	25%	0	0%	3	61%	0	0%	-	-	-	-	1	11%	16%
TY-71	0	0%	1	25%	1	25%	2	46%	0	0%	-	-	-	-	1	13%	18%
TY-72	1	25%	1	25%	1	25%	3	68%	2	28%	-	-	-	-	3	56%	38%
TY-74	2	50%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	8%
TY-76	2	50%	1	25%	1	25%	0	0%	0	0%	0	0%	0	0%	-	-	14%
TY-77	1	25%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	4%
TY-78	1	25%	1	25%	0	0%	2	38%	0	0%	0	0%	0	0%	-	-	13%
TY-79	0	0%	0	0%	0	0%	0	0%	0	0%	2	35%	0	0%	-	-	6%
TY-80	2	50%	0	0%	0	0%	0	3%	0	0%	0	7%	0	0%	-	-	8%
TY-81	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	-	-	0	1%	0,3%
TY-82	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	2	35%	-	-	6%
TY-83	0	0%	1	25%	0	0%	4	76%	0	0%	-	-	-	-	1	23%	21%
TY-85	0	0%	0	0%	0	0%	0	3%	0	0%	-	-	-	-	0	3%	1%
TY-86	2	50%	1	25%	0	0%	0	9%	0	0%	3	65%	0	0%	-	-	21%
TY-87	2	50%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	-	-	8%
TY-88	0	0%	0	0%	0	0%	0	0%	0	0%	1	11%	0	6%	-	-	3%
TY-90	0	0%	0	0%	0	0%	0	9%	0	0%	3	59%	0	0%	-	-	11%
TY-91	0	0%	0	0%	0	0%	0	3%	0	0%	1	24%	1	14%	-	-	7%
TY-92	2	50%	1	25%	0	0%	2	33%	0	0%	2	26%	0	0%	-	-	22%

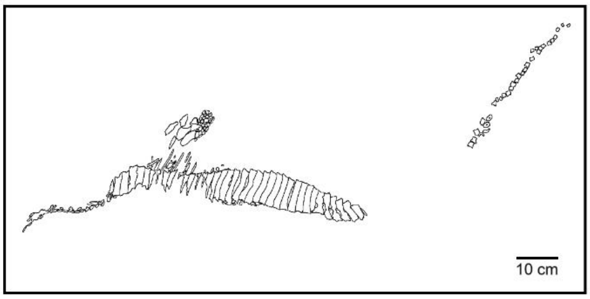
Appendix 2. Preservation State Table, indicating the preservation state of the Tyndall ichthyosaurs. The total corresponds to the total points obtained after analyzing and scoring each of the parameters (cracks, erosion, visible mineralization and biological colonization). Scoring system: 2 (unstable), 1 (stable) and 0 (does not present). The higher the score, the worse the state of preservation.

Specimen	**Percentage of Exposition**	**Cracks**		**Erosion**			**Visible Mineralization**				**Biological Colonization**		
ID	(%)	Empty	Filled	Loss of material	Fossil Erosion	Glaciar Striae	Oxides	CO_3	Pirite	Other	Lichen	Moss	**Total**
TY01	20%	2	0	1	1	1	1	0	0	0	0	0	6
TY02	3%	1	0	0	2	1	0	1	0	0	0	0	5
TY03	13%	1	0	0	2	1	0	0	0	2	0	0	6
TY04	11%	1	0	2	1	1	0	0	0	2	1	0	8
TY05	24%	1	0	1	2	1	1	1	0	1	0	0	8
TY07	0,4%	0	0	0	1	1	0	0	0	0	0	0	2
TY08	0,2%	0	0	0	1	1	0	0	0	0	0	0	2
TY09	19%	1	1	0	2	1	1	1	1	0	0	0	8
TY10	2%	1	0	0	2	1	0	0	0	2	0	0	6
TY11	36%	2	0	2	2	1	2	0	0	1	0	0	10
TY12	14%	2	1	0	2	1	1	0	0	1	0	1	9
TY13	3%	1	0	0	1	1	0	0	0	1	0	0	4
TY15	15%	1	1	1	2	1	0	1	0	1	0	0	8
TY16	9%	1	0	1	1	2	0	0	0	1	0	0	6
TY17	36%	1	1	0	2	1	1	0	0	0	1	0	7
TY18	4%	1	1	2	2	2	0	0	0	0	0	0	8
TY20	2%	0	0	0	1	1	0	0	0	2	0	0	4
TY21	4%	2	0	1	1	0	1	0	0	0	0	0	5
TY22	16%	2	0	1	2	1	1	0	0	1	0	1	9
TY23	1%	0	0	0	1	0	0	0	0	0	0	0	1
TY24	19%	1	1	2	2	2	0	0	0	1	0	0	9
TY25	13%	2	1	1	2	1	0	1	0	1	0	1	10
TY27	1%	0	0	0	1	1	1	2	0	0	0	0	5
TY29	5%	1	1	0	2	0	0	0	0	2	0	0	6
TY34	3%	2	1	2	2	1	1	2	0	0	0	0	11
TY38	40%	2	2	1	1	1	0	1	0	1	2	2	13
TY43	6%	2	1	2	2	1	2	0	0	0	2	2	14
TY44	16%	2	0	2	2	1	2	0	0	1	2	2	14
TY47	0,7%	1	0	1	1	1	0	0	0	0	0	0	4

TY48	17%	2	1	0	1	0	1	2	0	0	1	1	9
TY51	0,4%	1	0	0	1	0	0	1	0	0	0	1	4
TY52	6%	2	2	1	2	1	1	1	0	1	0	1	12
TY53	39%	2	2	1	2	1	1	2	0	2	0	1	14
TY-54	31%	1	1	1	2	1	1	1	0	1	0	0	9
TY55	12%	2	1	0	2	1	1	1	0	2	0	0	10
TY57	1%	1	0	0	1	0	2	0	0	0	0	0	4
TY61	22%	1	0	1	2	1	2	1	0	0	0	0	8
TY62	4%	1	1	1	2	1	0	0	0	1	2	1	10
TY68	4%	1	1	0	1	1	0	0	0	1	0	1	6
TY69	4%	2	0	1	2	1	1	2	0	0	0	0	9
TY70	16%	1	0	0	2	1	0	0	0	1	0	1	6
TY71	18%	2	1	1	2	1	1	1	0	0	0	0	9
TY72	38%	2	1	1	1	1	0	0	0	0	0	1	7
TY74	8%	1	0	2	1	1	1	0	0	0	0	0	6
TY76	14%	1	1	2	2	1	1	0	0	0	0	0	8
TY77	4%	2	0	2	1	0	2	0	0	0	0	0	7
TY78	13%	1	1	0	1	0	1	1	0	0	0	0	5
TY79	6%	1	1	0	2	1	1	2	0	1	0	0	9
TY80	8%	1	0	0	2	2	2	0	0	1	0	0	8
TY81	0,3%	1	0	1	1	0	1	0	0	1	0	0	5
TY82	6%	1	0	0	2	2	0	0	0	1	0	0	6
TY83	21%	2	1	1	2	1	2	1	0	0	0	0	10
TY85	1%	0	0	2	2	1	2	0	0	0	0	0	7
TY86	21%	1	0	2	1	1	1	0	0	1	0	1	8
TY87	8%	0	0	1	1	1	1	0	0	1	0	0	5
TY88	3%	1	1	0	2	1	2	1	0	0	0	0	8
TY90	11%	1	0	0	1	1	0	0	0	0	0	0	3
TY91	7%	0	0	0	2	1	0	0	0	2	0	0	5
TY92	22%	2	1	1	1	1	1	2	0	0	0	0	9

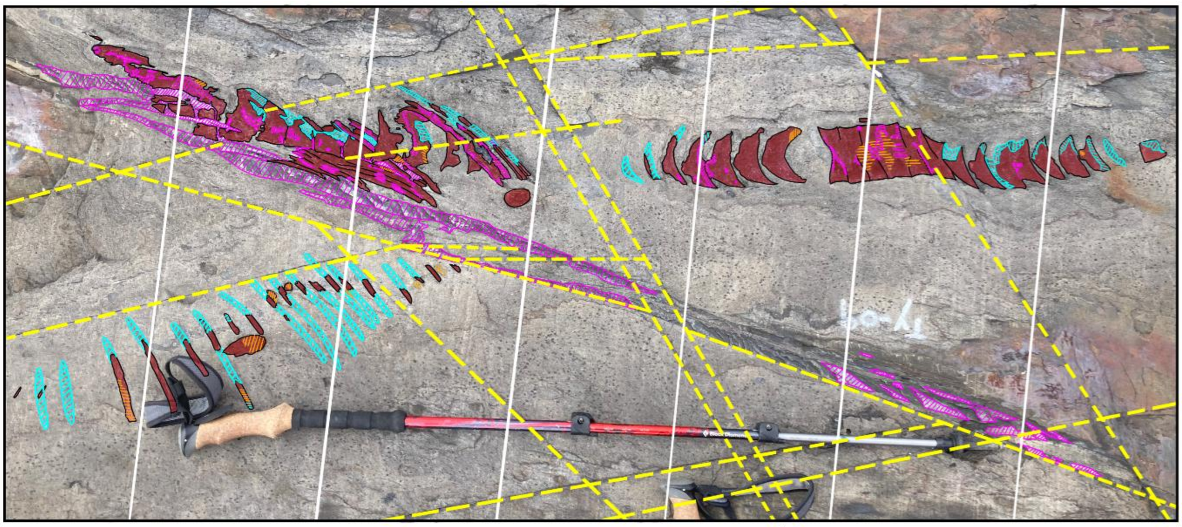
Appendix 3. Damage map of specimen TY-05. Author's own elaboration.

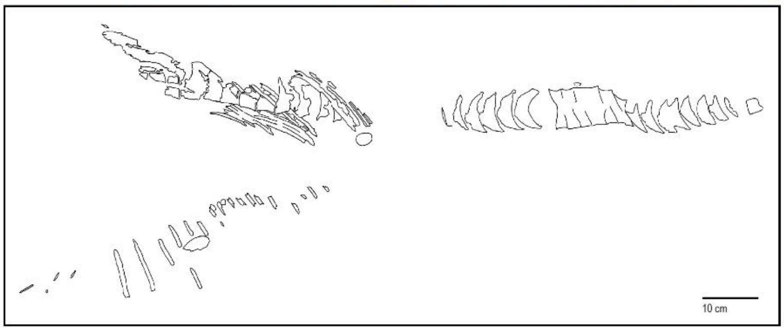




Additional Information	
Specimen	TY-05
General Description	Articulated skeleton of an adult specimen
Exposed Lenght	2.00 meters
Estimated Total Lenght	5.00 meters
Age	131 Myr
Exposition Aspect	Right lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

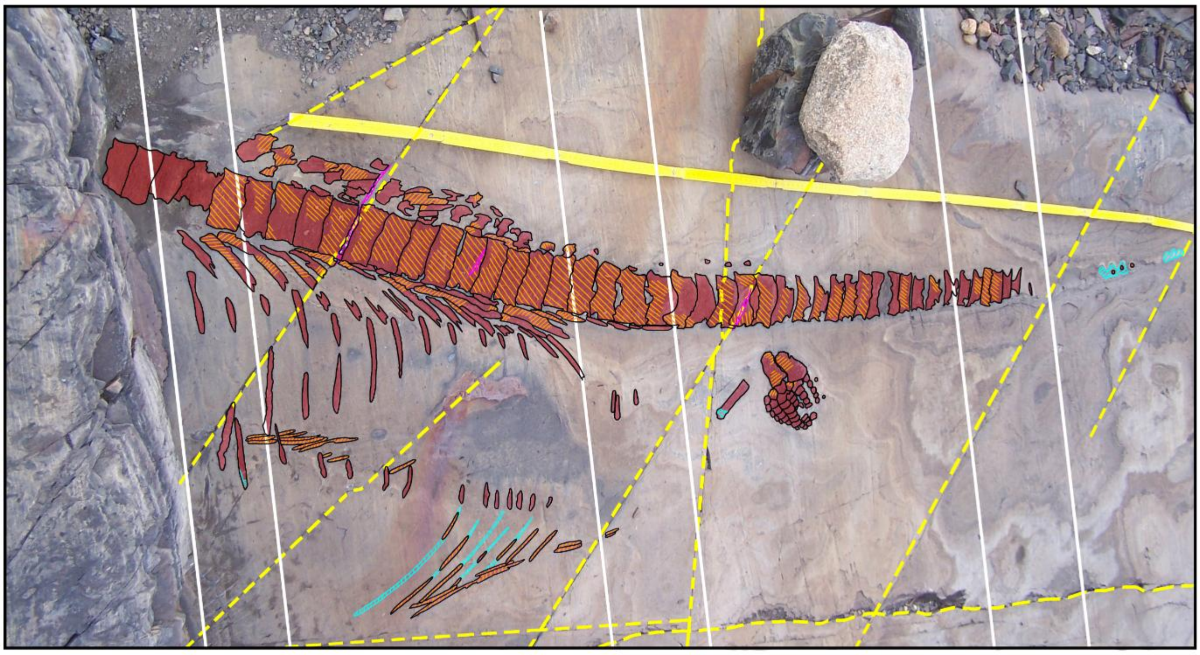
Appendix 4. Damage map of specimen TY-09. Author's own elaboration.

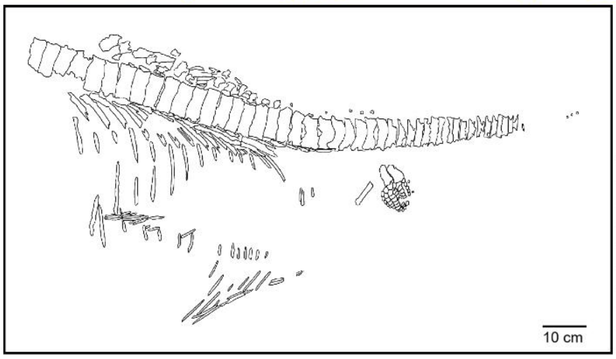




Additional Information	
Specimen	TY-09
General Description	Articulated skeleton of an adult specimen
Exposed Lenght	1.70 meters
Estimated Total Lenght	2.00 meters
Age	131 Myr
Exposition Aspect	Right lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

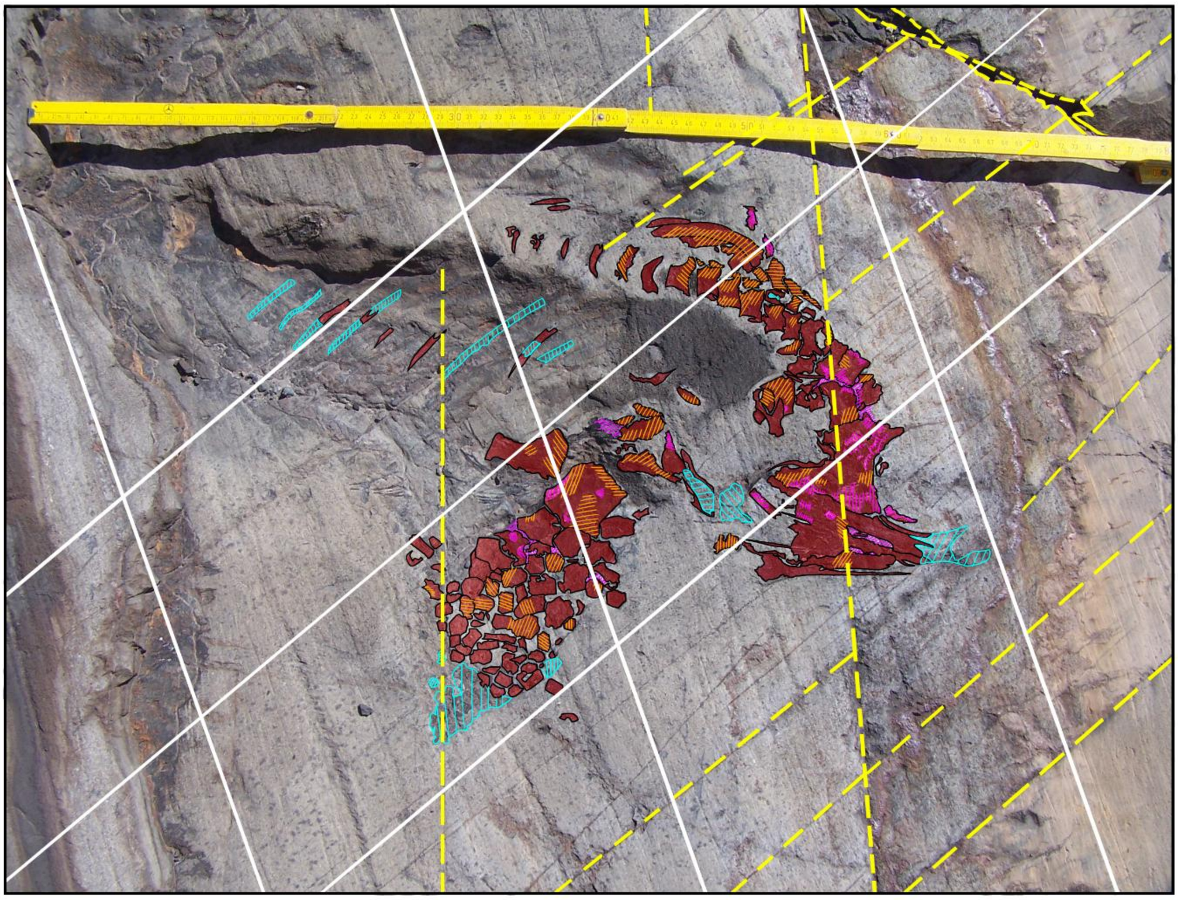
Appendix 5. Damage map of specimen TY-17. Author's own elaboration.

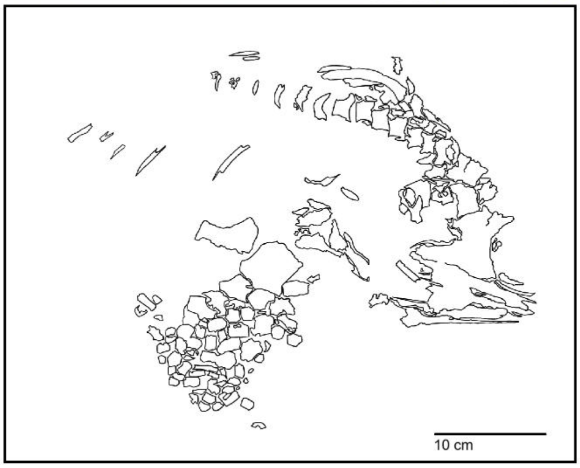


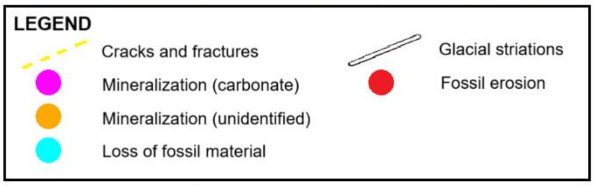


Additional Information	
Specimen	TY-17
General Description	Articulated skeleton of an adult specimen
Exposed Lenght	2.00 meters
Estimated Total Lenght	4.00 meters
Age	131 Myr
Exposition Aspect	Left lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 6. Damage map of specimen TY-24. Author's own elaboration.

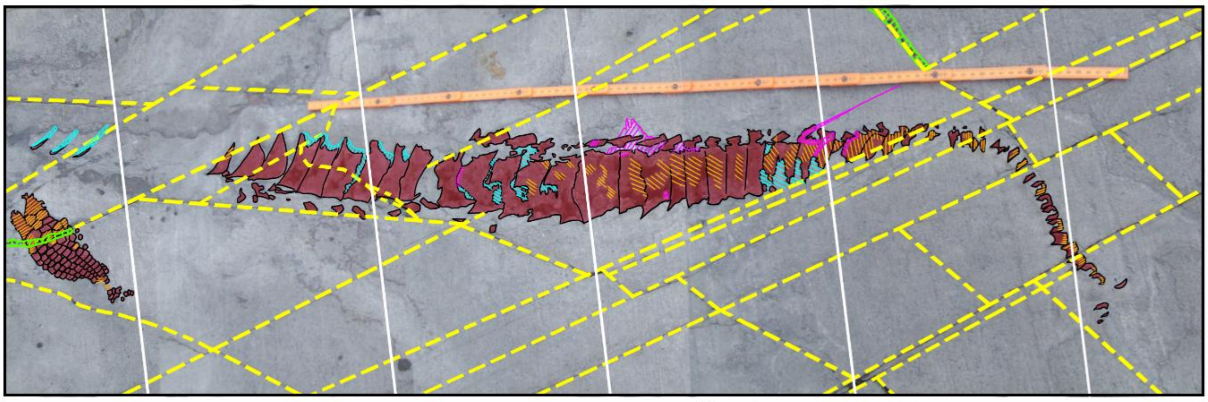


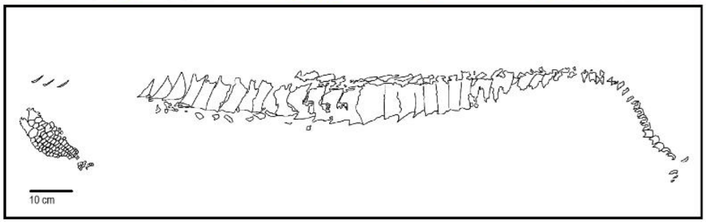


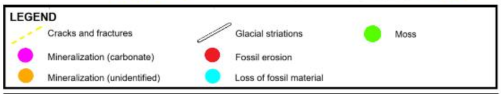


Additional Information	
Specimen	TY-24
General Description	Juvenile specimen with disarticulated craneal elements
Exposed Lenght	0.68 meters
Estimated Total Lenght	1.00 meters
Age	131 Myr
Exposition Aspect	Right lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 7. Damage map of specimen TY-25. Author's own elaboration.

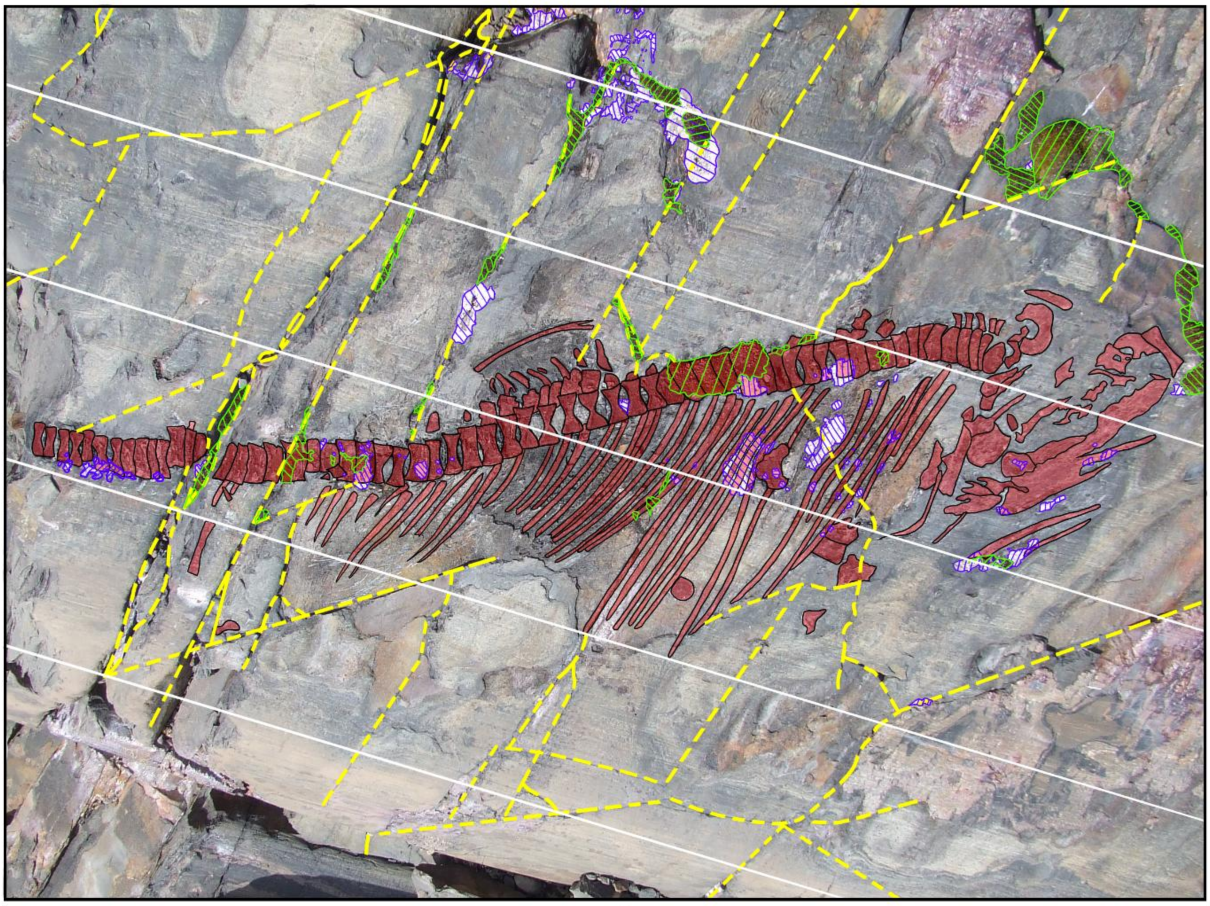


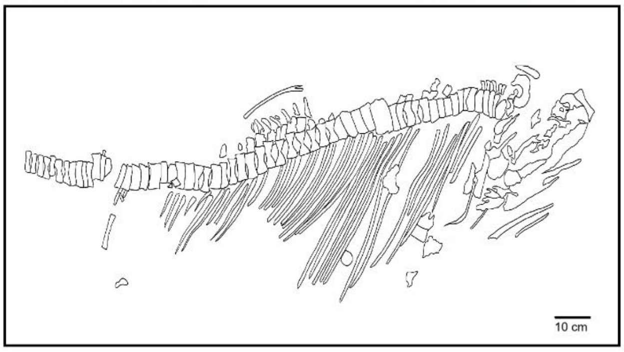


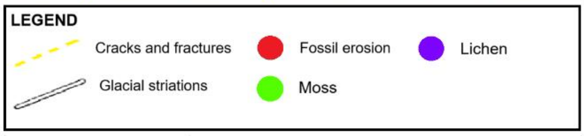


Additional Information	
Specimen	TY-25
General Description	Articulated skeleton of an adult specimen
Exposed Lenght	1.90 meters
Estimated Total Lenght	3.00 meters
Age	131 Myr
Exposition Aspect	Left lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 8. Damage map of specimen TY-38. Author's own elaboration.

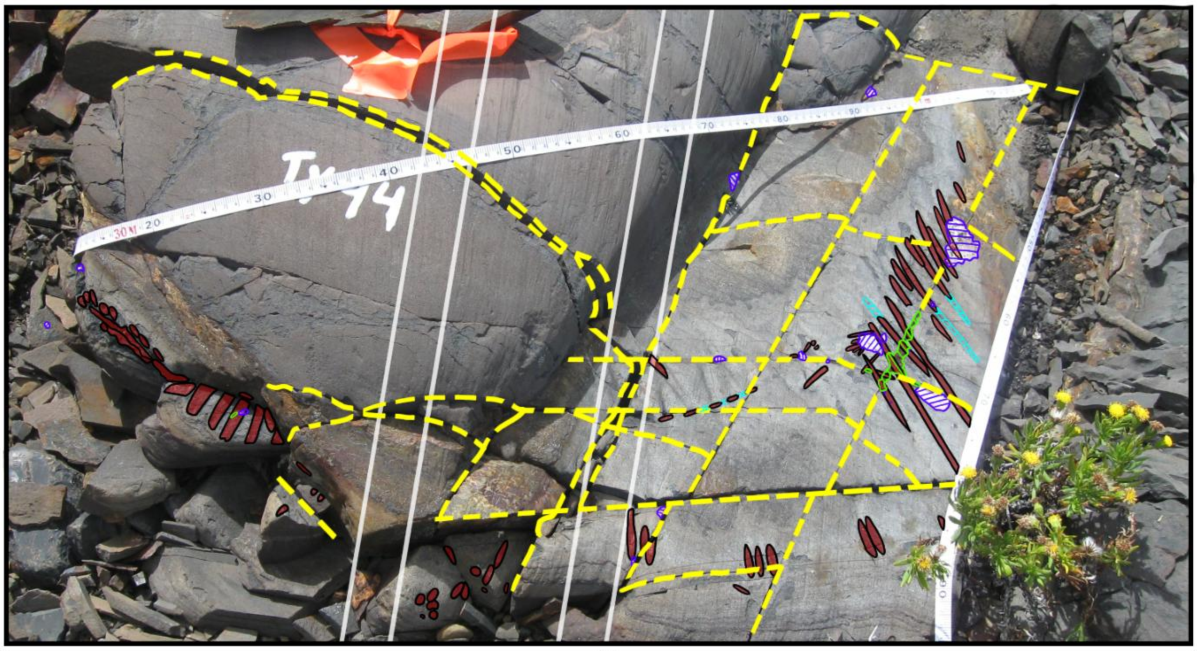


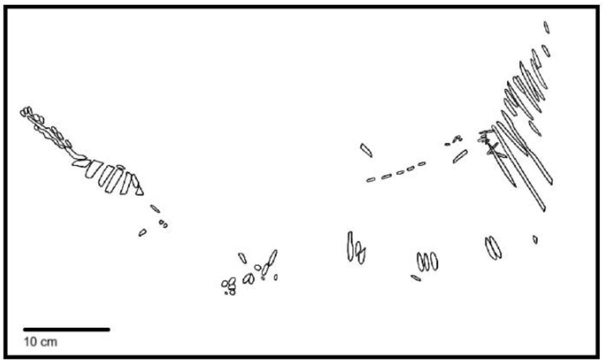




Additional Information	
Specimen	TY-38
General Description	Partially exposed elements of a juvenile specimen
Exposed Lenght	1.13 meters
Estimated Total Lenght	1.30 meters
Age	131 Myr
Exposition Aspect	Right lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 9. Damage map of specimen TY-44. Author's own elaboration.



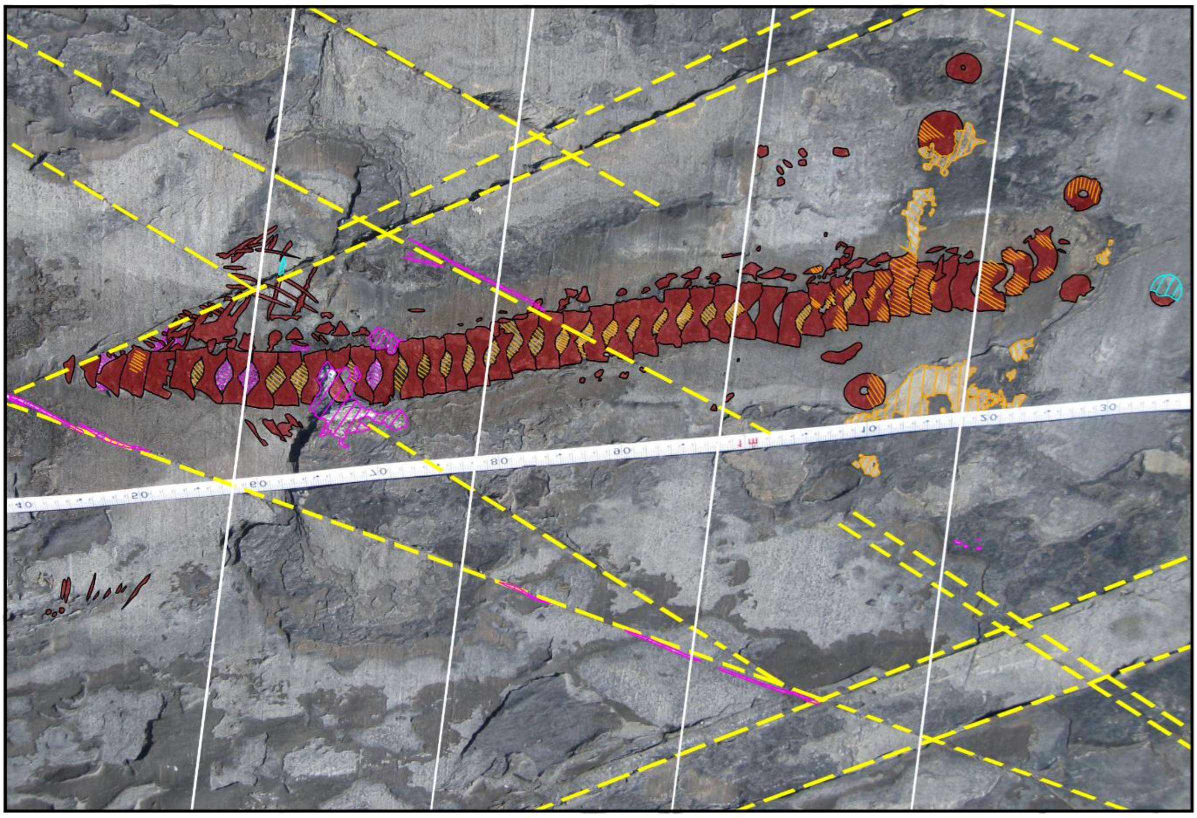


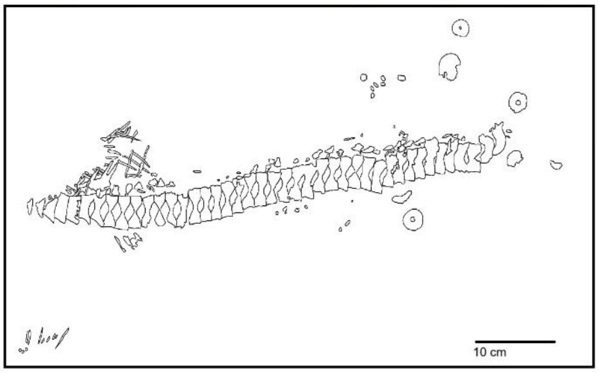
LEGEND

- Cracks and fractures
- Glacial striations
- Loss of fossil material
- Moss
- Fossil erosion
- Lichen

Additional Information	
Specimen	TY-44
General Description	Articulated adult specimen covered with sediment
Exposed Lenght	1.20 meters
Estimated Total Lenght	2.00-2.50 meters
Age	131 Myrs
Exposition Aspect	??
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

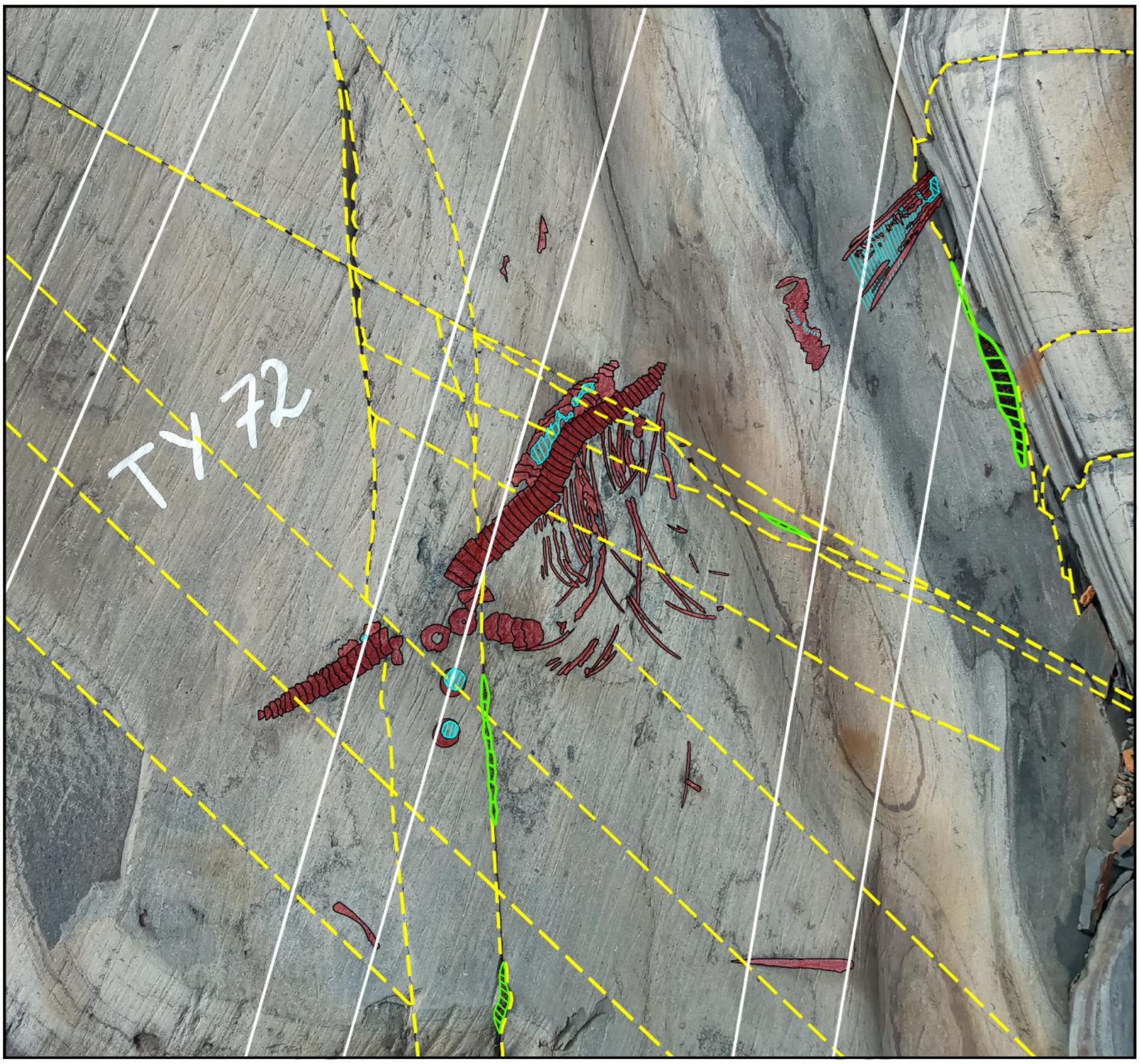
Appendix 10. Damage map of specimen TY-54. Author's own elaboration.

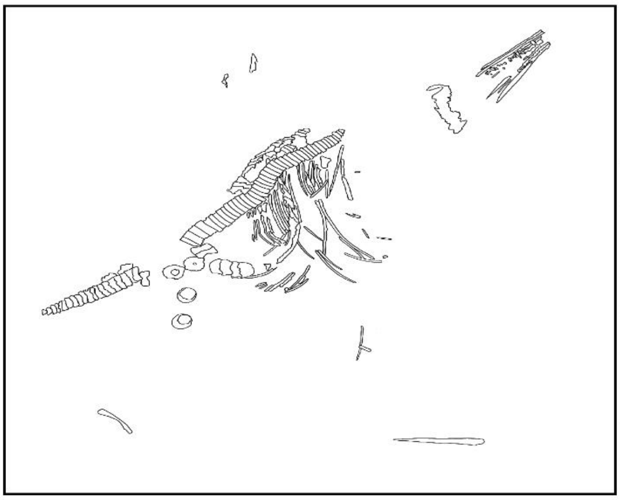




Additional Information	
Specimen	TY-54
General Description	Partially articulated skeleton of a juvenile specimen
Exposed Lenght	0.65 meters
Estimated Total Lenght	1.00 meters
Age	131 Myr
Exposition Aspect	Right lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 11. Damage map of specimen TY-72. Author's own elaboration.



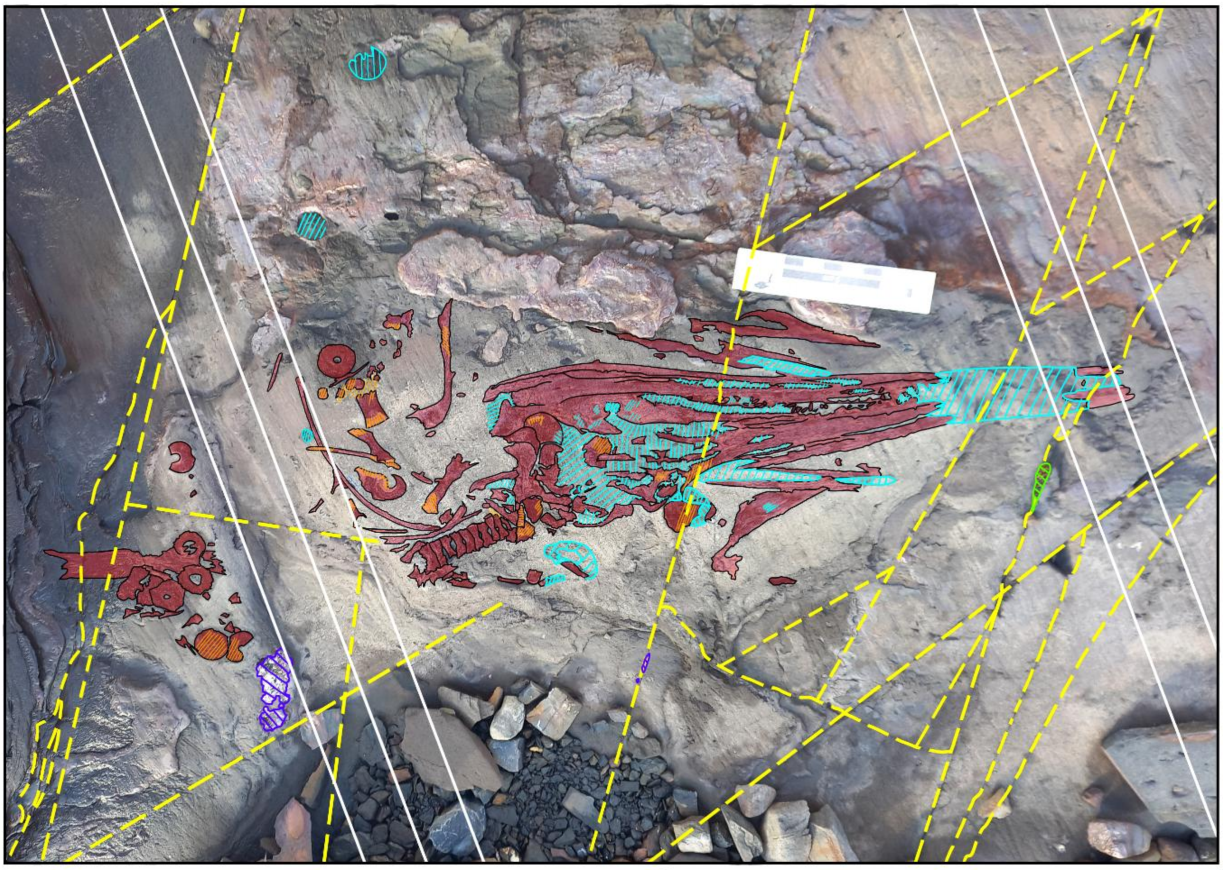


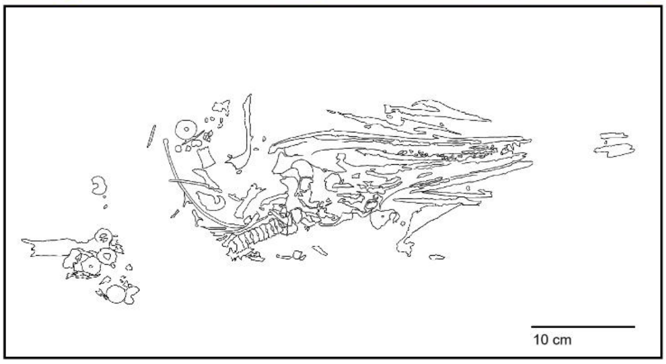
LEGEND

- Cracks and fractures
- Glacial striations
- Loss of fossil material
- Moss
- Fossil erosion

Additional Information	
Specimen	TY-72
General Description	Articulated juvenile specimen with craneal elements
Exposed Lenght	
Estimated Total Lenght	
Age	131 Myr
Exposition Aspect	Right lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 12. Damage map of specimen TY-86. Author's own elaboration.





LEGEND

- Cracks and fractures
- Glacial striations
- Lichen
- Mineralization (unidentified)
- Fossil erosion
- Loss of fossil material
- Moss

Additional Information	
Specimen	TY-86
General Description	Specimen with cranial and postcranial elements
Exposed Lenght	0.57 meters
Estimated Total Lenght	0.62 meters
Age	131 Myr
Exposition Aspect	Left lateral
Site	Tyndall glacier locality
Geological Formation	Zapata Formation

Appendix 13. Variation of temperature during winter months (June, July and August) between 2012-2019. Data source: Tyndall station (DGA: 12288000) of the DGA (Dirección General de Aguas), Climate Explorer Cr2.