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GIS-based methodology for mapping and modeling microbialite deposits in high mountain lakes and wetlands of Central Andes (Catamarca, Northwestern Argentina)

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Modern microbialites in Argentina's Puna (Central Andes) are considered a reliable tool for understanding the evolution of early life on our planet and developing strategies for detecting life on Mars. The morphological, structural and geochemical variations in these deposits, together with their distribution and architecture, are some of the most important parameters for understanding and characterising them. However, the lack of appropriate cartography and/or the high price to access it, added to the complex geological and geomorphological context in this region, complicate a traditional mapping on a good scale of detail. This paper presents a GIS-based methodology for a detailed mapping and architectural modeling of Las Quínoas microbialitic deposit (Holocene). To meet this objective, the geoprocessing of the information obtained from drone surveys, fieldwork and laboratory work, is carried out using ArcGIS software. The result is a high-resolution reconstruction of the deposit architecture, together with several thematic maps that represent the variation of the morphological, structural and geochemical characteristics of the oncoids (microbialites) with respect to depth and their position in the water body. From an integral point of view, this work provides a new methodological approach for microbialites mapping and improves the survey strategies in Central Andes.

Introduction

Microbialites have been defined as organo-sedimentary structures formed by the interaction between benthic microbial communities and detrital and/or chemical sediments present in marine, coastal or lake environments (e.g., Burne and Moore, 1987; Riding, 2008). Their construction can be accomplished by three processes that can act individually, together, or even alternate during their development: (1) trapping of sedimentary particles called-trapping and binding; (2) biomineralization of organic tissue; and (3) surface precipitation of minerals on organisms and/or sediments (Riding, 1991; Reid et al., 2000).

These structures are the oldest evidence of life on our planet and have been in the geological record for 3.45 billion years. The microbial communities that participated in their formation comprise the earliest ecosystems and have been the dominant life form for eighty percent of Earth's history, preserving their evolutionary lineage to the present day (Schopf, 1996; Grotzinger and Knoll, 1999). Because of this, microbialites records are considered tools of great importance for studying the evolution of life on our planet (e.g., Grotzinger and Rothman, 1996; Allwood et al., 2006; Awramik, 2006) and developing strategies for detecting life on other planets, such as Mars (e.g., Russell et al., 1999; Bianciardi et al., 2014; Blanco et al., 2014; Olcott Marshall and Cestari, 2015). Furthermore, the discovery of microbialitic oil reservoirs in the last decades (e.g., Grotzinger and Al-Rawahi, 2014; Coman et al., 2015; Muniz and Bosence, 2015) has considerably increased the interest in microbialite research, both fossil and modern ones, as an important source of information to parameterize and model these reservoirs (de Lima et al., 2018). In this context, the study of Holocene microbialites has become very important and many research efforts have been applied in the last years in several regions of our planet (Laval et al., 2000; Reid et al., 2000; Sprachta et al., 2001; Jahnert and Collins, 2012; White, 2020; among others).

In Puna region (Central Andes, Argentina), 12 Holocene microbialitic systems have been recognized to date, most of them still active (*see* Farías et al., 2020; Vignale et al., 2021). These belong to 45 Andean Microbial Ecosystems (AMEs) reported in Central Andes. Unlike modern marine microbialites, Puna microbialites formed under extreme extrinsic factors such as high salinity (125 mS), high

UV radiation, daily thermal amplitudes ranging from 20 to -10°C in summer and 10 to -40°C in winter, the highest surface solar radiation in the world (ca. 310 Wm^{-2}), a high monthly average daily insolation (6.6k Whm^{-2} d^{-1}), low level of nutrient availability, high content of arsenic (As) and high concentrations of heavy metals along with other elements toxic to human life (Farías et al., 2011; Belfiore et al., 2013; Farías et al., 2013; Albarracín et al., 2015). These extreme environmental conditions, similar to that predicted in primitive Earth ecosystems, increases the importance of Central Andes microbialites as an open window to the past (Farías et al., 2011; Acuña et al., 2020). The need to understand the interaction between the physical, chemical and biological parameters that generate these structures has positioned these systems as important records to study the origin of life on Earth and develop strategies for the search for life on Mars (e.g., Grotzinger and Rothman, 1996; Russell et al., 1999; Allwood et al., 2006; Awramik, 2006; Bianciardi et al., 2014; Blanco et al., 2014; Olcott Marshall and Cestari, 2015).

An important tool for determining and interpreting these parameters is the understanding of the spatial and bathymetric distribution of microbialites throughout the water bodies, since it can condition directly or indirectly factors that affect their growth and morphologies such as sedimentary contribution, calcium carbonate saturation, hydrodynamic energy, ecological factors, etc. (Playford and Cockbain, 1976; Sprachta et al., 2001; Suosaari et al., 2016; Baskin and Wright, 2018; Trembanis and Gutsche, 2019). This is why numerous studies show among their results the mapping of the microbialites spatial distribution and/or the modeling of the host water bodies (e.g., Andres and Reid, 2006; Mullins and Bird, 2007; Gischler et al., 2008; Suosaari et al., 2016; Berg, 2019; Trembanis and Gutsche, 2019; Wilcock et al., 2020).

Nevertheless, mapping and modeling any parameter of the Earth's surface is a complicated and delicate process, requiring some prior information. So the development and implementation of new methods that fulfill this work is a task of great urgency today (Kerimov, 2009). In Puna region, some issues make this delicate process even more difficult. The lack of appropriate cartography (and/or the high price to access it) and a complex a tectonic context are the firsts obstacles to overcome. In addition, the small size of the microbialites with respect to the large depositional areas, and the narrow bathymetric ranges in which they develop, make difficult to carry out a traditional mapping at a good scale of detail. However, thanks to advances in data processing and computational modeling derived from the use of remote sensors (through aerial drone surveys) and geographical information systems (GIS) applications, it is possible the mapping of these organo-sedimentary structures -at high-resolution.

This contribution proposes the use of a GIS-based methodology to perform a detailed mapping of the Holocene microbialites from Las Quínoas (Catamarca province), and a modelling of the host water body. In addition to this, it seeks to provide a detailed characterization of these organo-sedimentary structures throughout the deposit. Processed data produced cartography and 3D digital model which allowed a preliminary geometrical characterization and parameterization of the microbialitic deposit. The mapping provided a new and unique source of information for the region that can be useful to interpret the different properties of this deposit, allowing paleoenvironmental reconstructions, and enabling environmental conservation studies.

Study Area

Puna high plateau is a morphotectonic unit of Central Andes (Alonso and Rojas, 2020). Puna (in Argentina) and Altiplano (in Bolivia) are an elevated region rising to an average of 3,700 m.a.s.l., characterized by a steep local relief caused by contractional "basins and ranges, volcanoes, and sluggish erosion due to an arid climate (Kraemer et al., 1999). Puna region exhibits sedimentary basins with thick sequences of Miocene to recent in age continental evaporates, unconformably overlying Late Eocene to Miocene clastic deposits (Kraemer et al., 1999; Alonso et al., 2006). The endoreic drainage of their basins, added to an arid-to-semiarid climate, allows the formation of lacustrine evaporites environments resulting in salt flats (Jordan and Mpodozis, 2006).

One of the salt flats found in the Puna region is Salar de Antofalla. This salt flat, located in the province of Catamarca, is approximately 140 km long and 4 km to 10 km wide (Voss, 2002). The evaporitic deposits that make up Salar de Antofalla consist essentially of chlorides and sulfates of sodium, calcium, potassium, magnesium and lithium (Seggiaro et al., 2019). In its interior and margins, several water bodies (lakes and wetlands) with the presence of microbialites have been reported (*see* Farías et al., 2020; Vignale et al., 2021).

Las Quínoas is a Holocene microbialitic deposit of oncoid type, located in the west margin of the Salar de Antofalla salt flat, at 3,334 meters above the sea level (Farías, 2017) (Fig. 1a, b). The oncoids are distributed along channels, in a transitional area between Las Quínoas wetland and the salt flat, which make up a narrow belt that extends about 800 m on the salt flat margin in a North-South direction (Villafañe et al., 2021a) (Fig. 1c, d). Based on their morphology and water flow, channels can be divided into two areas: i) Distal area, close to the wetland, where the channels born (Fig. 1e); and ii) proximal area, close to the salt flat, where the channels discharge (Fig. 1f). The water flows mainly from distal to the proximal area, in a west-east direction (Farías, 2017; Villafañe et al., 2021a) (Fig. 1d). Villafañe et al. (2021a) suggest that size and shape of the oncoids is control by their position in the channels. Upstream of the channels (distal area), predominate sub-rounded oncoids of sizes smaller than 8 cm. Near the discharge area of the channels in the salt flat (proximal area), the size of the oncoids increases (they exceed 10 cm), as well as the presence of the discoid shapes.

Data and Methodology

Remote Sensors and Softwares

The support mapping was obtained from the software SAS Planet, the information available from the Argentine Mining Geological Service (SEGEMAR) and the map HG 2769-II Paso San Francisco. Added to this, a bibliographic compilation of the Salar de Antofalla and the associated microbialitic deposits was made.Remotely sensing data of the outcrop was obtained with a drone Mavic Pro of DJI. To get the georeferenced photographs the drone uses a camera with an Effective Pixel of 12.35 M, a Total Pixel of 12.71 M and a camera sensor type 1/2.3" (CMOS). The camera lens is FOV 78.8 mm × 26.0 mm types, with a distortion <1.5% and a focus from 0.5 m.

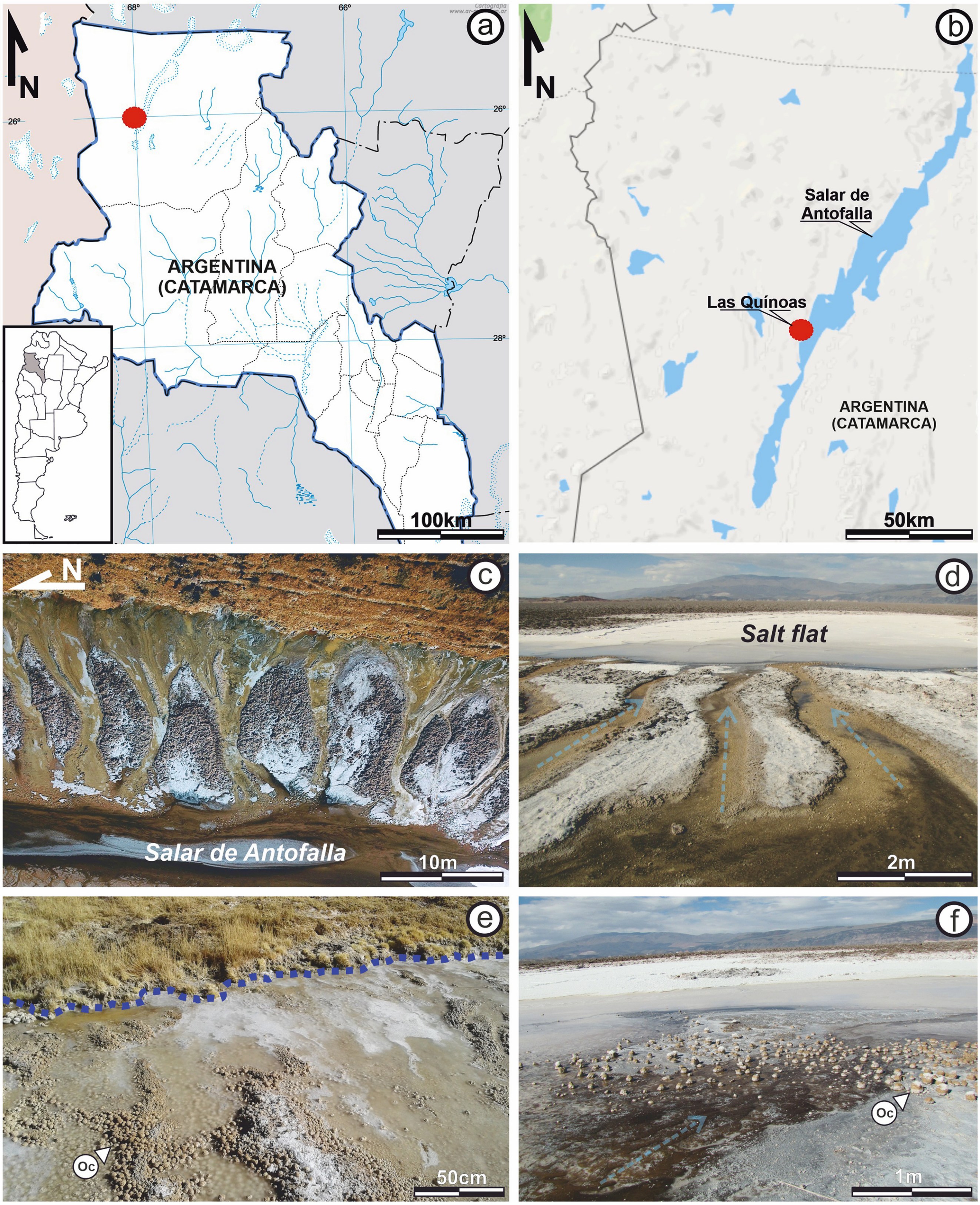

Figure 1. Geographical location of the study area. a) Location of the study area (red circle) in the province of Catamarca, Argentina. b) Location of the study area (red circle) in the salt flat (Salar de Antofalla). c) Narrow transition area developed between the salt flat and the wetland, in which channels flow into the salt flat and where the oncoids are deposited. Sky-blue arrows indicate the direction of water flow. d) Channels of up to 1.5 m width, which flow into the salt flat. Sky-blue arrows indicate the water flow direction. e) Channel distal area with rounded oncoids (Oc) of small diameters (less than 7 cm), close to the wetland (dotted blue line). f) Channel discharge area in the salt flat (proximal area), where the channels open in the form of fans. In this area the size of the oncoids (Oc) increases (>10 cm in diameter) and they have discoidal morphologies. Sky-blue arrow indicates the direction of water flow.

Based on this photographic information, Agisoft Metashape Pro software was used to obtain a nonprojected georeferenced orthomosaic in WGS84 Datum. This orthomosaic was processed from ArcGIS software to elaborate the mapping of the workplace.

Methodology

With supported satellite images obtained from SAS Planet software and the geological information provided by SEGEMAR, a delimitation of the microbialitic deposit was made. Combining both information sets, a geological map of the work area and its surroundings was carried out using ArcGIS software.

The deposit was relieved by the use of a drone. A close-range photogrammetric survey was conducted and 120 images were selected to achieve a good image overlap. In addition, a systematic and representative sampling of the oncoids was carried out. For this, 6 channels have been sampled, both in the distal and proximal area, obtaining 12 sampling points along the deposit (Supp. 1). Four samples were taken at each sampling point, giving a total of 48 samples studied for this work (Supp. 1). Samples collected are currently housed in the Paleontología de Invertebrados Lillo collection (PIL17.150–17.160) of the Universidad Nacional de Tucumán (UNT, Tucumán, Argentina). Morphological, structural and geochemical information of oncoids in the sampling point are registered according several variables generating an Attribute Table (Table 1).

Oncoids were processed at the Centro de Investigaciones Geológicas de la Universidad de la Plata (CIG–UNLP–CONICET, La Plata, Argentina) for the preparation of thin and polished sections, and were analysed at the Instituto Superior de Correlación Geológica (INSUGEO-UNT-CONICET, Tucumán, Argentina). Their study was carried following the traditional multiscale approach methodology (e.g., Shapiro, 2000; Vennin et al., 2015), and its results and interpretations are complemented by the information published in Villafañe et al. (2021a).

High-resolution digital photogrammetry was applied to achieve an objective representation of the deposit. Generation of a non-projected georeferenced orthomosaic in WGS84 Datum, textured mesh, was obtained running the process through the software Agisoft Metashape Pro (version 1.5.2, Educational License). To correctly scale the model, a set of metric reference markers was used. To control georeferencing, the orthomosaic was projected using ArcGIS software on a satellite image of the work area obtained from SAS Planet software.

The orthomosaic was processed from ArcGIS software. First, a high-detail topographic map of the deposit was obtained, and after that a 3D modelling (TIN) was carried out, in which the architecture of the outcrop was reconstructed. Secondly, the channels were delimited with their respective bathymetry.

After channels delimitation, a georeferenced layer of sampling points was generated. Georeferencing allows relate morphological and geochemical characteristics from the sampling points with respect to the depth and geographical position in the deposit, so allowing generate thematic maps representing the variation of oncoids characteristics in relation with the depth and position in the water body.

Attribute Table Structure

In the Attribute Table, variable "Sample point" expresses the channel where the samples were taken with a number, and with a letter the position of the samples in the channel. Samples obtained from the distal area are named by the letter A, while those from the proximal area by the letter B. The next column, "Deposit", contains the name of the deposit. This is done in case in the future is needed to extend the mapping or correlate with other deposits. Finally, coordinates of the sampling points are represented in the variables "Latitude" and "Longitude" by means of decimal degrees.

Variable "Diameter" of the Attribute Table represents an average of the oncoids diameters at each sampling point. If this average is between 1 and 6 cm is named with the letter S, if this average is between 6 and 12 cm is named with the letter M, and if this average is between 12 and 18 cm is named with the letter L. "Relative diameter" expresses through numerical values diameter categories, 10 for letter S, 20 for letter M and 30 for letter L. Finally, "External morphology" represents by means of letters the two types of external morphologies observed in the oncoids samples: R for rounded external morphology and D for discoidal external morphology (Table 1, Supp. 2). These morphologies were determined through visual evaluations, supported by the concepts proposed by Seul et al. (2020).

Table 1. Attribute Table. Table showing the different parameters measured at the sampling points along the site

FID	Shape	Sample point	Deposit	Latitude	Longitude	Diameter	Relative diameter	External morphology	Nucleus zone	Well laminated zone	Poorly laminated zone	Surface without porosity	Surface with porosity	Ca/Mg Ratio
0	Point	1 A	Las Quínoas	25°52′5.836″S	67°54′23.910″W	S	10	R	1.5	2.5	1.0	80.40	19.60	20
1	Point	1 B	Las Quínoas	25°52′5.996″S	67°54′23.119″W	L	30	D	1.5	2.5	2.5	74.40	25.60	20
2	Point	2 A	Las Quínoas	25°52′7.750″S	67°54′24.285″W	S	10	R	0.5	1.5	0.5	90.60	9.40	20
3	Point	2 B	Las Quínoas	25°52′7.814″S	67°54′23.875″W	M	20	D	0.5	2.0	3.5	84.22	15.78	30
4	Point	3 A	Las Quínoas	25°52′10.331″S	67°54′24.804″W	S	10	R	1.0	1.5	0.0	88.40	11.60	30
5	Point	3 B	Las Quínoas	25°52′10.535″S	67°54′24.480″W	M	20	D	1.5	2.5	5.0	79.50	20.50	30
6	Point	4 A	Las Quínoas	25°52′12.304″S	67°54′25.089″W	S	10	R	0.5	1.5	0.0	85.20	14.80	20
7	Point	4 B	Las Quínoas	25°52′12.180″S	67°54′24.711″W	L	30	D	1.0	3.0	3.0	78.40	21.60	30
8	Point	5 A	Las Quínoas	25°52′13.875″S	67°54′25.404″W	S	10	R	3.0	1.5	0.0	86.10	13.90	20
9	Point	5 B	Las Quínoas	25°52′14.045″S	67°54′25.013″W	L	30	D	4.0	2.0	1.0	79.80	20.20	20
10	Point	6 A	Las Quínoas	25°52′15.504″S	67°54′25.497″W	S	10	R	1.0	1.0	0.0	89.90	10.10	20
11	Point	6 B	Las Quínoas	25°52′15.403″S	67°54′24.736″W	M	20	R	1.5	1.5	4.0	82.90	17.10	10

Based on their textural and lithological characteristics, Villafañe et al. (2021a) indicates the presence of three types of internal structures (zones) in Las Quinoas oncoids: A *nucleus zone* made up of various lithologies in the central part of the samples, a *well-laminated zone* where the lamination is continuous around the nucleus, and a *poorly-laminated zone* in the external part of the sample where the lamination is interrupted by the presence of clastic material. The variables "nucleus zone", "well-laminated zone" and "poorly-laminated zone"), indicate in centimeters the thickness of these zones for each sampling point measured on polished sections (Supp. 2). It should be taken into account that the thicknesses of these internal structures are variable throughout the sample, so measurements are made on the best preserved areas.

Using thin sections, percentage of porosity was calculated for each sample, estimated by point counting. "Surface with porosity" represents the average percent porosity at each sampling point. While "Surface without porosity" represents the average percentage of non-poral space at each sampling point (Supp. 3). Finally, the thin sections were dyed according to the methodology of Kaufman et al. (1990). It allows us to determinate in a qualitatively way Ca / Mg ratio. Parameter "Ca/Mg Ratio" presents values of 10 when Ca > Mg, values of 20 when Ca = Mg and values of 30 when Ca < Mg (Supp. 3).

Analysis Approaches and Results

In order to delimit the distribution of Las Quínoas oncoids, reconstruct the architecture of the deposit and know the relationship between the characteristic of the microbialites and the lying area, different thematic maps have been prepared to improve the resolution of the existing cartography and satellite images. The methodology for preparing this new cartography and its results is as follows.

Preparation of General Geological Map

In a first stage, a geological map of the work area and its surroundings was carried out. A satellite image of the area, obtained from SAS Planet software, was used as a basis. On this, lithological information provided by the HG 2769-II Paso San Francisco was digitized using ArcGIS software. Each lithological unit or rock type is classified according to the legend available on the geological map.

Subsequently, and in the same way, geological structural information (lineaments, faults and folds) provided by SEGEMAR were digitized. Different structures that should be mapped have been represented on the map with appropriate line symbols. Additionally, numerical and graphic scales were added, along with the coordinate grid.

As a result, a geological map with a scale of 1: 80,000 was obtained in which the work area is located (Fig. 2). Las Quinoas deposit develops on the west margin of the Salar de Antofalla (salt flat). However, despite the extensive development of the salt flat, the cartography show that the deposit is associated only with the lithology of the Upper Member of the Vizchera Formation. This formation has a lower to middle Miocene age and is composed of sandstones, conglomerates, tuffs and pyroclastic deposits.

Preparation of Georeferenced Orthomosaic

In the first instance, using the images captured in the aerial survey carried out by drone, an orthomosaic of the site was made. For this, the images were processed with Agisoft Metashape Pro, obtaining an orthomosaic in TIFF format, with a resolution of 3747 × 4096 pixels, a horizontal resolution of 96 dpi, a vertical resolution of 96 dpi and a bit depth of 32. The orthomosaic was georeferenced in a geographic coordinate system and WGS84 Datum (Fig. 3).

Using ArcGIS software, the orthomosaic was projected on a satellite image of the work area obtained from SAS Planet software, to corroborate a correct projection and an improvement in image quality and resolution. Subsequently, as it is already known through previous work (Villafañe et al., 2021a) that the oncoids position is limited to the channels, the peripheral zones of the orthomosaic were cut out to obtain an image that was easier to work with and centered on the outcrop area. Additionally, numerical and graphic scales were added, along with the coordinate grid.

As a final result, a 1: 1,400 scale mapping is obtained which shows an orthomosaic of the deposit (Fig. 4). This map improves the resolution of the deposit with respect to satellite images, providing important information of the hydrology and geomorphology of the work area and allows the identifications of the channels where the oncoids lie.

Preparation of Detail Topobatimetric Map and DEM

Topographic information (contour lines) was obtained by geoprocessing of the orthomosaic with the ArcGIS software. The information from the images that make up the orthomosaic indicates that the work area it is between 3503.23 meters and 3504.34 meters above sea level (m.a.s.l.). 429,404 contour lines were designed with an equidistance of 12 cm, allowing a detailed reconstruction of the topography of the deposit (Supp. 4). Ten different height values were obtained, represented by the numbers 0 (3503.23 m.a.s.l.), 25 (3503.35 m.a.s.l.), 50 (3503.47 m.a.s.l.), 75 (3503.59 m.a.s.l.), 100 (3503.71 m.a.s.l.), 125 (3503.83 m.a.s.l.), 150 (3503.95 m.a.s.l.), 175 (3504.07 m.a.s.l.), 200 (3504.19 m.a.s.l.) and 225 (3504.31 m.a.s.l.).

With the topography, elaboration of a Digital Elevation Model (DEM) was carried out. This was developed based on an irregular network of triangles (TIN), generated from features that contain elevation information. In addition to this, based on the information available by SEGEMAR and the field survey, a drainage raster was prepared in the area to shows the direction of water flow along the channels. Finally, numerical and graphic scales were added, along with the coordinate grid.

As a final result, 1:1,400 scale cartography is obtained where by a legend colour-based the elevations of the terrain are represented, and the flow directions of the channels are expressed by arrows (Fig. 5). This cartography provides excellent information of the geomorphology of the work area and the morphology of the channels. In addition to this, it can be seen how the water flows from west to east direction (distal area to the proximal area). However, when water reaches the salt flat, its flows in a north-south direction.

Limitation of the Oncoids Lying Area

Based on field work and bibliography, it is known that Las Quínoas

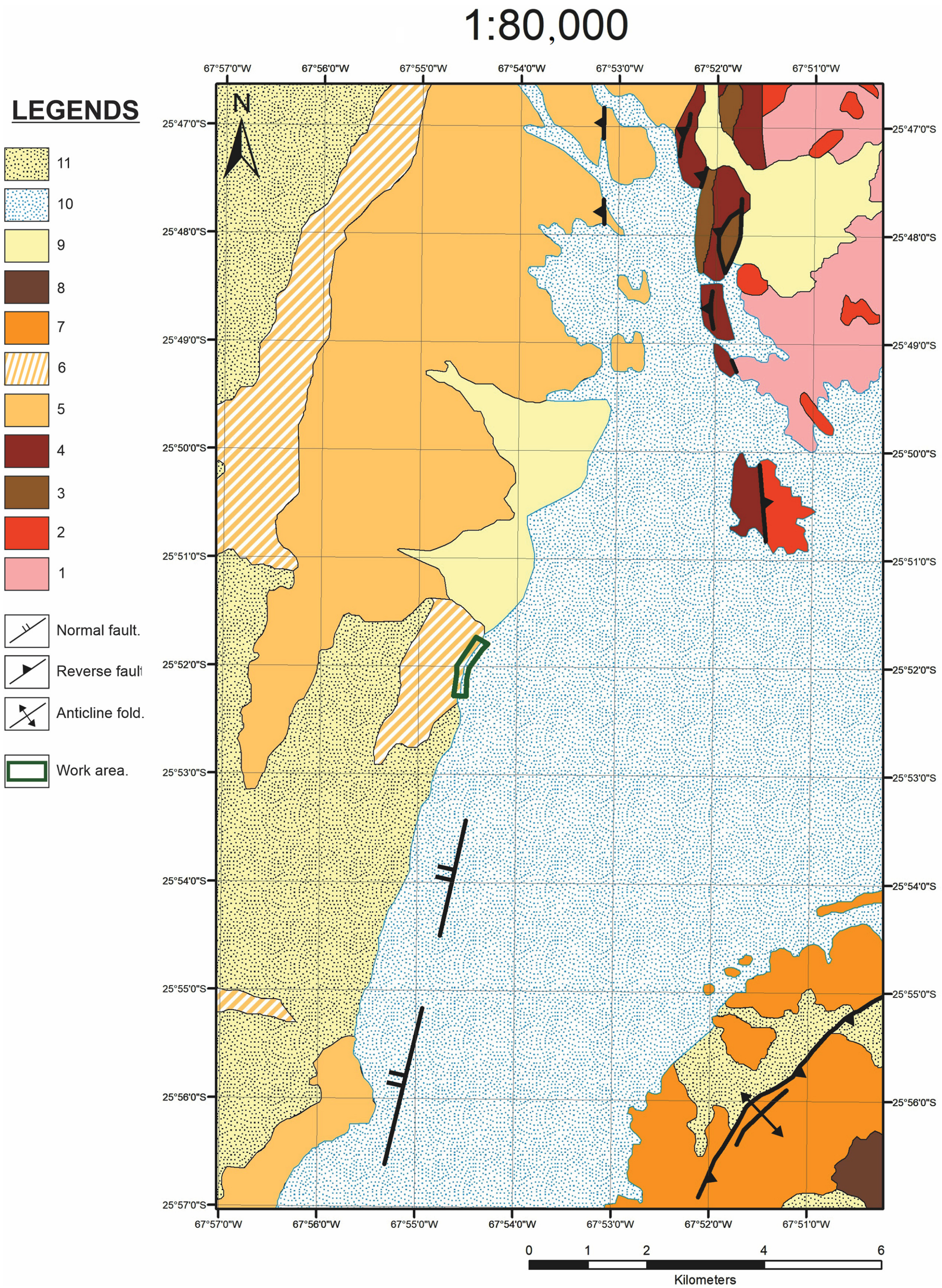

Figure 2. Geological and stratigraphic framework of Las Quinoas and its surroundings. 1- Medium to high-grade metamorphites (Upper Neoproterozoic to Cambrian), 2- Campo Negro Granite (Lower Ordovician), 3- Cortaderas Chicas volcanic-sedimentary complex (Middle to Lower Ordovician), 4- Patquia-De la Cuesta Formation (Ordovician), 5- Lower Member of the Vizchera Formation (Oligocene to Lower Miocene), 6- Upper Member of the Vizchera Formation (Lower to Middle Miocene), 7- Sijes Formation (Upper Miocene), 8- Vulcanites (Lower Pliocene), 9 - Alluvial deposits (Holocene), 10- Salar de Antofalla (Holocene) and 11- Colluvial deposits (Holocene).

Figure 3. Georeferenced orthomosaic obtained by image processing in Agisoft Metashape Pro software.

oncoids are distributed along channels, in a transition area between a wetland and the salt flat (Farías, 2017; Villafañe et al., 2021a). Therefore, to carry out the mapping of its lying area we need map the channels with a high degree of detail. For this, it is necessary to know the altitude range in which channels are included, their morphologies, and be able to differentiate them from other geomorphological structures included in the same altitude range. That is why for the preparation of this cartography the superposition of the orthomosaic with the topographic information and the Digital Elevation Model (DEM) of the work area are required.

Orthomosaic provides excellent information of the hydrology in the work area. Based on visual interpretation, a preliminary mapping of the channels was carried out. The photointerpretation criteria used to identify the channels are tone, texture, morphology and location in the image.

Using the superposition of the orthomosaic with the topography information, we can know that the channels are in a range of height comprised by the contour lines 100, 75, 50, 25 and 0. The contour line 0 it's the lowest not only for the channels but for the entire orthomosaic. Initially, the entire image was classified into two main areas: the areas above the contour line 100 and the areas below the contour line 100. However, not all the areas below the contour line 100 can correspond to channels, since the terrain may have other depressed areas that are not related to them.

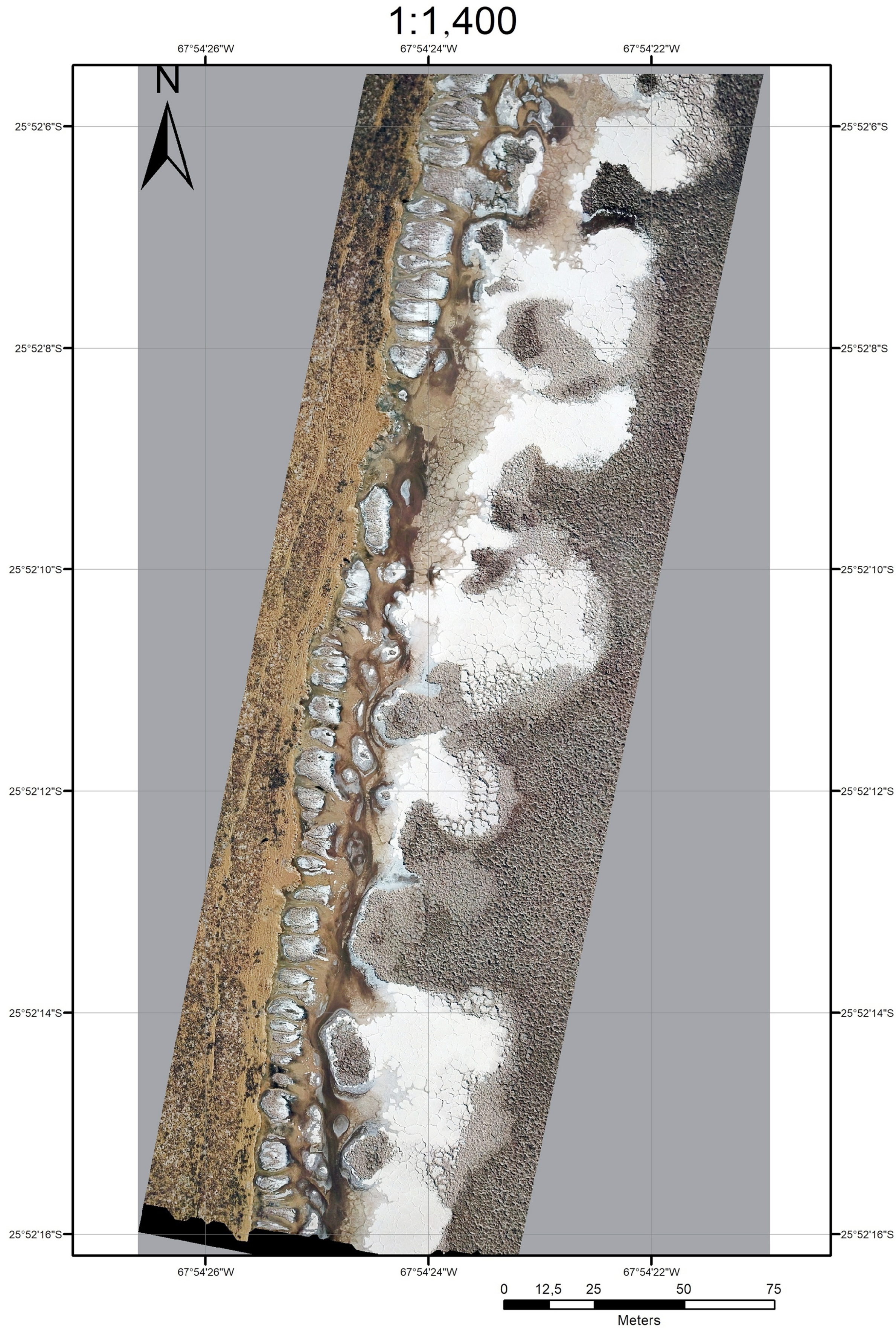

Figure 4. 1: 1,400 scale mapping, made using the orthomosaic obtained by drone survey. It highlights the high degree of resolution in the channels along the Las Quínoas deposit.

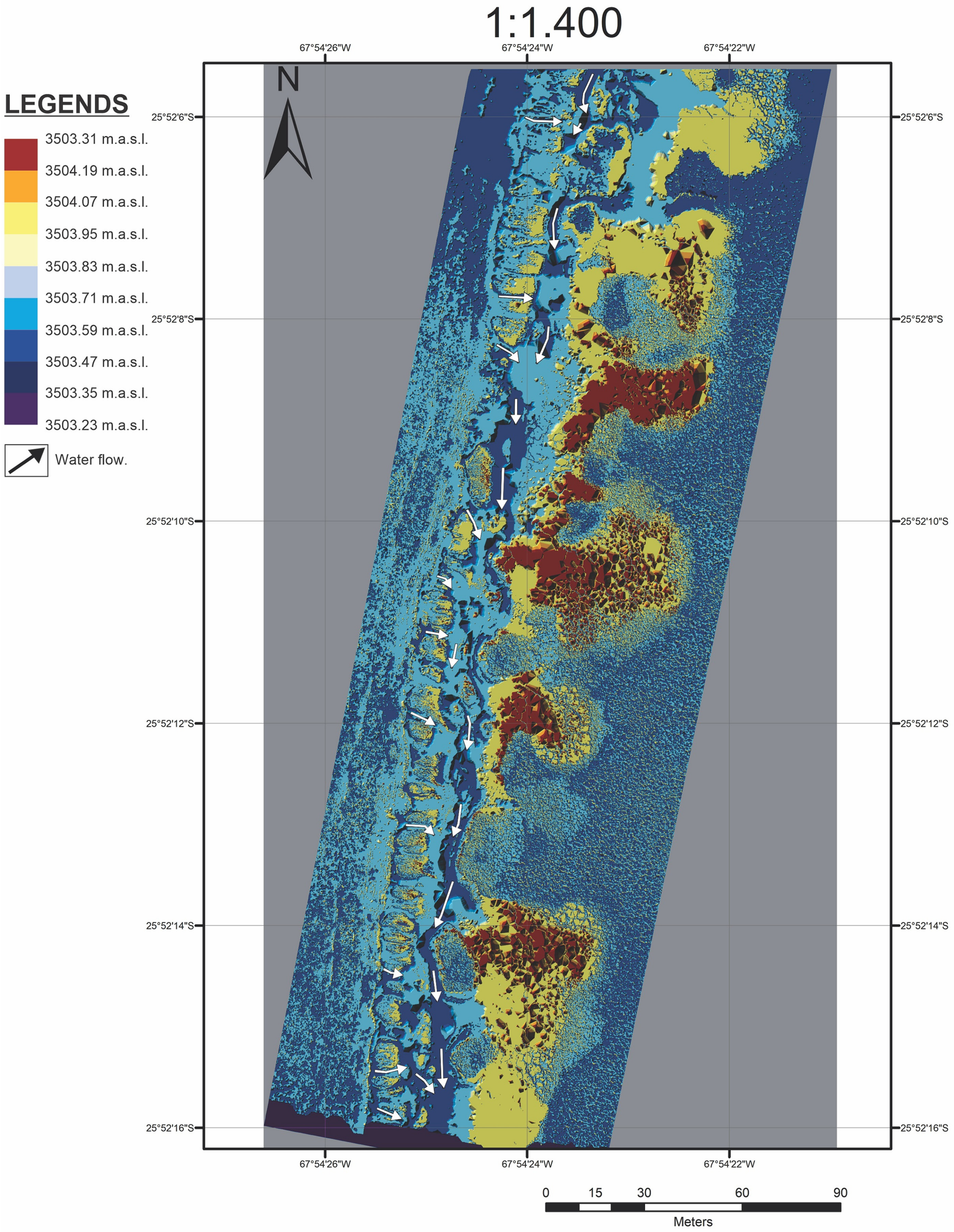

***Figure 5.** Cartography at a scale of 1: 1,400 where the elevations of the terrain are represented by a legend colour-based, and the directions of flow in the terrain are indicated.*

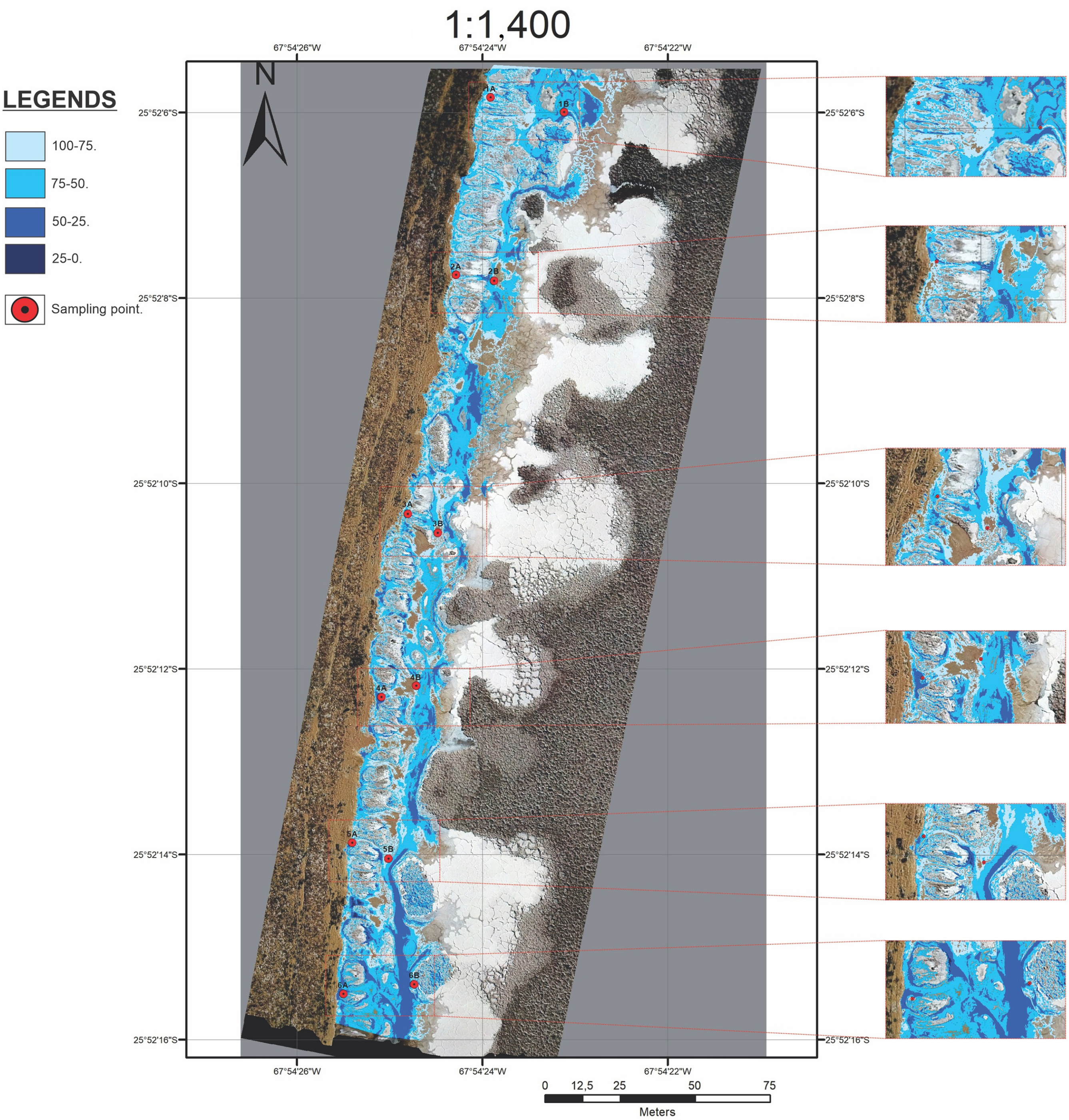

Figure 6. Cartography at a scale of 1: 1,400 showing the morphology of the channels, their depths and the location of the sampling points in the reservoir.

By superimposing the areas below curve 100 with the DEM, the channels are differentiated based on their location and morphologies from the rest of the depressed areas. Once differentiated, the channels are exported in a separate layer that is projected onto the orthomosaic. Since the channel layer is made up of various contour lines between the heights of 100 and 0, the internal section of the channels is colour based on their depth, obtaining a bathymetric representation through a legend colour-based.

Subsequently, with the Attribute Table (Table 1) a point layer is created based on sampling point's coordinates. This layer is projected on the channel layer and the orthomosaic, obtaining the position of the sampling points in the deposit and containing their morphological and geochemical information. Finally, numerical and graphic scales are added, along with the coordinate grid.

As a final result, a 1:1,400 scale mapping is obtained where the morphology of the channels, their depths and the location of the sampling points in the deposit are observed (Fig. 6). This map shows that channels have a length of up to 20 meters and a width of up to 2 meters, presenting anastomosed morphologies with intermediate bars. The depth of the channels is up to 0.48 meters, and it remains constant as we move from the distal to the proximal area. However, oncoids usually occur at depths of up to 0.24 meters.

Oncoids Distribution vs Morphological and Geochemical Characteristics

Knowing the relationship that exists between the characteristics of oncoids and their distribution along the channels, this allows us to discuss the influence of the extrinsic factors of the environment (such as depth, distance from transport and sedimentary input) in their growth. To show that a GIS-based methodology can be a very useful tool for this, different maps have been made integrating the information contained in the Attribute Table (diameter, external morphology, internal morphology, porosity and Ca/Mg ratio) with the lying area cartography.

Microbialites distribution vs external morphology and diameter

The purpose of this mapping is to represent the relationship between the external morphology of the oncoids, its diameter, and their position in the water body. That is why for its preparation the superposition lying area cartography with the information of the sampling points Attribute Table is used.

The information of the external morphology is found in parameter "External morphology" of the Attribute Table. Two types of oncoids external morphologies are represented: Rounded- R and discoidal- D. While for the diameter, the column "Diameter" of the attribute table was used (Table 1).

In the cartography, diameters and external morphology are represented with respect to the position of the sampling points both in the lying area map. To express the external morphology, the samples with an R value in the "External morphology" column of the Attribute Table are represented with the symbol *Circle 1*, while the samples with a D value in the "External morphology" column of the Attribute Table are represented with the symbol *Diamond 1*. On the other hand, the samples with an S value in the "Diameter" column of the Attribute Table are represented with a size 8 and the colour *Yucca Yellow*, the samples with an M value in the "Diameter" column of the Attribute Table are represented with a size 14 and the colour *Fire red*, and the samples with an L value in the "Diameter" column of the Attribute Table are represented with a size 20 and the colour *Tuscan Red*. Finally, numerical and graphic scales were added, along with the coordinate grid.

As a final result, a 1:1,400 scale mapping is obtained where the external morphology and the samples diameters are represented (Fig. 7). This cartography allows us to observe how the samples with a smaller diameter (S) are found in the distal area of the channels, and only present a rounded external morphology (R). While, the larger diameter samples (M, L) are closer to the salt flat (proximal area), and present discoidal morphologies (D). In addition to this, the cartography shows that regardless of size, samples are located at depths at depths of up to 0.24 meters.

Microbialites distribution vs internal morphology

This map seeks to show the relationship between the development of the internal structures of the oncoids (nucleus zone, well laminated zone and poorly laminated zone) and their position in the water body. That is why for its preparation the superposition lying area cartography with the information of the sampling points Attribute Table is used.

The developments in centimetres of the three internal structures of the oncoids are represented in the columns "nucleus zone", "well laminated zone" and "poorly laminated zone" (Table 1). In the cartography, the development of these internal structures is expressed with respect the position of the sampling points lying map, using the symbology of "Bar/ Column" in "Charts". The column "nucleus zone" it's represented by a bar colour *Cherry wood brown*, the column "well laminated zone" it's represented by a bar colour *Fir green*, and the column "poorly laminated zone" it's represented by a bar colour *Electron gold*. Additionally, numerical and graphic scales were added, along with the coordinate grid.

As a final result, a 1:1,400 scale mapping is obtained where the development of the internal structures of the oncoids it is observed with respect to its position in the channels (Fig. 8). This cartography allows us to observe how the "nucleus zone" and the "well laminated zone" are found in all samples, both distal and proximal area. While the "poorly laminated zone" is null or has almost no development in the distal area of the channels. All the structures increase their development from the distal to the proximal area. However, it is the "nucleus zone" that increases the least, and the *poorly* "laminated zone" that experiences the greatest growth.

Oncoids distribution vs porosity

The purpose of this mapping is to represent the relationship between the porosity of the oncoids, its diameter, and their position in the deposit. That is why for its preparation the superposition lying area cartography with the information of the sampling points Attribute Table is used.

The porosity is indicated with respect to the values of the columns "Surface with porosity" and "Surface without porosity" of the Attribute Table (Table 1). To represent these values, a pie symbology is used, where the percentage of the poral space appears in *Black* colour and the nonporal in *Leaf Green* colour.

To determine the relationship of porosity with respect to the diameter of the samples, the pies where porosity is represented were size-graphed with respect to values from "Relative diameter" parameter. Pie charts corresponding to samples whose "Relative diameter" value is 10 are represented with a size of 8, pie charts corresponding to samples whose "Relative diameter" value is 20 are represented with a size of 14, and pie charts corresponding to samples whose "Relative diameter" value is 30 are represented with a size of 20. Finally, numerical and graphic scales were added, along with the coordinate grid.

As a final result, a 1:1,400 scale mapping is obtained where the porosity of the oncoids is represented with respect to the diameter of the samples and their position in the water body (Fig. 9). This cartography allows us to observe that as the size of the oncoids increase,

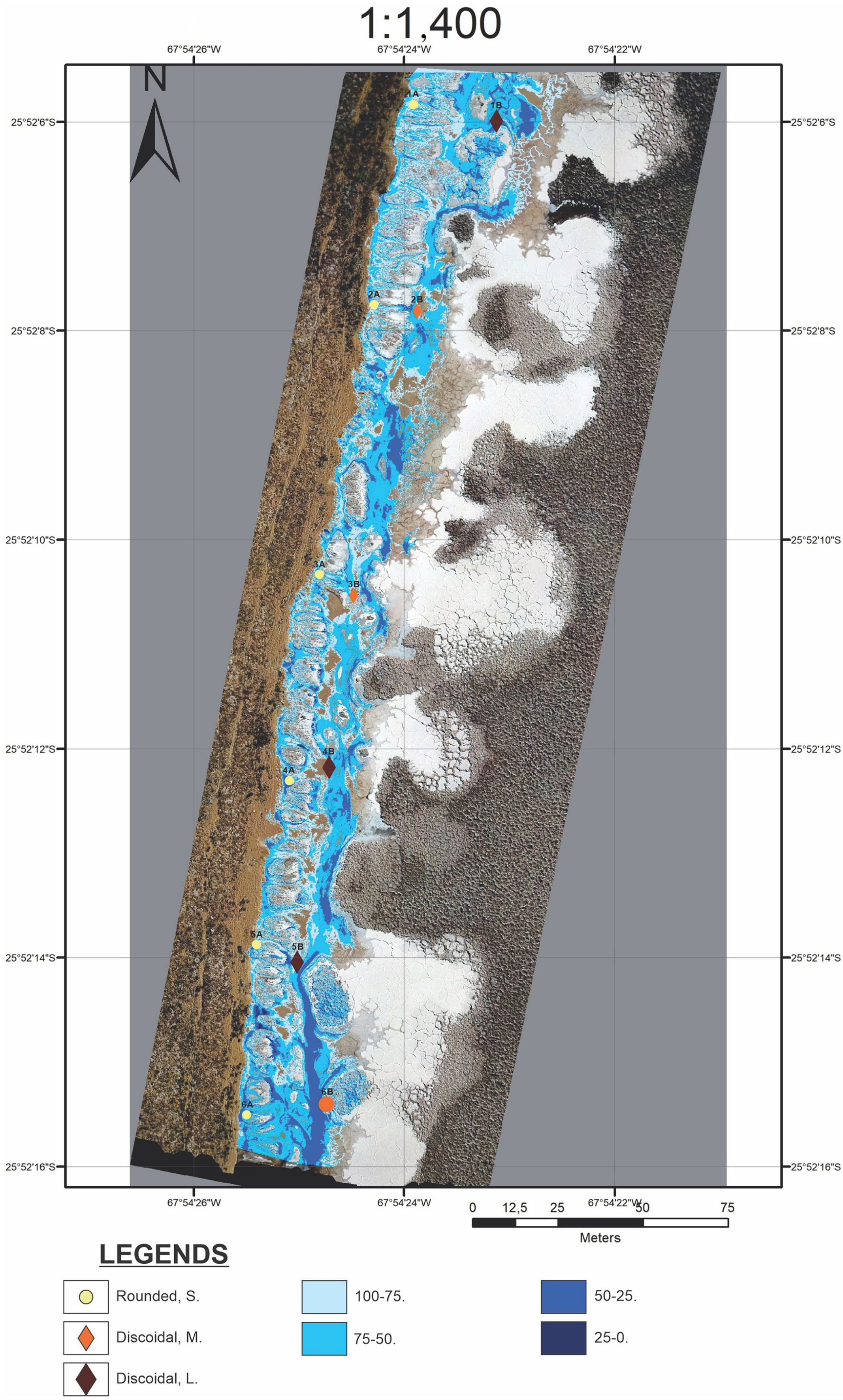

Figure 7. Cartography at scale 1: 1,400 showing the external morphology and diameters of the samples with respect to the position and depth in the channels.

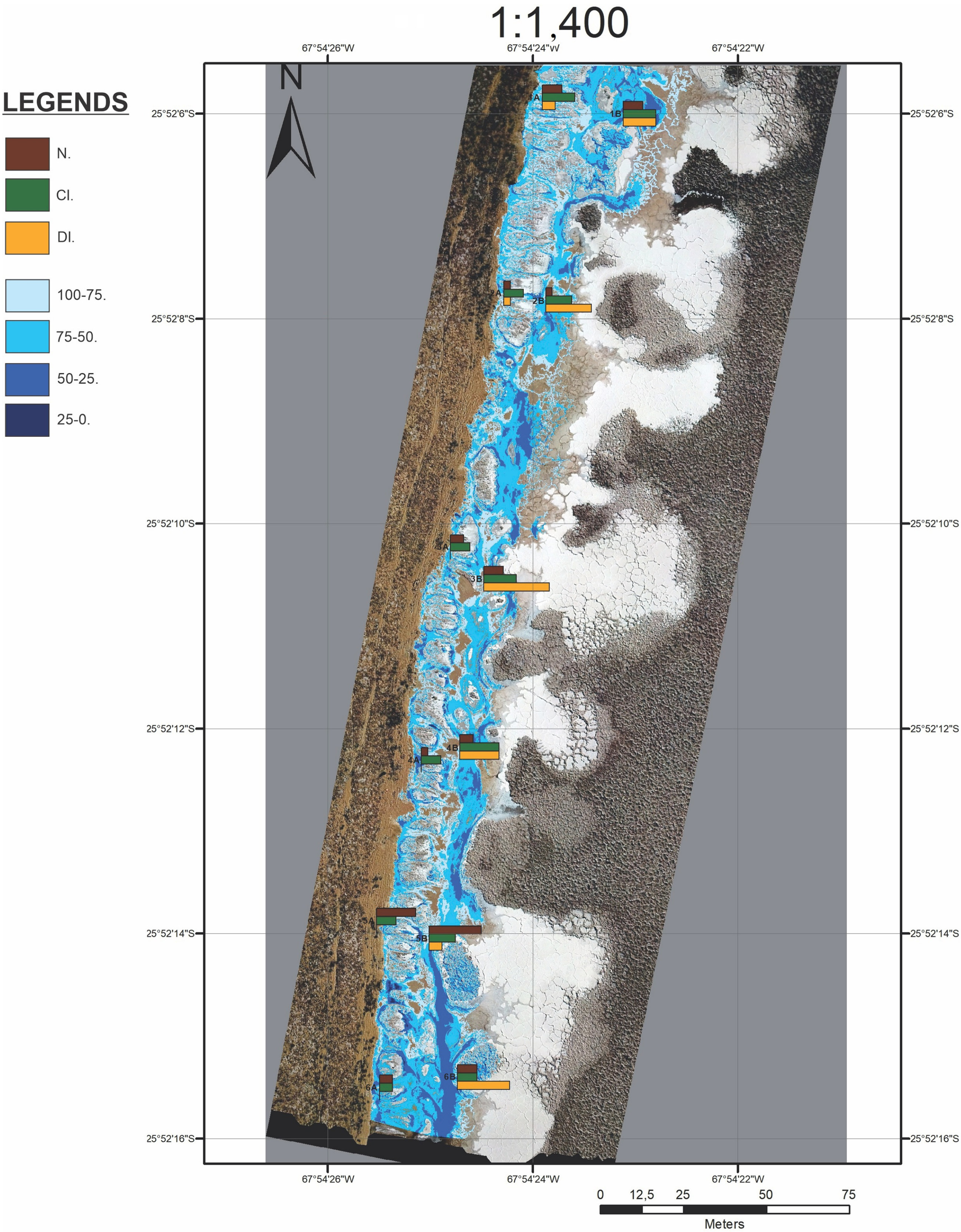

Figure 8. 1:1,400 scale mapping, showing the development of the internal structures of the oncoids with respect to their position in the channels.

their porosity also does. This is why the highest percentages of porosity are observed in oncoids greater than 7cm diameter in the proximal areas of the channels.

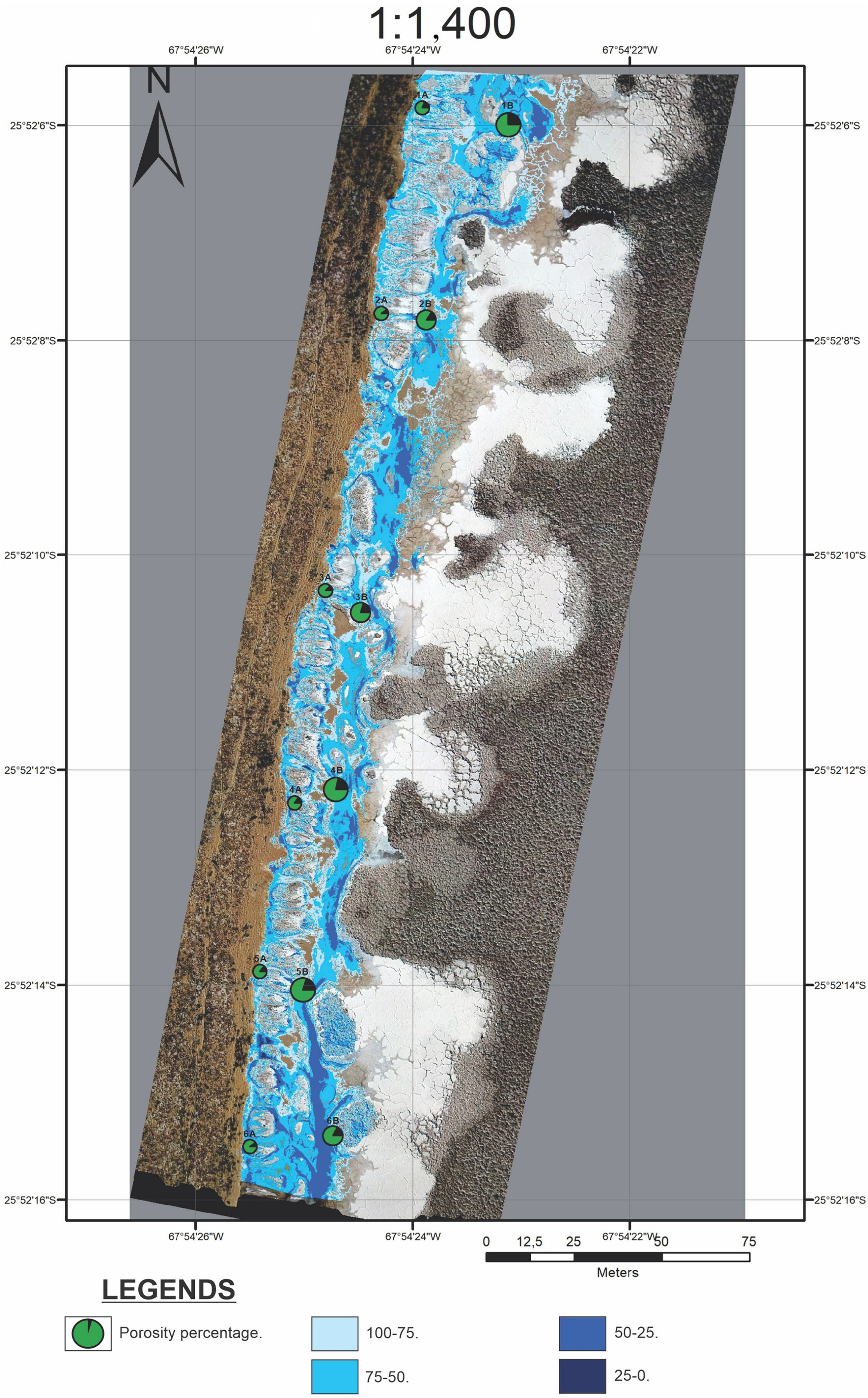

Figure 9. Mapping at a scale of 1: 1,400 showing the porosity of the oncoids with respect to the diameter of the samples and their position in the water body.

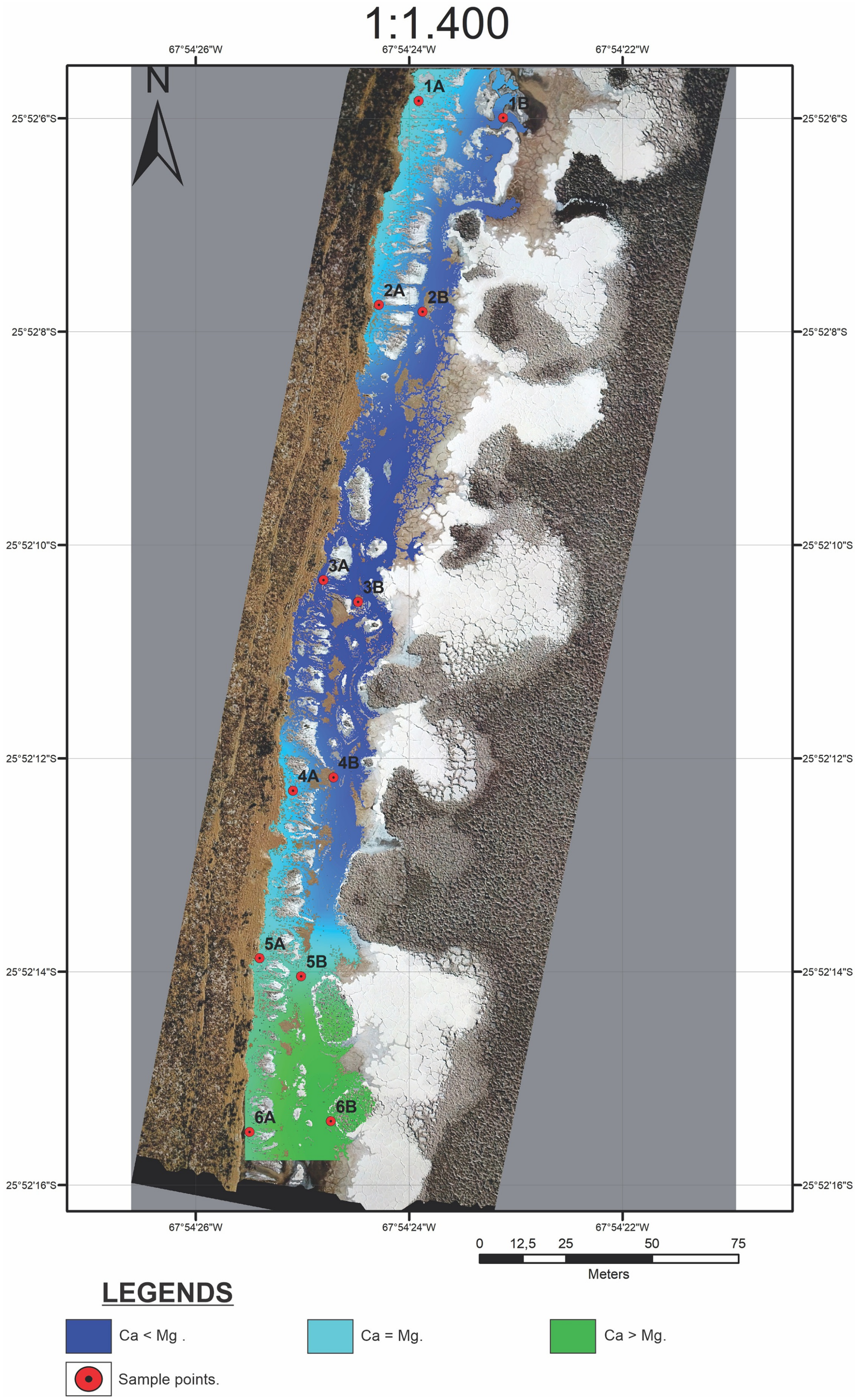

Figure 10. Mapping with scale 1: 1.400, which expresses the value of the Ca/Mg ratio of the oncoids along the reservoir.

Microbialites distribution vs relative Ca/Mg ratio

Studying oncoids through petrographic/chemical analysis allows us to determine which elements are predominant with respect to others throughout the deposit. However, sampling each channel is practically impossible due to space, time and resources.

Based on the sampling points of our Attribute Table, "Kriging" geoprocessing becomes a very important and useful tool to predict values in locations without measurements, evaluating the associated uncertainty. This geoprocessing is a geostadistical method, based on models that include autocorrelation (statistical relationships among the measured points). Geostadistical techniques not only have the capability of producing a prediction surface but also provide some measure of the certainty or accuracy of the predictions. In this sense, "Kriging" procedure assumes that the distance or direction between sample points reflects a spatial correlation and so, it is used to explain variation in the surface. This tool fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location (Esri, 2021). So, this procedure allows the preparation of a cartography that estimates the distribution and variation of some parameters throughout the deposit.

In this work, a cartography which reflects the variations in the calcium-magnesium ratio in the deposit was prepared. For it, the ArcGis tool "Kriging" is used with the column "Ca_MgRela" of the Attribute Table (Table 1) and layer of oncoids lying area (channels). As result, a new layer is obtained with the dimensions of the lying area, but in which the variation of the Ca/Mg ratio is represented with a colour gradient legend. In areas with a value of 10 (Ca > Mg) the layer turns a *Green* colour, where the value is 20 (Ca = Mg) the layer turns *Light Blue* colour, and where the value is 30 (Ca < Mg) the layer turns a *Blue* colour. Additionally, numerical and graphic scales were added, along with the coordinate grid.

As a final result, a 1:1,400 scale mapping is obtained where based on the study of the samples, values of the calcium-magnesium ratio of the oncoids in the channels of the entire reservoir are predicted (Fig. 10). It is observed that in the distal area, close to the wetland where the channels are born, the content of calcium in samples is equivalent to the content of magnesium (Ca = Mg). This relationship is associated with smaller diameter (S) microbialites with a rounded morphology (R) (Fig. 10, Table 1).

On the other hand, as we move to the proximal area of the channels (close to the salt flat) where the microbialites increase their diameter (M, L) and acquire discoidal morphologies (D), it is observed how the magnesium content increases in relation to calcium (Ca < Mg). Only in the sector of samples 6, where the morphology of the microbialites remains rounded (R) throughout the development of the channels, an increase in the content of calcium with respect to magnesium is observed (Ca > Mg) (Fig. 10, Table 1). This same process can be used to estimate other numerical values such as diameters, porosity, etc.; and even combined with other cartography.

The Scope of this Methodology

Since the 1960s, some pioneering works in the study of microbialites began to show interest in the distribution of these organo-sedimentary structures in the different water bodies they inhabit, and their relationship with their morphology and bathymetry. However, in most of these articles, mapping was carried out in a general way, without the digital support we have today, resulting in manually large-scale cartographies (e.g., Logan, 1961; Gebelein, 1969; Von der Borch, 1977). Moreover, only in some manuscripts of the time, the elaboration of this cartography was complemented by aerial photographs (Playford and Cockbain, 1976).

With the advance of technology, remote sensing began to become a great ally in mapping, gaining importance in many areas of Earth Sciences, where the study of microbialitic deposits was no exception. Numerous papers, no matter what their objective, started to complement their research with mapping (e.g., Andres and Reid, 2006; Camoin et al., 2006; Suosaari et al., 2016; Baskin and Wright, 2018; Gischler et al., 2018). However, these mappings continued to be of low resolution and limited practically to two dimensions (they usually do not consider depth), used more to enrich the geological framework of the work than to be part of its discussion.

Several authors began to highlight the importance of defining the position of microbialites in a water body in order to parameterize the intrinsic and extrinsic factors involved in their formation (Gischler et al., 2008; Berg, 2019; Wilcock et al., 2020). It has been demonstrated in numerous modern environments that the distribution of these organo-sedimentary structures directly influences both their final morphology and the construction processes carried out by their producing microorganisms (e.g., Sprachta et al., 2001; Jahnert and Collins, 2012). Thus, the need arises to reconstruct the architecture (modeling) of the microbialitic deposits and to delimit the layering areas in them.

Performing a topographic mapping and modeling a microbialitic reservoir can be a great challenge. However, in recent years, the application of various technologies has made it possible to overcome the obstacles encountered in these systems.

The main complication in determining the architecture of modern microbialite-bearing environments is the presence of water, which prevents a topographic survey by direct use of satellite images. A low cost solution to this problem, but more labor, is the geoprocessing of satellite images with data measured in the field. This allows the relationship between the spatial distribution of microbialites and their bathymetry to be examined (e.g., Gischler et al., 2008; Berg, 2019). In a system such as Las Quinoas, the presence of water does not represent a problem for the mapping of its channels, as it is scarce in the dry seasons. However, the small size of the oncoids and the narrow bathymetric ranges in which they develop with respect to the large depositional areas they cover, make the use of satellite images difficult. For this reason, it was decided to work with drones, achieving a high-resolution topographic survey.

In the case of wanting to study microbial deposits in underwater conditions (lakes, lagoons, marine environments, etc.) the same GIS-based methodology could be applied without problem, but the survey method would be different. The use of drones would be replaced by tools such as acoustic sonar, something already used in modern environments such as Pavilion Lake (e.g., Mullins and Bird, 2007; Trembanis and Gutsche, 2019). This type of methodology could also be combined with techniques applied for the three-dimensional reconstruction of fossil microbialitic sites such as traditional photogrammetry (Villafañe et al., 2021b), Ground Penetrating Radar (de Lima et al., 2018), among others.

On the other hand, some authors began to look for a way to represent the relationship between the position and bathymetry of microbialites with some of their characteristics such as external morphology, growth patterns, spatial patterns, etc. Currently, several works of this type can be found in modern environments such as Shark Bay (Australia) (Suosaari et al., 2016), Pavilion Lake (Canada) (Trembanis and Gutsche, 2019), Great Salt Lake (USA) (Wilcock et al., 2020), among others. However, unlike the aforementioned works, which only focus on one or two reservoir characteristics, limiting themselves to rather punctual studies; the methodology proposed in this manuscript involves several factors (bathymetry, external morphology, internal morphology, porosity, etc.). In addition, it allows the incorporation of new components and can be applied in a predictive way in analogous environments.

Finally, in the Central Andes, the use of methodologies for achieving high-resolution mapping and modeling of microbialitic deposits is still not used. The diverse works in these environments were only limited to present satellite images, in most cases geoprocessed, as a simple basis to indicate the zones of layering of these structures at a general level, sampling points or local topographic surveys with equidistances not less than 50 mts (e.g., Gómez et al., 2014; Fernandez et al., 2016; Gómez et al., 2018; Ercilla Herrero, 2019; Vignale et al., 2021; Villafañe et al., 2021c). To date, no author has presented an altimetric reconstruction, at a centimeter scale, in these water bodies. If we add to this the ability to associate in the same cartography the distribution of microbialites with measurable parameters both in the field and in the laboratory, we position the methodology presented in this work as a tool of great importance when studying and parameterizing these systems over their entire surface.

Conclusions

This work shows the use GIS-based methodology in the Holocene oncoids of Las Quínoas. The methodology not only enables detailed mapping and modelling of the architecture of the deposit, but also allows expressing the information of the lying area with respect to the data measured in the field and in the laboratory.

Combining the use of ArcGIS with drone photography and photogrammetry software improved the resolution of the deposit over satellite imagery. Geoprocessing with the ArcGIS software makes it possible to obtain high-detail topographic cartography, build a Digital Elevation Model (DEM) of the deposit and differentiate the channels where the oncoids lie from other depressed areas. On the other hand, GIS-BASED methodology allows us to know the relationship between various characteristics of the oncoids measured in field and laboratory, with respect to their distribution in the deposit. This provides a useful tool for the study of these structures.

The mapping and modelling show the distribution of the oncoids along a narrow strip of channels in the edge of the salt flat (Salar de Antofalla). The channels have a length of up to 20 meters and a width of up to 2 meters, water flows from west to east direction (distal areas to proximal areas) and to a lesser extent in a North-South direction. The depth of the channels is up to 0.48 meters; however, oncoids usually occur at depths of up to 0.24 meters both in the distal and proximal areas.

To determine the relationship between the distribution of oncoids and their morphological, structural and geochemical characteristics, several thematic maps were made using ArcGIS software. These show that not only the external morphology and the diameter are controlled by the position of the microbialites along the channels, but also their internal structure, together with petrophysical and geochemical factors.

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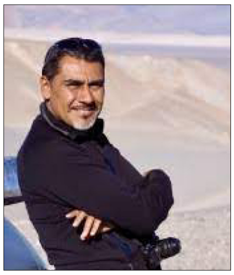

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