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Influence of Subsurface Geology on Freshwater Delivery to the Former Island of Tyre

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Abstract

Tyre developed on a small, porous island, with restricted access to freshwater. The extraction of freshwater from beneath the island represents one of the ways the Tyrians could have reached self-sufficiency. Underground freshwater is contributed by rainwater and possibly by a deep, pressurized coastal aquifer below the sea. In order to document the geometry of this aquifer, a coring campaign was undertaken in 2023, revealing the spatial arrangement of permeable and impermeable layers under the peninsula of Tyre. The bioclastic sands that form the isthmus of Tyre are soaked in seawater. They rest on a saddle of impermeable clays between Tyre and the mainland. They protect an underlying body of freshwater from seawater contamination. The clay seal tappers against the calcarenitic ridge of Tyre, allowing freshwater to rise to the surface along the land-facing side of the island, feeding freshwater springs used since Antiquity.

Introduction

Some Phoenician cities as well as their Mediterranean outposts were settled on small islands located in close proximity to large landmasses. These islands provide good protection from mainland attacks, but often lack space and water access to support large settlements (Desruelles 2004). The city of Tyre, one of the most famous of these Phoenician cities, perfectly embodies these challenges. In its heydays the city reportedly hosted several thousand inhabitants, crammed on a small, 1000 × 700 m island (Marriner, Morhange and Meulé 2007; Brocard, Goiran, de Graauw et al. 2024). Nonetheless, by the Late Bronze Age, the city had become a major maritime power, endowed with several ports, and possessing a thriving manufacturing industry. Despite its insular setting, Tyre managed to remain a major sea power for a millennium without seemingly suffering from a dearth of water. The city was even able to withstand months- to years-long sieges, such as, for instance, in the Iron Age, under the Assyrian king Shalmaneser V (5 years) and by the Babylonian king Nebuchadnezzar (more than 12 years) and then, at the beginning of the Hellenistic period, a 7 to 10 months-long siege by Alexander the Great in 332 Bc (Jidejian, Lipi ski 1992; Jidejian 1996).

The insular period of Tyre ended with its conquest by Alexander the Great, who had a military causeway laid down in the strait separating the island from the mainland (Jidejian 1996). The causeway interrupted the net northwards drift of sand along the mainland coast, forcing sand to pile up over the causeway. Its accumulation built an isthmus that thickened rapidly during the following Hellenistic and Roman periods (Nir 1996; Carmona and Ruiz 2004; Marriner, Morhange and Meulé 2007; Brocard, Goiran, de Graauw et al. 2024). It likely reached its presentday size by Roman or Byzantine times (Nir 1996; Brocard, Goiran, de Graauw et al. 2024). This new terrestrial access made it easier to bring freshwater from the mainland. The harvesting of mainland freshwater includes the construction of an aqueduct in the first century ad (fig. 1) which taps the artesian springs of Ras Al Ain south of Tyre (Bakalowic, Fleyel, Hachache et al. 2002; Kahwagi-Janho 2016), and possibly other springs in the

north, such as the Roman spring of Al Baqbouq (Badawi 2017). During the following millennium, the aqueduct fed Roman and Byzantine periods monumental baths, and latter, public fountains, ablution baths (Rousset 2016), and workshops, before falling into final disrepair after a siege in 1291 ad (Kahwagi-Janho 2016).

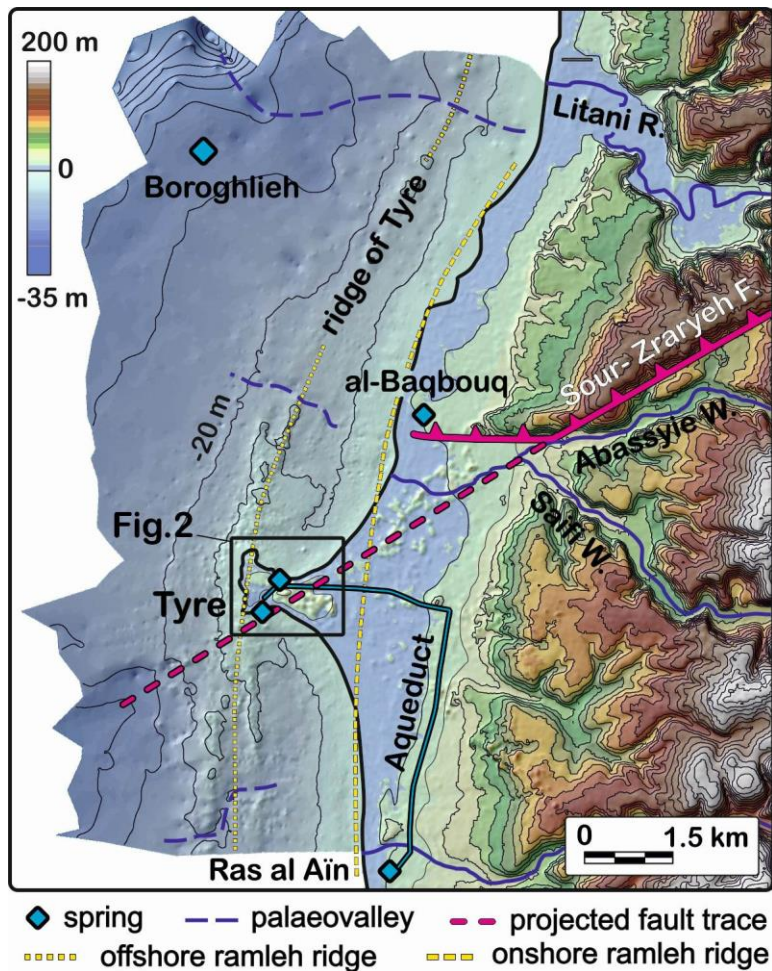


Fig 1. Topography of the coast near Tyre, showing the location of some freshwater springs known or suspected to have been used to water the island. Contour line spacing 10 m. Onshore topography: DSM ALOS W3D (AW3D30). Offshore bathymetry: interpolation of depth point measurements acquired in 1921 by the SHOM (Service Hydrographique et Océanographique de la Marine, France).

by the French Service Hydrographique de la Marine (SHOM). Completed in 1921, the soundings are reported on two sheets of paper at scales of 1:10,000 and 1:20,000, totalling more than 9,300 depth readings. These documents, used in the field by Poidebard during his work in Tyre from 1934 to 1936 (Poidebard 1939), were used to produce the 1923 SHOM chart 5614, 'Mouillage de Sour (Ancienne Tyr)'. GIS digitalisation of these points, and subsequent interpolation, has enabled us to obtain a coherent bathymetric model down to a depth of 30–40 m, corresponding to a distance of about 3 km from the coastline (fig. 1). The use of the original sounding maps provides more accurate bathymetry than subsequent nautical charts. The bathymetry reveals geomorphological features that help understanding the geological context of these exurgences and of groundwater path below the island. Indeed, the closest source of freshwater is an aquifer located directly beneath the island. Its existence is attested by two springs (fig. 2): one is currently located offshore and consists of water seepage along a now-submerged structure known as the 'Quay of the Spring' (Poidebard 1939). The other spring is found beneath

The present paper presents the result of coring campaigns conducted in 2023 to provide constraints on subterranean water flow below the former island of Tyre, as part of the Franco-Lebanese Research Project ANR AquaTyr. The project seeks to highlight the strategies developed by the Tyrians to meet their water needs and optimise water use, in response to palaeogeographical constraints. Within this framework, multidisciplinary research involving archaeology and coastal geology aims at clarifying the multidisciplinary research involving archaeology and coastal geology aims at clarifying the topography of the peninsula over time and at contextualising the archaeological structures associated to water supply to the city, from the Phoenician to the Byzantine/ medieval period. While the tapping of coastal springs is well established during the peninsular phase, little is known of the water supply to the island. The origin of the water used on the island might have been diverse, including, in any apportionment, the collection of seasonal rainwater in cisterns, distant supplies by merchant ships (e.g. ballast water), proximal supply by ship or other means from the nearby mainland springs, or from some of the powerful submarine freshwater springs known to exist in the area, such as the Boroghlieh spring to the north (fig. 1), which has a reported discharge of 2 m³/s (Saad, Kazpard, Slim et al. 2005). The collection of submarine freshwater from boats is a practice mentioned by Strabo at Arwad [16.2.13]. The context of these offshore springs benefits from a better knowledge of the offshore bathymetry computed by modelling old surveys carried out

'Hiram's Tower' (Badawi 2016). Tyre was settled on an island made of porous sandy limestone locally called ramleh (Badawi 2017). Freshwater bodies are common under islands made of porous limestone. These are small, lenticular bodies fed by the infiltration of rainwater which ponds above a denser body of saline water, fed by lateral infiltration of seawater (Werner, Sharp, Galvis et al. 2017). The yield of such aquifers is small. Being fed by rainwater, their yield is even further reduced if rainwater is collected at the surface and stored in cisterns. In rare and peculiar circumstances, however, coastal islands can benefit from a freshwater inflow from the mainland via underground pathways (Palausi 1965). The Lebanese coast is dotted with large coastal artesian as well as submarine freshwater springs, which are fed by karstic conduits draining nearby mountains (Bakalowic, Fleyel, Hachache et al. 2002; Saad, Kazpard, Slim et al. 2005). The existence of submarine springs near Tyre therefore raises the possibility that the freshwater body under Tyre Island is fed from below by a pressurized deep aquifer, provided that the arrangement of rock layers below the island is favourable to water rise and prevents contamination by seawater. An aquifer fed from below would be a game changer to develop the island, especially if deep freshwater inflow yields enough water year-round, or, alternately, if coping strategies are implemented to store water on the island when the aquifer is depleted. The coring campaign of 2023 provides the first constraints on the geological structure of the island, as far deep as 15 m below sea level, complementing, for this purpose, a series of earlier scientific cores collected in 2002 and 2018.

Previous Coring Campaigns

Scientific coring started at Tyre in 2002 by a campaign during which more than twenty-five cores were collected by unwalled rotational coring using a thermal rig (T-I to T-XXV). Coring sites spanned the entire isthmus of Tyre, as well the coastal plain, and were aimed at constraining the palaeogeography of Tyre during Antiquity. Six of these cores were collected in the vicinity of the modern harbour of Tyre.

Below the modern harbour of Tyre, they exposed Hellenistic-Byzantine fine-grained sediments which were interpreted as the sedimentary fill of the ancient, 'Sidonian' northern harbour of Tyre (Marriner, Morhange, Boudagher-Fadel et al. 2005), which should be more properly referred to as 'Astronoe's Port' (Aliquot 2020). Two other cores (Marriner, Goiran and Morhange 2008) were collected to the east of the Phoenician necropolis of Al-Bass. They confirmed the existence of a lagoon in this area, documented earlier by small outcrops and trenches (Carmona and Ruiz 2004). The lagoon is separated from the sea by a sand barrier onto which the necropolis is built. Six cores were collected along the sandy isthmus of Tyre (Marriner, Morhange and Meulé 2007). They confirmed earlier suspicions (Nir 1996) that Alexander the Great had built his military causeway on a submerged sand bank produced by the diffraction/ refraction of waves in the lee of Tyre Island during the millennia preceding the erection of the causeway. The cores showed that the sandbank rests on massive impervious dark clays, deposited behind the island of Tyre in a transgressive lagoon between 6000 and 4500 Bc, during the early stages of marine flooding of the strait that separates Tyre Island from the mainland, after the Last Glacial period (Marriner, Morhange and Meulé 2007). Renewed scientific coring started in 2018 with the collection of seven cores along the lee side of Tyre Island (TYR-1 to TYR-7). Some of these 7 m to 20 m-long cores intersected silts and fine sands lying next the coarser-grained sediments of the marine sand bank on which Alexander's causeway was built, which were interpreted as infillings of ancient ports now buried under the sandy isthmus (Brocard, Goiran, de Graauw et al. 2024).

Because the 2002 and 2018 campaigns were conducted to constrain the palaeogeographic evolution of Tyre during Antiquity, coring was stopped upon reaching layers which state of compaction or cementation indicated that they predate Antiquity. This is the case, for example, of the calcarenite which forms the ridge of Tyre, which is made of sand dunes cemented and karstified by meteoric water well before the post-glacial marine transgression. It is also the case of compact clays that underlie the transgressive lagoonal clays between Tyre and the mainland. For the purpose of understanding groundwater flow at depth, it was therefore necessary to conduct deeper coring, beneath the archaeological layers, especially near the Quay of the Spring and Hiram's Tower spring. Archaeological layers also affect water routing in the nearer subsurface. It was therefore also necessary to densify

shallower coring around the springs. Two types of cores were therefore collected: long cores documenting the geological structure, and shorter cores, close to the springs, aimed at understanding the routing of freshwater through the archaeological layers. The stratigraphy of the coastal plain and of the marine shelf are well documented farther south along the Levantine coast (Mauz, Hijma, Amorosi et al. 2013; Shtienberg, Dix, Waldmann et al. 2016; Goff, Austin and Goodman-Tchernov 2018), and therefore provided clues on what geological structure can be expected beneath Tyre. Pleistocene marine sediments can be expected to reach thicknesses of at least a few tens of metres, if not more. The karstic conduits that bring freshwater from the mountains along the coast of Lebanon are located in Cretaceous to Palaeogene limestones, covered by these Pleistocene sediments. A full appraisal of water routing, from the karstic conduits up to the springs would therefore require the drilling of numerous deep boreholes, at a cost that largely exceeds the funding of academic research. Nonetheless, documenting the subsurface geology, as far as 15 m below sea level, is sufficient to establish whether the freshwater aquifer beneath the island is only fed by rainwater, or if there is some inflow from deeper levels, owing to a favourable arrangement of geological layers.

Methods: Terrestrial Rotational Coring

Twenty-one cores were collected during two campaigns in 2023 (fig. 3 and tab. 1 and 2). Boreholes TYR-8 to 18 were drilled in March 2023 by Geoscience Engineering and Laboratory Services, using rotational coring operated from a track-mounted drill rig. The coring barrel was equipped with a diamond coring bit and was driven down the hole by a flight of drill rods. Water was used for cooling and lubricating the coring bit. It was used in the smallest possible amount to core across block-rich dry sands above the water table to prevent complete flushing of the sandy/silty matrix around the blocks. Upon reaching the water table, recovery improved, and only natural ambient water was used for coring. Boreholes TYR-8 to 10 were uncased, leading to sample contamination by material falling from the walls. Boreholes TYR-11 to 18 were cased with steel liner along the topmost 2 to 6 m. Such casing prevented contamination by the layers the most susceptible to crumbling. The outer steel liner was equipped with a cutting shoe, lowered by down to the depth of the coring front, after each increment of lowering of the coring barrel. During the lowering of the outer liner, wall material could contaminate the lowest 1.5 m of the hole down the bottom. This fallen material was recovered in the topmost part of the subsequent core, from which it was removed after visual inspection.

Boreholes TYR-19 to 29 were drilled in October 2023 by Moubarak Associates, using a rig mounted on an industrial trailer. Boreholes were entirely walled from top to bottom. During coring operations, the coring bit was clipped to the outer steel liner, such that the core barrel and outer steel liner were lowered and rotated in lockstep down to the desired coring length. In this case the core was never exposed to contamination by fallen wall material. The core barrel was then unclipped from the outer steel liner and brought back to the surface using a wireline. The cored material was then transferred to standard core storage boxes, while the barrel was brought back to the bottom of the borehole using the same wireline. It was then clipped to the outer steel liner in preparation for the next coring increment. The length of each coring increment (0.3 to 1.5 m) was tuned by the operator depending on soil resistance, such as to optimise sediment recovery. To ensure the best recovery possible in sandy soil devoid of blocks (e.g. TYR-23 and 24), water-free mechanical drop hammering replaced rotational coring in the upper layers. In such cases the core barrel was also fitted with an additional inner plastic liner, manually extruded from the core barrel upon recovery. In wet gravelly sand, another recovery strategy was adopted: the core barrel was fitted with an inner split-spoon sampler made of two steel halves, that were cracked open upon recovery to expose the barrel content. Coring site elevations were measured using a handheld tachometer (laser rangefinder with integrated compass and clinometer) relative to either the closest located shore, or to the closest point which elevation was known with high precision owing to earlier land surveys conducted as part of the archaeological investigations by the Mission Archéologique de Tyr, readjusted to sea level (Brocard, Goiran, de Graauw et al. 2024; Gatier et al. 2010; Gatier 2011; Cahu et al. 2023). The cores were logged on site, transferred to conventional core boxes containing four, 1 m-long gutters, and stored on the archaeological site.

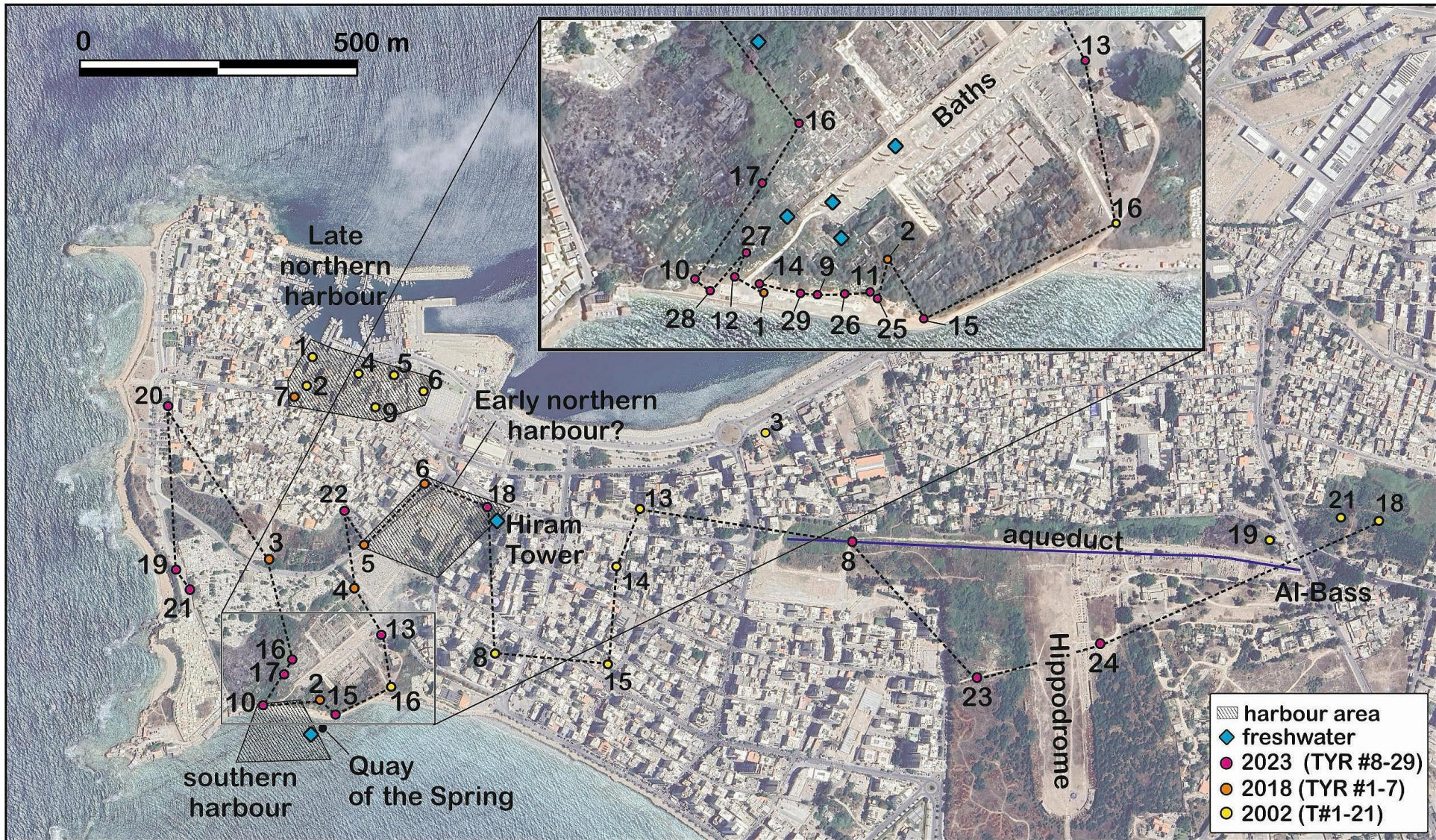


Fig. 2. Location of the 2023 coring sites and earlier coring sites along the peninsula of Tyre. Dashed line: transect followed for stratigraphic correlations on fig. 4. Background: satellite image © 2024 Airbus, accessed via Google Earth Pro 7.3.6.9750, version of January 12th 2024.

Results

The sediments collected in 2023 are dominated by cemented carbonaceous bioclastic sand (biocalcarene, or ramleh), siliceous and carbonaceous gravel, fine-grained quartz-rich sand, medium to coarse-grained bioclastic sand, malleable and compact clays, and archaeological mixtures of blocks into a sandy to clayey matrix. The matrix of these later diamictos is difficult to recover during coring, most of it being flushed by coring fluids. For this reason, on stratigraphic logs (fig. 4), blocks are drawn over matrix patterns wherever some matrix was recovered, or drawn in isolation, wherever no matrix was recovered. The stratigraphic synthesis of figure 4 includes earlier cores. An effort was made to apply a similar approach to depict the 2018 cores TYR-1 to 7, for which first-hand coring information is available. However, only idealised representations of the 2002 cores are available (Marriner, Morhange, Boudagher-Fadel et al. 2005; Marriner, Morhange, and Meulé 2007; Marriner, Goiran, and Morhange 2008), introducing a representation bias. Here we present first the facies encountered during coring, and then propose stratigraphic correlations between cores.

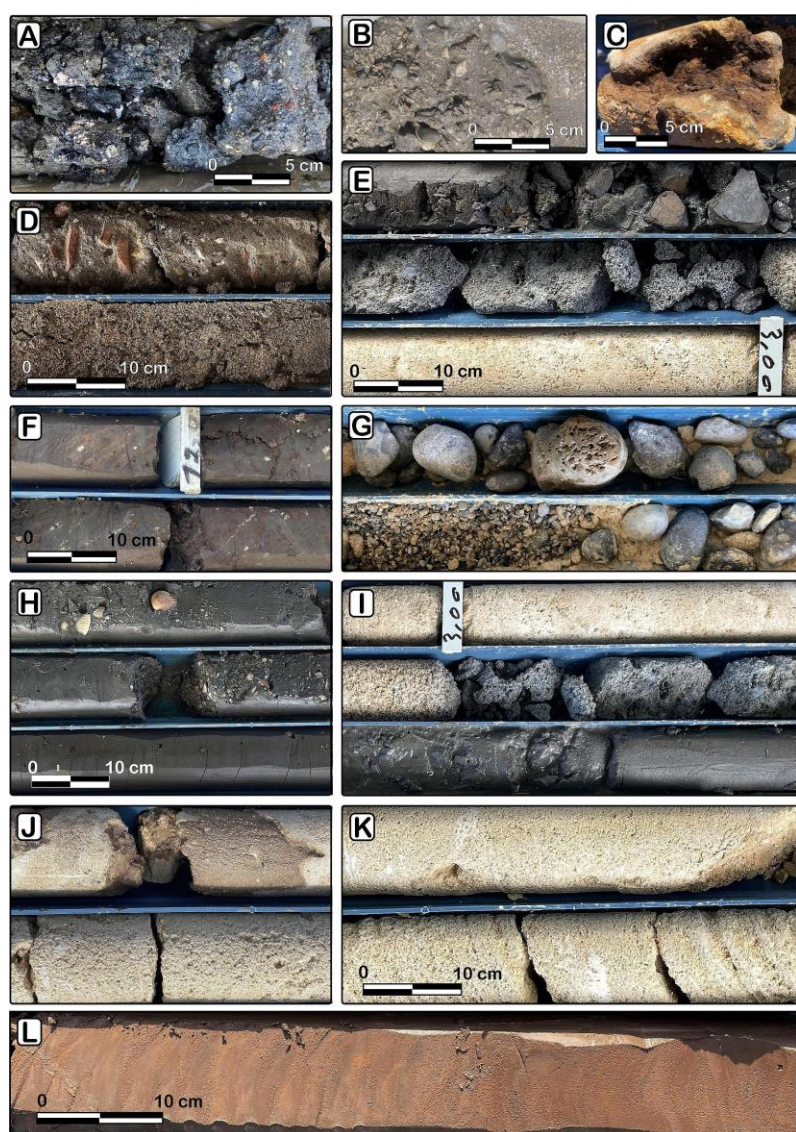


Fig. 3. Photographs of selected sedimentary facies. A: organic-rich silty clay (facies #4) with green clasts, charcoal, carbonate grains, and pottery shards (TYR-14), B: fine, beige, quartz-rich sand (facies #6), with abundant bivalve and gastropod shells (TYR-18), C: karstified surface of the calcarenite (facies #11), with orange to greenish weathering rims (TYR-12), D: top: artefact-rich, compact brown silt (facies #2), with pottery shards; bottom: bioclastic sand (facies #7), medium-size grained (TYR-24), E: top: anoxic, fetid organic-rich clays (facies #4) with darkened pottery shards, next to (middle) darkened (reduced) calcarenite construction blocks, and bottom: beige calcarenitic bedrock (TYR-27), F: brown to orange clayey silt and silty clays (facies #12), steeply dipping, with carbonate concretions (TYR-19), G: flint gravel and pebbles (facies #8), the largest pebble showing traces of coastal bioerosion (TYR-10), H: top two rows: lagoonal clays (facies # 9), rich in bivalve and gastropod shells; bottom: black compact clays (facies #10) devoid of visible fossils (TYR-22), I: bottom: fine grey, anoxic, well-sorted sands (facies #5), reduced calcarenite (middle), and original calcarenite (top) (TYR-27), J: brown sandy silt infilling karstic voids in the calcarenite (TYR-29), K: top: massive calcarenite (facies #11), bottom: steeply dipping cross-stratification in calcarenite (TYR-27), L: fine red sand (facies # 12), with alternation of sand with clay coating and sand with clay-filled porosity (TYR-19). Photo credits: Gilles Brocard.

Facies description

For the purpose of stratigraphic correlations, sediments are grouped into 12 main facies, based on the composition of the sediment matrix. These facies are presented below in order of increasing depth, and presumably of increasing age.

Facies 1: unconsolidated upper levels

Unconsolidated upper levels grouped under this denomination include street-level pavements, organic top soils, 20–21st century landfills, windblown sand deposited over the archaeological layers after the abandonment of the main occupation levels (Roman to medieval), and mixtures of dry sands and blocks and above the water table which correspond either to archaeological levels (most commonly Roman to Byzantine), or to artefacts reworked during the plundering of archaeological levels.

Facies 2: red clays

Scattered layers of sticky, plastic, red to orange clay, a few centimetres thick, were intersected above the water table. They owe their recovery to their resistance to flushing. They contain Roman pottery shards and charcoal and are found at the elevation of nearby excavated Roman-Byzantine levels.

Facies 3: artefact-rich, compact brown clayey silt

Some drier compact brown silts, rich in sand (grit) and larger elements (lime, shards, and charcoal) also resisted flushing (fig. 3: D). They are also found amidst the unconsolidated upper levels above the water table. They lie at the elevation of nearby Roman to Byzantine levels exposed in nearby archaeological excavations.

Facies 4: grey to black, clast-rich organic clays

Soft to moderately compact, these fetid black clays, rich in dark-green clayey clasts, grains of carbonate, and charcoal (fig. 3: A and I) are found below facies #3, or interlayered with facies #6. Some of the carbonate and charcoal grains seem to result from the decomposition of ancient cement. They are found in areas previously interpreted as harbour basin fills of putative Late Bronze to Phoenician Age (Brocard, Goiran, de Graauw et al. 2024).

Facies 5: fine-grained, well-sorted fine quartz-rich grey sand, clean to silty

Very well sorted, these usually clean but silty at places anoxic sands, composed dominantly of very fine, well-rounded grains of quartz are found below facies # 4, or interlayered with facies #7. They may contain seaweed and fine shell fragments (fig. 3: I). Their grain size is similar to that of the Hellenistic and Roman sediments that fill the northern harbour of Tyre (Marriner, Morhange, Boudagher-Fadel et al. 2005).

Facies 6: fine-grained, well-sorted fine beige quartz-rich sand

This well-sorted sand (fig. 3: B) is similar to the sand of facies #5 but is not currently anoxic. It was deposited in relatively quiet waters, either in a natural or in a manmade harbour, but in any case, in a less confined setting than sand #5.

Facies 7: medium to coarse-grained bioclastic sand

This abundant, widespread facies consists of wellsorted sand mostly made of carbonaceous marine bioclasts, with an ancillary fraction of fine, quartz-rich sand (less than 10 per cent). This sand (fig. 3: D) forms the bulk of the isthmus of Tyre, and was deposited mostly after 1500 Bc (Brocard, Goiran, de Graauw et al. 2024).

Facies 8: gravel and pebble

Gravel and pebbles are interspersed throughout the archaeological levels, where they reflect the use of distant beach material. They are nonetheless also extensively encountered in association with coarse bioclastic sands, toward the base of facies #7. Their highest concentration occurs immediately above the contact with the clays of facies # 9 and 10, or above the calcarenite (#11), at the base of the overlying bioclastic sands (facies #7) or

its harbour-type lateral equivalents (#5–7). Their concentration is so high that it prevents the recovery of the finer-grained sandy matrix. The gravels and pebbles are invariably composed of flint and chert (fig. 3: G), tracking from the Cretaceous to Eocene limestones of mainland Lebanon. Some flint contains silicified nummulites, indicating an Eocene age. These flints and cherts are the final weathering and erosional products of limestone that were transported by coastal rivers to the sea, and, from there, by waves and bottom currents all the way to Tyre. The pebble fraction also contains an ancillary population of hard, fine-grained (micritic), likely Cretaceous, beige to orange limestone.

Facies 9: ductile, shell-rich dark blue clays

These plastic, cohesive, impervious, blue-to-black clays display alternations of shell-poor clay beds and matrix-supported to shell-supported (coquina) shell-rich beds (fig. 3: H). The analysis of their macro and microfauna in the 2002 (Marriner, Morhange and Meulé 2007) and 2018 cores show that they were deposited in a lagoon. Radiocarbon dating (Marriner, Morhange and Meulé 2007; Brocard, Goiran, de Graauw et al. 2024), indicates that the lagoon spread behind the ridge of Tyre during the post-glacial marine transgression, between 6000 and 4500 Bc.

Facies 10: compact, dark brown clays

These cohesive, impervious, massive, brown-to-black clays are devoid of visible macrofauna remains. They underlay the lagoonal clays (facies #9). Their environment of deposition (continental or marine) is uncertain. They were exposed to subaerial weathering before the marine transgression, because they contain millimetre-sized carbonate concretions, which formed in the sediment during the evaporation of a shallow, calcium-saturated water table (fig. 3: F and H).

Facies 11: calcarenite (ramleh)

This highly porous, permeable, medium- to coarsegrained, cemented bioclastic sand (fig. 3: E and I) makes up the bedrock of Tyre island, and of its surrounding islets (Badawi 2016), along the submerged ridge of Tyre (Brocard, Goiran, de Graauw et al. 2024). In the cores, the calcarenite either comes from this rocky basement, or above, in the archaeological levels, as construction blocks (Badawi 2016). In the rocky basement, bedding is commonly shallow dipping, and less frequently steeply dipping (fig. 3: K). The calcarenite crops out extensively along the west coast of Tyre, where it displays steeply dipping planar cross-stratifications, slightly arcuate in plan view, typical of aerial sand dunes. The calcarenite is therefore commonly referred to as an eolianite, although the calcarenite ridge of Tyre also includes a basal layer of beach deposits. By analogy with well-dated calcarenitic ridges along the Levantine coast, the age of formation of the sand dunes is ascribed to the early stages of the last glaciation, between 105 and 75 ka (Brocard, Goiran, de Graauw et al. 2024), when sea level progressively lowered down to -30 m, through an irregular alternation of relative high stands and low stands. Following the dramatic fall of sea level after 75 ka, the calcarenite was exposed to weathering, soil formation, and water infiltration during the last glacial period (75-18 ka). The rocky basement therefore contains voids partially filled with brown silts (fig. 3: J). The top of the calcarenite is a karstified, contorted surface, capped with beige, brown, and greenish weathering fringes (fig. 3: C).

Facies 12: fine-grained, well-sorted, quartz-rich sand coated with red clay

These homogenous sands are typified by their red clay, which either occurs as coating on quartz grains, or as pore fills between the sand grains (fig. 3: L). In cores TYR-19 and 20, the sands morph up and down core into compact brown sandy clays with carbonate concretions, somewhat similar to facies #10 (fig. 3: F).

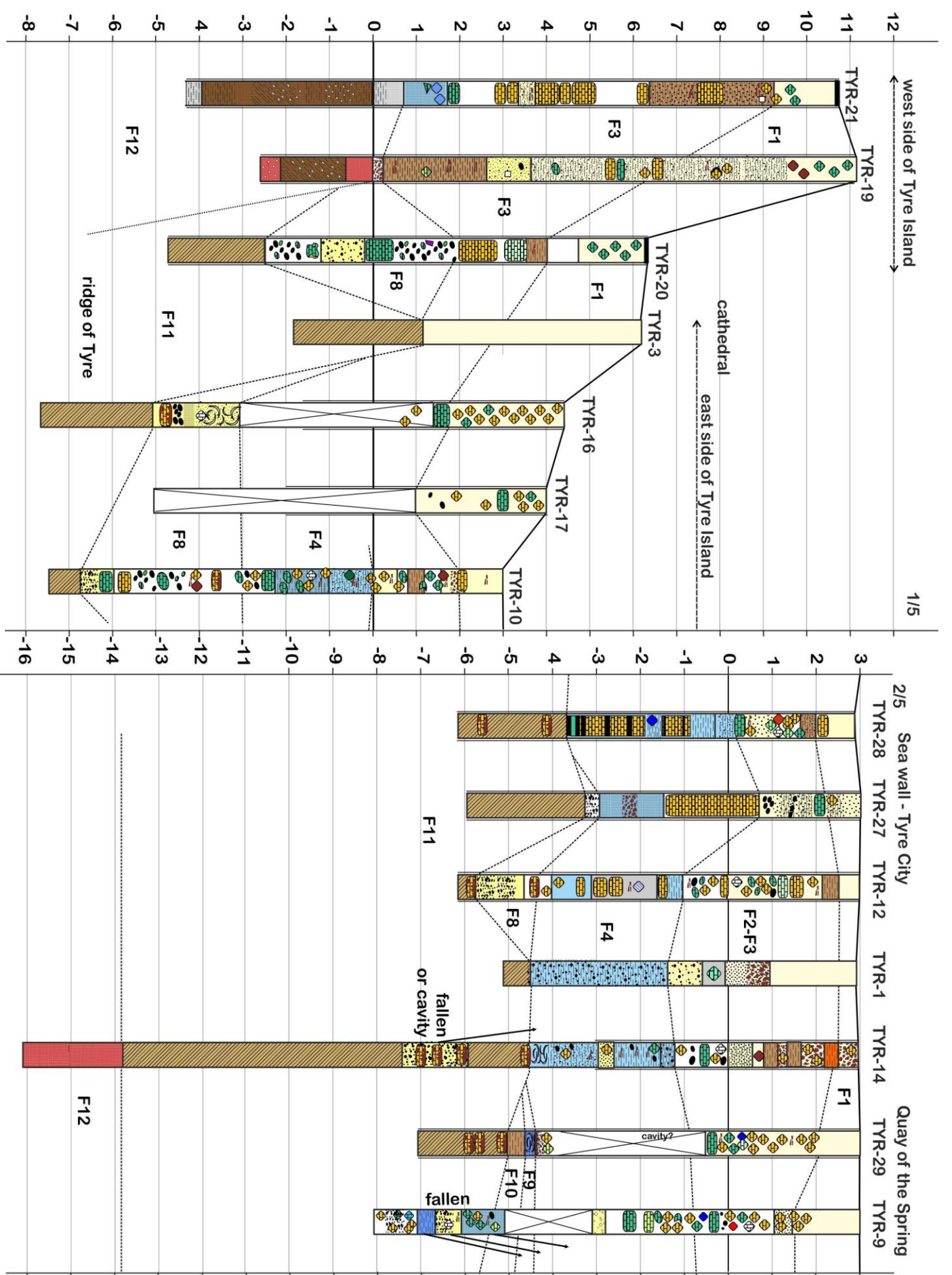
The blocks encountered during coring operations are either construction blocks larger than the core diameter (8 cm), or large pebbles and fragments of larger blocks smaller than the core diameter. Most of the cored construction blocks do not lie on top of one another, indicating that the boreholes crossed destruction and landfill layers. A vast majority of the blocks (80–90 per cent) are made of calcarenite, extracted from the ridge of Tyre or from nearby coastal quarries (Badawi 2016). Such blocks have been used throughout the history of Tyre to erect walls. Softer Eocene chalk is abundant in the Roman levels and above. It was used in foundations and underground stories (Gatier et al. 2010: 191). The third most abundant rock type is hard micritic limestone, used as street pavement in Roman and Byzantine levels. An ancillary fraction of exotic stones was used for decoration (Gatier et

al. 2010), and includes in order of decreasing frequency: marble, granite, ultramafic green breccia, and dolerite. All the decorative fragments were found at and above Roman levels. Blocks below the Roman levels consisted exclusively of calcarenite, and of hard limestone pebbles.

Stratigraphic correlations

The detailed logs of the cores, together with their correlation, are provided (fig. 4) and the correlations are summed up (fig. 5). Marriner, Morhange, and Meulé (2007) showed that the sandy isthmus of Tyre rests on lagoonal clays deposited between the ridge of Tyre and the mainland during the early stages of the post-glacial marine flooding (6000–4500 Bc). The lagoonal clays are therefore expected to lap over the calcarenitic ridge of Tyre, although previous cores were not drilled deep enough to demonstrate this relationship. A synthesis of available geologic information (Brocard, Goiran, de Graauw et al. 2024) suggests that the ridge of Tyre formed a little earlier than the lagoonal clays, during the early falling sea level that characterises the end of the last interglacial, more specifically, between 105 and 75 ka, during marine isotopic stages (MIS) 5.3 (5.c) or 5.1 (5.a). Farther south, along the Levantine coast, semisubmerged calcarenite ridges of this age accreted seaward of a calcarenite ridge emplaced during the maximum of the last marine transgression (Eemian, MIS 5.5 or 5.e, Sivan, Sisma-Ventura, Greenbaum et al. 2016). The calcarenite found north and south of Tyre, along the mainland, is therefore likely of the same age (MIS 5.5, 110–130 ka). South of cape Naquoura, behind the Eemian calcarenite ridge, older calcarenite ridges of ever-increasing age with distance from the sea are found as far as 15 km inland. They were deposited during earlier, successive interglacials of the Pleistocene (Mauz, Hijma, Amorosi et al. 2013). These ridges are separated from one another by blankets of fluvial, colluvial, and aeolian deposits emplaced during the intervening glaciations, when sea level is at its lowest. The most common of these deposits are fluvial clays followed by red sandy soils (Gvirtzman and Wieder 2001; Porat, Wintle and Ritte 2003; Shtienberg, Dix, Waldmann et al. 2016; Goff, Austin and Goodman-Tchernov 2018). A vertical stacking of calcarenite, continental clays and red sands (Mauz, Hijma, Amorosi et al. 2013) was therefore expected to be found below Tyre. The layers encountered during coring are here presented in chronological order, and an interpretation of their environment of deposition is proposed in light of these former studies.

Red sands (F12). The quartz-rich sands coated with red clay lie at current depths of 12–14 m below sea level (in TYR-14, 15, and 18). These fine-grained sands are reminiscent of the red sandy soils deposited in thin veneers between imbricate calcarenite ridge systems farther south, which are commonly referred to as hamra ('red'). The red clay found in the sand may have formed in situ, by weathering of sand-sized to clay-sized minerals deposited together with the quartz grains as fine marine sand, at greater depth than the coarser, coastal bioclastic sands, the latter becoming calcarenite (Porat, Wintle and Ritte 2003). Alternately, it may have formed by illuviation of clays, translocated from overlying soils. The clay in these soils, in turn, could have formed in situ, or alternately, could have been brought in by the wind. The quartz grains, as well, could have been brought in by aeolian processes, together with the clays, or before them, from areas affected by wind deflation in the Near East (Gvirtzman and Wieder 2001). Cores TYR-14 and 15 demonstrate that the bioclastic sands that make the ridge of Tyre were emplaced onto these red sands, and therefore postdate them. The red sand layer is expected to rest landwards onto the older coastal calcarenite. Such superposition was not found in TYR-23 and 24, as no red sand lies over the calcarenite. There, the red sands may have been eroded before deposition of continental brown clays. Such an interpretation is suggested by the fact that TYR-23 and 24 may have been drilled in a paleovalley incised into the coastal calcarenite (see below). Alternately, the absence of red sand may be explained by a lateral change in facies, the red sand being the weathered residue of a fine marine sand deposited during the accumulation of coarser bioclastic sands closest to the coast, the latter being subsequently cemented to form the coastal calcarenite.



west side of Tyre Island

cathedral
east side of Tyre Island

ridge of Tyre

Sea wall - Tyre City

Quay of the Spring

1/5

TYR-21 TYR-19 TYR-20 TYR-3 TYR-16 TYR-17 TYR-10 TYR-25 TYR-28 TYR-27 TYR-12 TYR-1 TYR-14 TYR-29 TYR-9

F1

F3

F1

F8

F4

F8

F11

F8

F4

F2-F3

F1

F9

F10

F12

F11

F4

F8

F11

F1

F12

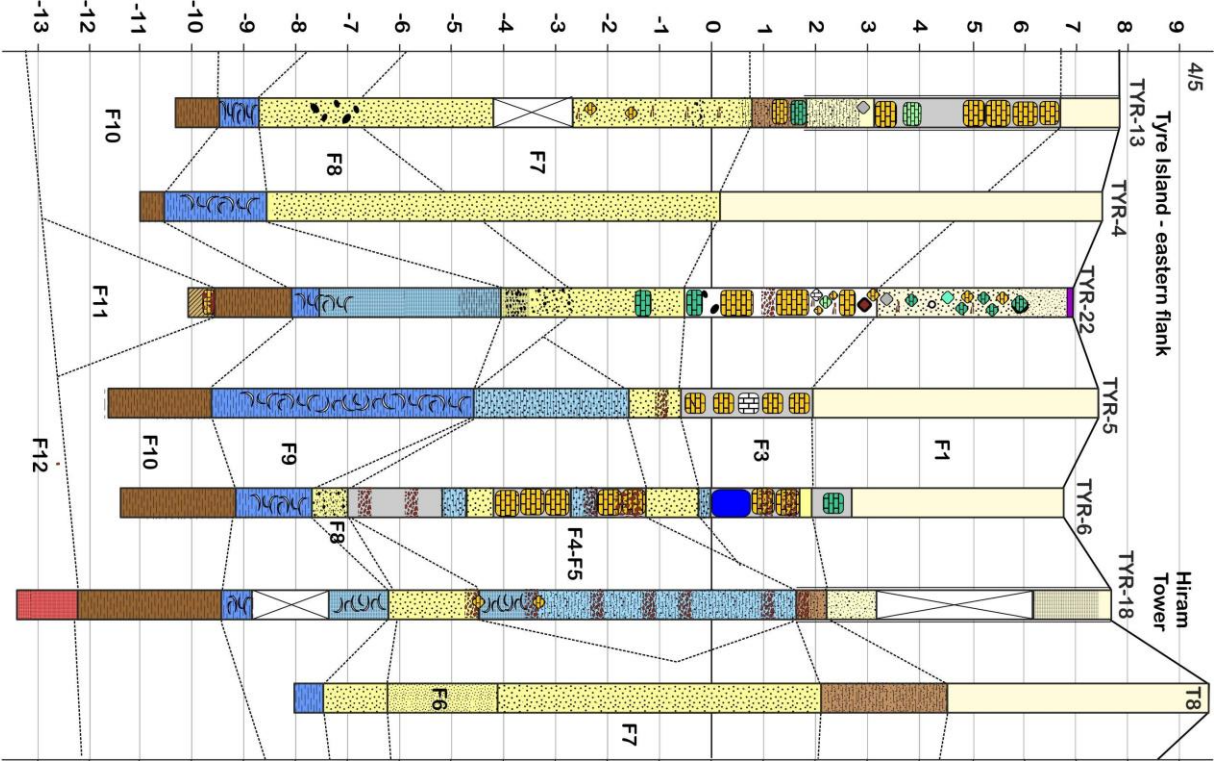
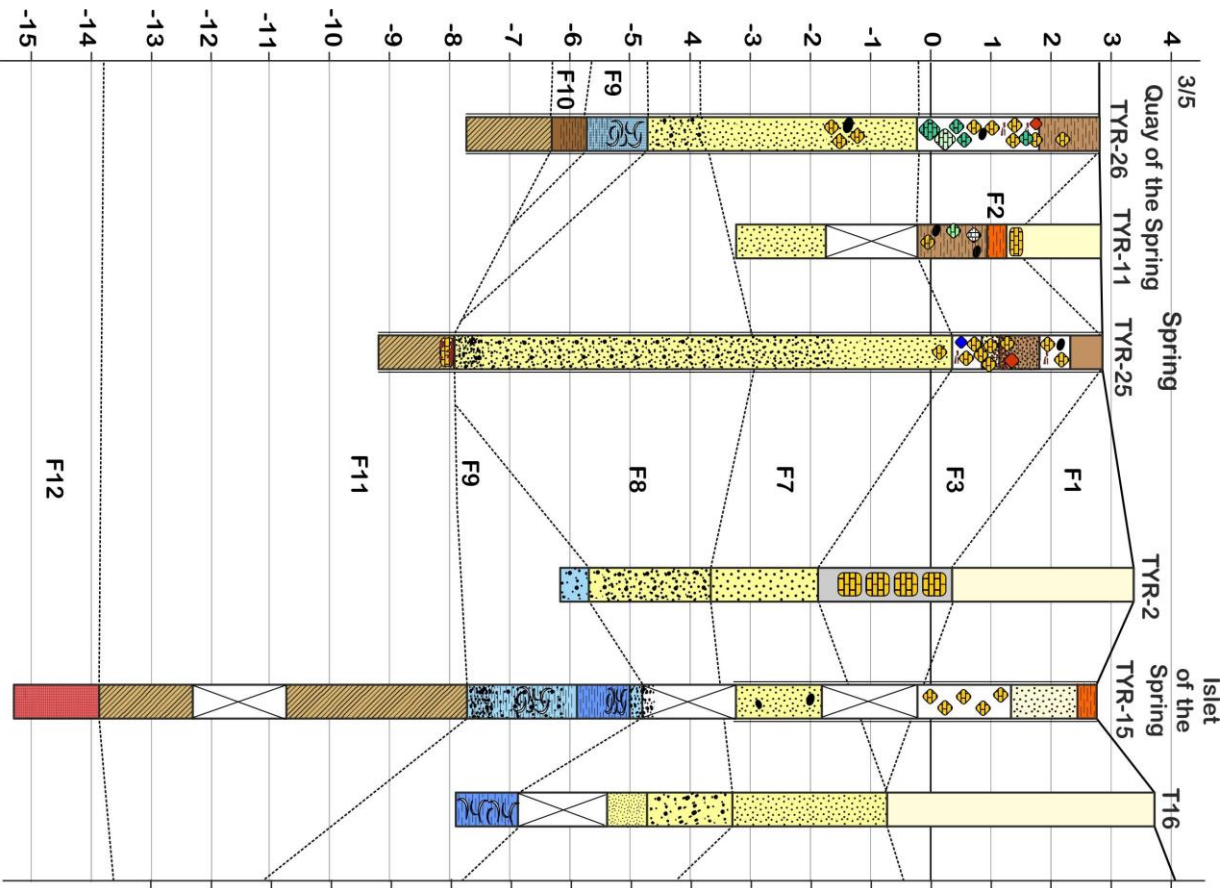
F9

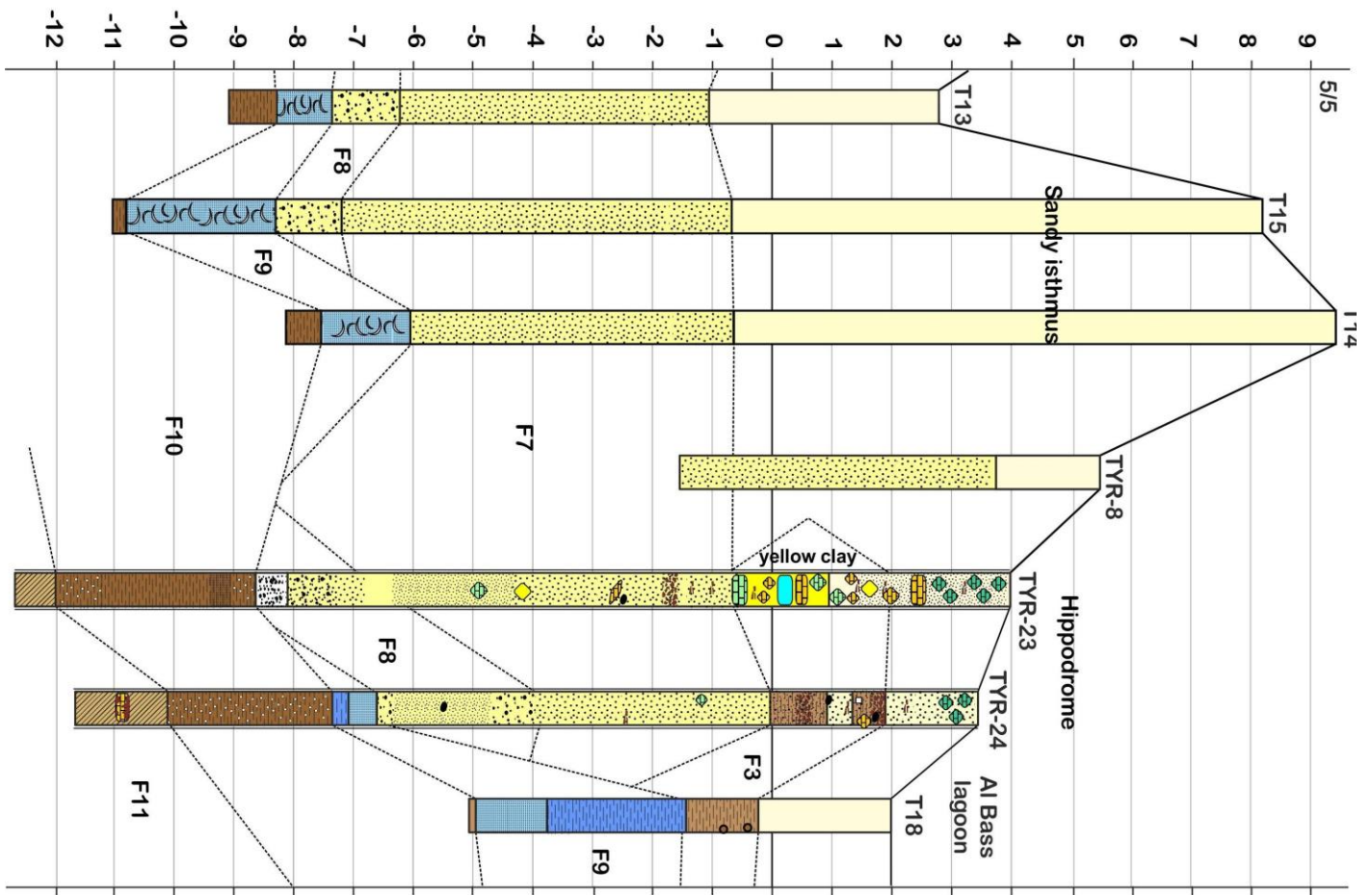
F10

fallen
or cavity

cavity?

fallen





Blocks and clasts

- ◊ Smaller than core diameter
- Larger than core diameter
- ┆ Pottery shards
- ◆ Brick
- ⊕ Marble
- Dolerite, basalt
- ◻ Calcarenite (ramleh)
- ◻ Kastified calcarenite
- ◻ Micritic hard limestone
- ◻ Chalk
- ◻ With cement coating
- ◻ Limestone pebble
- Flint pebble
- ☞ Shells

Sediment

- Undifferentiated loose matrix (F1)
- ◻ Shard-rich layer
- Reddish clay (F2)
- Artefact-rich compact brown silt (F3)
- Black-grey clay with clasts (F4)
- Fine, well sorted quartz-rich sand with clay (F5)
- Fine, grey to beige quartz-rich sand (F6)
- Well-sorted medium beige bioclastic sand (F7)
- Coarse bioclastic sand (F7)
- Poorly sorted clayey sand
- Gravel and pebble (F8)
- Holocene ductile lagoonal clay (F9)
- Pleistocene compact dark clay (F10)
- Pleistocene dark clay with carbonate concretions (F10)
- Calcarenitic sandstone (F11)
- Fine quartz-rich sand with clay coating (F12)

Fig. 4. Detailed core logs and stratigraphic correlations

The occurrence of red sands at sea level, along the west coast of Tyre, in cores TYR-19 and 21, was not expected, as sands at this location should lie below the calcarenite ridge of Tyre, more than 14 m below sea level. Cores TYR-19 and 21 are also the only cores that exhibit post-depositional deformation, evidenced by steeply dipping layers of sands and brown silts. It is unclear whether the sediments were tilted early, by soft-ground deformation before compaction, or later, by a tectonic dislocation. An inspection of calcarenite beds exposed offshore, 30–70 m to the west of TYR-19 and 21, failed to detect any abnormal bedding attitude or tectonic dislocation in the calcarenite. No tectonic disruption has been observed in the calcarenite so far (Goiran, Brocard, De Graauw et al. 2021), such that this geological anomaly cannot be explained for the time being.

Calcarenite (F11). Around the rocky headland of Tyre, the calcarenite crops out up to elevations of no more than 1 m above sea level, rising progressively to 2.5 m at the south-western tip of the peninsula. TYR-20 shows that, farther onshore, the calcarenite lies as low as sea level, and even below (-2.5 m). Therefore, the current headland, which culminates at +5 m in the north, west of the modern harbour, and at +12 m in the south, west of the archaeological site of TyreCity, is mostly a manmade landfill above sea level. Along the mainland-facing side of Tyre Island, the calcarenite lowers from +1 m in TYR-3, down to -10 m in TYR-22 (140 m farther east), and below -12 m in TYR-4 (170 m east of TYR-3). TYR-22 allowed the first direct observation of the predicted lap of the transgressive lagoonal clays over the calcarenitic ridge of Tyre. The calcarenite vanishes farther east, within 240 m of TYR-22, before reaching TYR-18, where the lagoonal clays rest directly on fig. 4 red sand. Along the southern coast of the peninsula, the mainland-facing flank of the calcarenitic ridge of Tyre is shallower, and better constrained by a dense array of eleven cores along the seawall of Tyre-City. The cores track a calcarenite sill which connects the main ridge of Tyre, to an isolated outcrop of calcarenite in the east, which forms the 'Islet of the Spring', on which Poidebard's Quay of the Spring has been built (Brocard, Goiran, de Graauw et al. 2024). The islet is located 30 m south of TYR-15. The sill, which currently lies 5 to 7 m below sea level, is overlapped by the lagoonal clays that fill the strait between Tyre and the mainland in TYR-9, 15, 26, and 29. Seaward-dipping beds of calcarenite crop out along the mainland coast, north and south of Tyre. These straight, almost continuous rocky beds are buried under the sandy isthmus of Tyre and were expected to be encountered at shallow depth (-3 m to -5 m) below the sands of the isthmus at TYR-23 and 24. The calcarenite was found much deeper (-10 m to -12 m). We tentatively interpret this discrepancy as revealing the presence of a valley incised in the calcarenite, buried beneath the sands of the isthmus, and possibly connected to the antique lagoon of Al-Bass farther east.

Compact brown clays (F10). Compact brown clays were initially found at the base of the 2002 and 2018 cores, below the transgressive lagoonal clays. They are devoid of marine shells and have been exposed to compaction and weathering during the last glaciation. They lie over the calcarenite of the ridge of Tyre and the mainland coast calcarenite. Being younger than the ridge of Tyre, and affected by continental weathering, they must have been deposited during the last glaciation, by small coastal streams, in low topographic position, within the saddle between the ridge of Tyre and the mainland. Similar fluvial clays are found between calcarenite ridges farther south along the Levantine coast (Shtienberg, Dix, Waldmann et al. 2016; Goff, Austin and GoodmanTchervov 2018). At TYR-23 and 24, the presence of the clays over the anomalously low calcarenitic bedrock supports the view that a former valley, incised in the calcarenite, is present there. Erosion in the valley would have removed the red sands overlying the calcarenite, incised the calcarenite, and the valley would have then been partially filled by these brown fluvial clays.

Lagoonal transgressive clays (F9). The lagoonal clays lap onto the calcarenitic ridge of Tyre up to an elevation of -9 m, except near the Quay of the Spring (TYR-25). Similar clays have been described further east in the lagoon of Al-Bass (Marriner, Goiran and Morhange 2008), but at higher elevation (-2 m to -5 m). The lagoon of Al-Bass may represent either a separate lagoon, or a late, restricted remain of the main lagoon.

Sandy gravel (F8). The importance of this unit was overlooked in earlier works. The compilation of the 2002 and 2018 cores shows that there is a significant time gap between the deposition of the lagoonal clays (from 6000 to 4500 years Bc), and the deposition of the bioclastic sands of the sandy isthmus (after 1500 years Bc), which represents a period during which sea bottom currents prevented the deposition of bioclastic sands and eroded the lagoonal clays (Brocard, Goiran, de Graauw et al. 2024). The irregular elevation of the top of the lagoonal clays (from -9 m to -14 m) supports this view, as does the presence of sandy gravel above this erosion surface. The gravel was transported by stronger currents than the ones that accumulated the overlying bioclastic sands, which are devoid of gravel. The transition from gravel to sand deposition, and from sand bypass to sand accumulation, coincides with the time at which permanent settlement is documented on Tyre Island (see supra).

Bioclastic sands (F7). The bioclastic sands accumulated to form a marine sand bank by diffraction and refraction of waves behind the island. The bank is the basement on which Alexander the Great's causeway was built (Nir 1996; Carmona and Ruiz 2004; Marriner, Morhange and Meulé 2007). It started to grow after 1500 years Bc, when the earliest evidence of development is documented on the island (Aubert 2020). Some early developments may have promoted sand accumulation, such as, for example, the connection of separate islets to make a larger island. Sand accumulation over the bank increased dramatically after the construction of Alexander-the Great's causeway, turning the marine bank into a large sandy isthmus (Nir 1996; Carmona and Ruiz 2004; Marriner, Morhange and Meulé 2007; Brocard, Goiran, de Graauw et al. 2024).

Fine sands and organic clays (F4-6). During the deposition of bioclastic sands on the bank, finer grained sands were deposited closer to Tyre (Marriner, Morhange, Boudagher-Fadel et al. 2005; Brocard, Goiran, de Graauw et al. 2024). The deposition of these fine sands in quiet water requires the existence of intervening natural or artificial barriers to shelter them from waves and bottom currents. In the absence of identified intervening natural barriers, it is likely that manmade structures must offer that sheltering. This is why such sediments generally interpreted as harbour sediment (Marriner and Morhange 2006). Fine-grained sediments around the modern harbour of Tyre led Marriner, Morhange, Boudagher-Fadel et al. (2005) to report the discovery of the ancient Sidonian harbour of Tyre, filled with Roman-Hellenistic fine sands. Similar sediments in the 2018 cores led Brocard, Goiran, de Graauw et al. (2024) to report the discovery of the southern, Egyptian harbour, and of an older northern harbour of Tyre in the area of Hiram's Tower. First identified in TYR-1 (2018), the sediments of the southern harbour were found again in seven of the 2023 cores, stretching 100 m along the modern seawall at the archaeological site of Tyre-City (fig. 2 and 4). These sediments lie either directly over the ridge of Tyre or are separated from it by a thin accumulation of gravel or continental and lagoonal clays. Sediments of the putative early northern harbour, first identified in TYR-6, were found in the new cores 120 m farther east, 25 m to the west of Hiram's Tower (TYR-18).

Brown and red clays (F2-3). These patchy layers were found above the water table (0-3 m) in association with pottery shards and construction material assemblages (calcarene, chalk, hard limestone, decorative breccia, marble, dolerite, granite), reminiscent of the Roman and Byzantine levels, exhumed at the same elevation on the archaeological sites of Tyre-City and Al-Bass. They are locally found at higher elevation, near the Roman-Byzantine baths (+6m, TYR-13), and on the southern part of Tyre Island (+9 m).

Undifferentiated later layers (F1). The accumulation of sand dunes over the isthmus of Tyre was left unmanaged after the abandonment of the Roman-Byzantine levels. They led to a progressive inflation of the sandy isthmus, up to +13 m near the archaeological site of Tyre-City. Sporadic developments, land filling, and ancient building plundering led to the dispersal of blocks throughout the peninsula amidst the sand.

Discussion: Freshwater Routing under Tyre Island

Natural rise of freshwater to the island

Numerous submarine freshwater springs have been identified along the Lebanese coast (Saad, Kazpard, et al. 2005). Rainwater falling in the mountains is conveyed to the coast through long karstic conduits, opened in Jurassic to Eocene limestones. Some of these conduits extend offshore all the way to the ledge of the marine shelf, which has been exposed to dissolution during the numerous glacial periods of the Pleistocene, when sea level lied as low as 125 m below the current sea level (Benjamin, Rovere, Fontana et al. 2017). Some karstic conduits may have extended even much deeper when the Mediterranean Sea dried up during the Messinian Salinity Crisis (MSC), 5.5 million years ago (Bakalowicz, Fleyfel, and Hachache 2002; Saad, Kazpard, Slim et al. 2005). These karstic conduits are now flooded at their downstream end, and their outlets are sealed by impervious overlying marine deposits. They host pressurized aquifers. Breaches through the impervious cover allow water to ascend to the ground surface, forming artesian exurgences along the coastline, such as at the spring of Ras el Aïn (fig. 1), which was tapped by the Roman aqueduct of Tyre (Bakalowicz, Fleyfel, and Hachache 2002). Provided that favourable geological conditions are met, water can ascend to the seafloor, feeding submarine springs, wherever water head is high enough offshore to overcome marine hydrostatic pressure (Saad, Kazpard, Slim et al. 2005). Several such springs are present in the vicinity of Tyre, the most important of which is the spring of Boroghlieh (fig. 1), which discharges 2 m³/s of freshwater at a depth of 35 m (Saad, Kazpard, Slim et al. 2005). The rise of water to the seafloor requires the breaching of the impervious lid that overlies the limestones offshore. Such breaching is thought to be achieved by two completely different geological processes. The first one is the erosion of the lid during sea level low stands when rivers incise valleys across the emerged part of the continental shelf. Incision can proceed all the way down to the base of the impervious layers, exposing the limestones and their conduits either directly, or exposing some overlying aquifers fed from below by these conduits (Saad, Kazpard, Slim et al. 2005). Such valleys are on the seafloor around Tyre (fig. 1) and may have contributed to the formation of the springs of Ras el Aïn and Boroghlieh. The second process is the tectonic dislocation of the impervious lid produced by slip on recently active to currently active faults. Water ascends to the seafloor along the fractures created by tectonic displacements. The coastal spring of Al Baqbouq, north of Tyre (Badawi 2017), which is a putative source of water for Tyre, may have formed by tectonic dislocation, along the recently active fault of Sour-Zraryeh (fig. 1).

Below the peninsula of Tyre, karstified carbonates likely lie at several tens of meters below the seafloor, being overlain by an overlap Pleistocene assemblage consisting of an alternation of marine and continental layers, deposited during successive glacial and interglacial periods. How water rises from the karstic conduits to the subsurface can only be speculated, because this routing occurs below the reach of the cores (16 m below sea level). The springs of Tyre are located in the seaward projection of the recently active fault of Sour-Zraryeh (fig. 1), such that it is tempting to ascribe freshwater rise to tectonic dislocation by the fault. So far, however, there is no evidence that this fault extends across the coastal plain all the way to Tyre, and the calcarenite of Tyre does not exhibit any evidence of dislocation, suggesting that, if a fault splay passes below Tyre, it has not been active over the past 100 ky (Goiran, Brocard, De Graauw et al. 2021). However, earlier slip on the Sour-Zraryeh fault may have disrupted older, underlying layers of Pleistocene age, promoting the ascent of freshwater below the calcarenite. Alternately, the combined flows of Wadi Saifi and Wadi Abbassiye, which valleys debouch on the coastal plain 4 km to the northeast of Tyre (fig. 1), may have, at some point in the past, incised a low sea-level valley deep enough to pierce the impervious lid under the current location of the isthmus of Tyre.

The way groundwater flows to the surface within the topmost 20-25 m is better documented by the cores (fig. 5). The transgressive lagoonal clays and their underlying compact, brown continental clays form an aquiclude that efficiently separates the bioclastic sands above, soaked in seawater, from the freshwater that soaks the underlying red sands. The clays prevent contamination of the deep freshwater by seawater in the area comprised between the mainland and the island of Tyre. The calcarenite forming the ridge of Tyre hosts freshwater in close proximity to the Quay of the Spring. That spring is located where the clay lid tapers off against the calcarenite ridge. The spring is therefore located where freshwater can ascend buoyantly or forcibly through the calcarenite and overlying permeable layers. In fact, the spring may have even prevented the deposition of lagoonal clays at this

location. If water rises with some pressure, the spring may have even existed, perched on the mainland-facing flank of the ridge of Tyre well before the ridge was submerged, preventing deposition of brown compact clays. The ascent of water at Hiram's Tower is more enigmatic, because a thick layer of continental and lagoonal clays was found within 25 m of the spring in TYR-18. Nonetheless, a small reef of calcarenite could be present closer to the tower and may provide the permeable window needed for water to ascend through the clay layer.

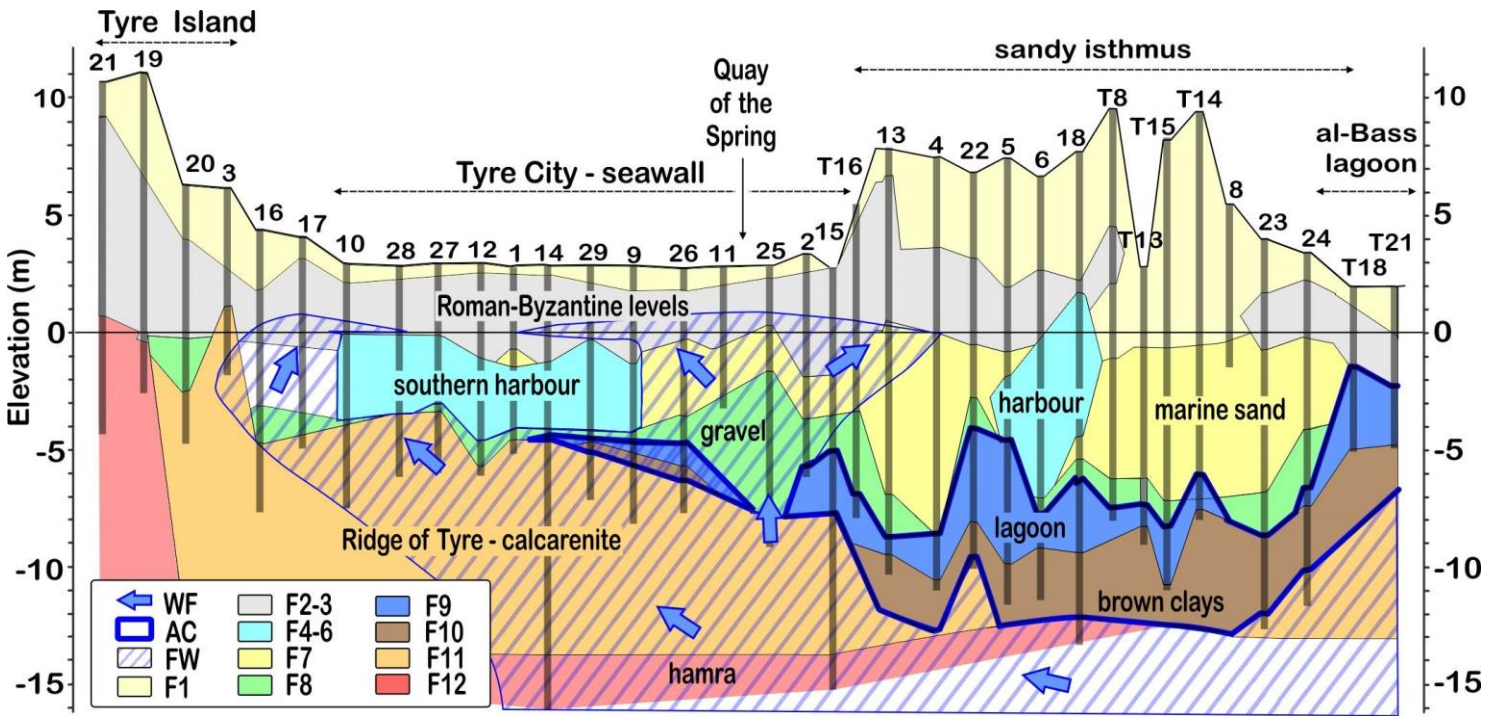


Fig. 5. Stratigraphic synthesis of the cores (dark vertical bars) between Tyre Island in the west (left) to the mainland in the east (right), displaying the interlayering of the main facies identified (F1 to F12, as numbered in the text), and inferred freshwater routing (FW: freshwater body, AC: overlying aquiclude, WF: freshwater flow).

The circulation of water above the calcarenite has changed during Antiquity, influenced by the deposition of archaeological layers. Freshwater was deflected by the deposition of impervious harbour basin fills, which are located near the Quay of the Spring and the spring of Hiram's Tower. The choice of these locations for developing harbour basins may have been constrained, in part, by the location of the springs. However, the precise location of the springs and wells may have been determined by harbour development.

Management of the freshwater aquifer underlying the island

Today, the water release along the Quay of the Spring consists of diffuse exhalations of freshwater into the sea, 30 m south of the seawall that protects the archaeological site of Tyre-City. Water percolates 1 m below sea level amidst scattered construction blocks, on the western flank of the Islet of the spring. Freshwater was found and collected in the cores located along the sea wall, as well as in the deepest excavations conducted on the archaeological site. Numerous wells have been unearthed on land, over the years (fig. 2), within 150 m of the spring, such as circular Persian and Phoenician wells, and rectangular, high-yield Roman wells. Two modern, square wells are also present along the basilical hallway of the Roman baths. Numerous cisterns of Persian and Hellenistic ages are also found around the wells. Field campaigns have exposed extensive parts of piped-water network (Gatier 2011, 2012; Gatier et al. 2010; Rousset 2016). The spring of Hiram's Tower is accessed through a monumental stairway, highlighting its importance during Antiquity, but not much documentation is left from the time of its archaeological unearthing.

Research is underway, as part of the AquaTyre project, to determine to which extent the numerous wells, piped-water networks, and storage systems are connected to the harvesting of freshwater from different potential sources, including the aquifer located beneath the island. This research includes the isotopic tracing of water sources, and pumping tests in order to determine the transmissivity, reactivity, and behaviour of the underlying aquifer.

Laboratory analyses of the sediment cores

Radiocarbon, U-Th dating on carbonates, and Optically Stimulated Luminescence (OSL) dating will be undertaken to provide better age constraints on the stratigraphy of the peninsula of Tyre, in particular to obtain a chronostratigraphy of the Pleistocene layers independent from the chronology established farther south along the Levantine coast. Such analysis is necessary to firmly establish the age of the calcarenitic ridge of Tyre, the age of the seaward-dipping calcarenite beds that crop out along the mainland coast, and that the age of the intervening red sands. Samples of red sands and calcarenite will be submitted to hydrogeological tests to establish their permeability and transmissivity. These data will be combined with hydrogeological cross-sections of the peninsula of Tyre, elaborated using the stratigraphy presented here, to feed a numerical hydrogeological model meant at simulating the seasonal behaviour of the freshwater aquifer that underlies the island. Different behaviours promote different water harvesting strategies, and can strongly influence the design of water extraction, storage, and dispensing facilities.

In addition, the analysis of the organic, mineralogical, chemical, and isotopic composition of the sediments which fill the antique harbour basins will provide insightful information on water usage and urban life, because the harbours are the ultimate outlets of water sewage. Their sedimentary archives therefore contain a rich record of water usage during Antiquity.

Conclusions

The coring campaigns conducted in 2023 provide new insights into the geological structure of the peninsula of Tyre, from its surface (+13 m) down to 15 m below sea level. Earlier cores were halted upon reaching the rocky basement of calcarenite and compact clays, such that their stratigraphic relationships remained unconstrained and speculative.

The new cores show that the transgressive lagoonal clays and the underlying compact, continental clays form a continuous layer between Tyre and the mainland that overlap the calcarenite ridge of Tyre in the west, and the coastal plain calcarenite in the east. It reaches its maximum thickness in the saddle between these two calcarenite highs.

The cores showed that a layer of fine red sand underlies both the clays and the island of Tyre. These stratigraphic relationships are consistent with the general imbrication of red sands and calcarenite ridges documented along the Levantine coast farther south. Rainwater falling on the mainland travels underground to the coast via karstic conduits opened in Cretaceous-Eocene limestones. Some of these conduits extend across the marine shelf, because the shelf was above water during glacial periods. The shelf is covered by Pleistocene sediments that are less permeable than the underlying limestones. This cover prevents the flooding of the conduits by seawater during interglacials, and, if freshwater is pressurized enough, the conduits can feed submarine freshwater springs, such as the ones observed on the seafloor around Tyre. Pressurised water ascends to the seafloor at places where the cover is breached.

It is likely that the cover is breached between Tyre and the mainland, although the structure responsible for this breaching remains speculative (ancient valley or recent fault).

The clay layers deposited between the ridge of Tyre and the mainland form an aquiclude that prevents the mixing of this rising freshwater with the seawater that soaks the bioclastic sands located above the clays. The rising freshwater is deflected toward the ridge of Tyre, where it rises through the porous calcarenite, along the former land-facing shoreline of the island. This configuration is particularly favourable for harbour development, as the coast of Tyre not only provides sheltering from sea waves, but also freshwater springs. As a matter of fact, the freshwater springs identified on the island are located near silty clay deposits interpreted as harbour sediments. It is likely that harbour sedimentation during Antiquity has played a role in water routing, deflecting freshwater flow around the harbour basins and concentrating it along their sides.

Acknowledgements

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