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Research Article

A Geological overview of the Maltese Archipelago with reference to the Area of Sliema

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Abstract. This study offers an overview and account of the geological and geographical characteristics of the Maltese islands, with a particular emphasis on the Sliema peninsula. The stratigraphic sequence of the geology on the islands, including the lithostratigraphy and sedimentary structure dating back to the Oligo-Miocene Epoch, is described starting from the oldest layer, the Lower Coralline Limestone, up to the most recent rock deposition in the newly discovered quaternary rock deposition. Additionally, the report delves into the general seismic activity on the island that has contributed to the unique geomorphology, hydrology, and hydrogeology that exist on Malta and Gozo. The interrelationship between these geological components is evident on the islands, particularly in the tectonic activity that has resulted in the formation of cliffs and bays throughout. After providing a general geological overview of the islands, the report focuses more specifically on the Sliema area, a town located in the east of the main island of Malta known for its numerous rocky beaches and heavy urbanization.

Keywords: Geology, Maltese archipelago, geomorphology, tectonics, hydrogeology.

1 Introduction

The Maltese archipelago is situated in the middle of the Mediterranean Sea with latitude between 35° ∧ 36° and longitude between 14° ∧ 15°. It consists of three main islands: Malta, Gozo, Comino and other smaller islands like Cominotto and Filfla (Figure 1). The areal coverage of the islands is about 316 km^2. Their strategic location has led to colonization by various groups over the years, including the Phoenicians, Greeks, Romans, and other European countries. It is likely that each of these groups contributed to the anthropogenic causes of soil erosion on exposed limestone surfaces (Bonnici et al., 1993).

The Maltese archipelago is unique because it emerges from the Pelagian Platform, which is mostly submerged under the sea. The islands are composed of sedimentary rocks formed during the Oligo-Miocene epochs and consist of five main stratigraphic formations (Pedley et al., 1976) (Figure 2).

The islands are primarily structured by two fault systems: The Great Fault and Magħlaq Fault. The fault systems contribute to the northeast tilt of the island (Alexander, 1988; Micallef et al., 2019b), have a significant impact on the subaerial geomorphology of the archipelago (Alexander, 1988) and are closely associated with the development of the Malta Graben (Illies, 1981; Reuther & Eisbacher, 1985). The Great or Victoria Fault is the more extensive system, consisting of ENE-WSW trending normal faults with a dip of 55–75°. These faults mainly occur between Malta and Gozo, creating a horst and graben structure approximately 15 km wide. The second system, the Magħlaq Fault, is the youngest and consists of NW-SE trending, oblique flank-rift faults. These faults mainly affect the southern coastline of Malta (Bonson et al., 2007; Reuther & Eisbacher, 1985).

Sliema: The exposed limestone surfaces are very evident in the study area of Sliema, a town located in the north-eastern coast of island.

Aim: The aim of this study is to present a general overview of the geology of the Maltese Archipelago, with special reference to the urban area of Sliema. This can be useful for tourism purposes.

2 Geographic and Geological Setting

The Maltese archipelago is linked by a shallow submarine ridge, consisting of a 25–30 km thick continental crust,

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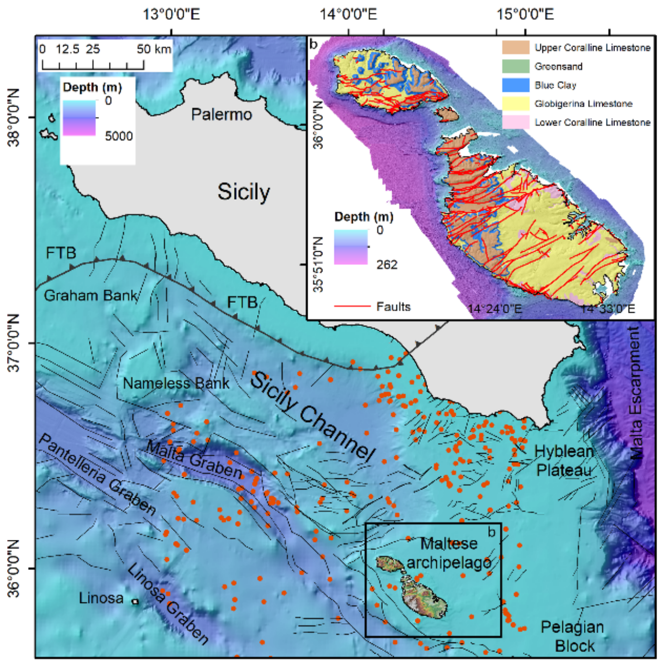

Figure 1: Bathymetric map of the Pelagian Platform (central Mediterranean Sea), showing the principal morphological and structural features (faults in black). Background bathymetry from EMODnet bathymetry (http://www.emodnet-bathymetry.eu). FTB: Fold and Thrust Belt.

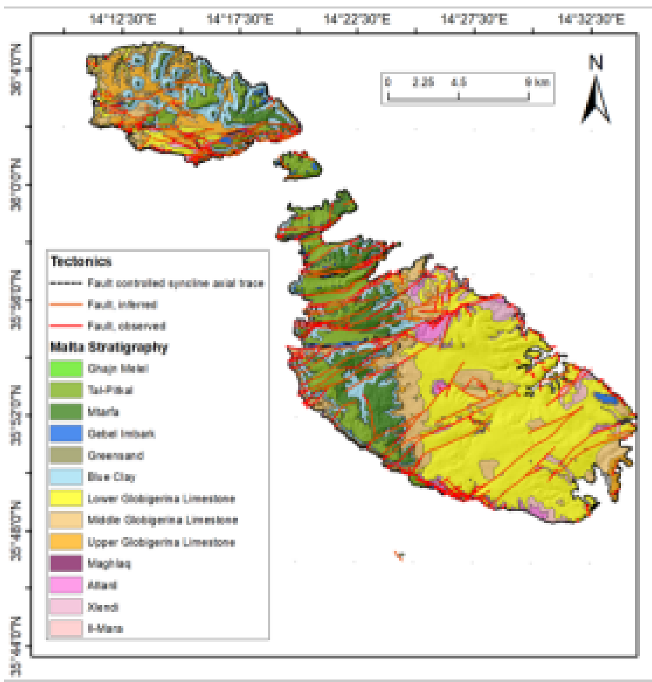

Figure 2: Stratigraphic and tectonic Map of the Maltese Archipelago.

known as the Pelagian Platform or Pelagian Block (Spatola et al., 2018; Todaro et al., 2021) to Sicily and Africa. The islands emerge from the central eastern part of the Pelagian Platform, which served as a land bridge during the Pleistocene and allowed for the migration of exotic fauna (e.g. dwarf elephants) both northwards and southwards.

The upper sedimentary units of the Pelagian Block contain Plio-Pleistocene units of terrigenous, pelagic and hemipelagic sediments, together forming layers that are up to 300 m thick (Max et al., 1993; Osler & Algan, 1999; Todaro et al., 2021). Underlying these units are the sedimentary sequences of the Miocene to Cretaceous shelf edge carbonate buildups, with thickness greater than 4 km and the Cretaceous to Triassic shallow platform carbonates. These carbonate sequences are accentuated by extensive depositional hiatus, together with tufts and pillow lavas that were deposited during numerous volcanic episodes. In the northern section of the Pelagian Block lies the Sicily Channel, or Sicilian Strait, consisting of shallow waters typically less than 400 m in depth, except in the Pantelleria, Linosa and Malta grabens, which range from 1300 to 1700 m in depth (Civile et al., 2010; Spatola et al., 2018). In the north-eastern boundary of the Pelagian Block, lies the Malta Escarpment, a steep submarine cliff consisting of limestone and dolomite. It is 290 km long with a relief of more than 3 km and stretches from the eastern margin of Sicily southwards towards the Medina Seamounts. Numerous submarine canyons are present across the escarpment, which were most likely driven by subaerial fluvial erosion during the Messina Salinity Crisis (Micallef et al., 2019a; Spatola et al., 2020).

3 Data and Methods

The baseline information presented in this study was collected from:

1. Published literature,
2. LiDAR data and aerial photographs acquired during project ERDF 156 (Environment and Resources Authority),
3. Google Earth imagery,
4. Field surveys were also undertaken in May 2021.

Thematic maps of this study were generated using ArcGIS (http://www.esri.com).

4 Geology of The Maltese Islands

4.1 Lithostratigraphy

The geology of the Maltese islands is young considering the geological time frame. The Maltese Islands include five main formations which are, from bottom to top (oldest to youngest): Lower Coralline Limestone, Globigerina Limestone, Blue clay, Greensand and lastly the Upper Coralline Limestone Formation (Figures 1 and 2). These formations are composed mostly of mid-Tertiary rocks and took around 21 million years to form (Alexander, 1988). The table below (Table 1) shows the epochs for each of these formations.

Lower Coralline Limestone (LCL): locally referred to as Żonqor, it is the oldest exposed layer lying at the bottom of the stratigraphic sequence. It was formed during the late Oligocene and is visible in vertical cliff faces such as the base of the Dingli Cliff section and Mtaħleb. The LCL, characterized by a hard and grey limestone, contains numerous fossils such as the Conus species and coral (Figure 3). It is subdivided into four geological members, named after the locations where they occur: the Magħlaq member, Attard member, Xlendi member, and il-Mara member, with Magħlaq being the oldest.

Globigerina Limestone: this formation overlies the LCL and is locally referred to as Franka. It is mainly composed of fine granite rocks with a yellow to pale grey colour (Figure 4). The Globigerina Limestone outcrops approximately 70% of the island forming gentle slopes such as those located at the lower cliffs at Dingli, as well as outcrops in the Marsaxlokk area. Two distinctive fossils, the Sea urchin and Sand Urchin, dating back 30–25 million years ago, are commonly found embedded in the formation. The formation is subdivided by two beds of phosphorite pebbles into three members, from oldest to youngest being the Lower, Middle and Upper Globigerina Limestone.

Blue Clay: this formation is characterized by alternating shades of grey ranging from dark to pale and a low to high carbonate content percentage, was formed during the middle Miocene period. The formation is primarily located in the northwestern regions of the Maltese islands, with its maximum thickness found in the North of the Gozo Island (as depicted in figure 2). According to Alexander (1988), the carbonate calcium content in the Blue Clay can range from a minimum of 2% to a maximum of 30%. The Blue Clay strata are composed of soft fine clay, easily erodible and prone to slope formation. Furthermore, the Blue Clay being impermeable acts as a collection point for groundwater, leading to the creation of the perched aquifer (Stuart et al., 2010).

Greensand: it outcrops locally and attains its greenish colour in unweathered areas, whilst its orange colour is a result of oxidation and exposure to air (Figure 6). The Greensand layer also contains fossils such as the Domed Sand-Dollar, dating back 15 million years ago. It is less than 1 m thick in the Maltese islands, except for sections in il-Gelmus hill in Gozo, where the formation can be found to be as thick as 12 m.

Figure 3: The lower Coralline Limestone Formation located on the Dingli Cliffs.

Figure 4: Cliffs of Upper Globigerina Limestone Formation at Il-Hofra l-Kbira near Marsaxlokk.

Figure 5: The Blue Clay Formation at Gnejna Bay.

Figure 6: Greensand layer at Il-Gelmus hill in Gozo.

Upper Coralline Limestone: it is the youngest formation containing coralline algal content, similar to the LCL Formation (Figure 7) (Pedley et al., 1976). It is composed of four different members which are in the order from oldest to youngest: the Malal member, Mtarfa member, tal-Pitkal member and the Ġebel Imbark member.

Quaternary Deposits: the most recently laid geological strata are the Quaternary deposits, formed almost 2.5 million years ago, after the emergence of the Maltese islands. The Quaternary deposits are not thick enough to be classified as a formation, but they are easily identifiable by their reddish-brown colour, which can be mistaken for soil (as shown in figure 8). These deposits are primarily composed of terrestrial, aeolian, and alluvial sediments, and they can be found in a wide variety of locations such as valleys, plains, seashores, and even on seafloors like in Wied Magħlaq, Pembroke, and Sliema.

4.2 Tectonics

The Maltese rocks are characterized by gentle folds and several faults of different sizes, greatly affecting the topography of the Maltese Islands. The two main extensional fault systems of the Maltese Islands are the NE-SW Victoria Fault and the Magħlaq Fault (Figure 2). In the northern part, the Victoria Fault crossing from Fomm ir-Riħbay to Madliena likely forms alternatively horst and graben features that are not visible in the southern part.

Numerous normal faults are present in Malta, with a dominant trend in the northeast direction, rapidly decreasing eastwards. In the southern part of Malta, a second movement with a northwesterly trend is observed. At Għar Lapsi, the Magħlaq Fault can be seen, which has a smooth, sliced fault plane facing the sea, running parallel to the coast. The fault has displaced the Upper Coralline Limestone at least 230 m to the south, with the downward sloping fault layers inclined at a high angle. The Magħlaq Fault consists of two spaced parallel faults, as is common with many larger faults in Malta. Consequently, pieces of Globigerina Limestone and Blue Clay are trapped between the two fault walls at various points throughout the fault complex. To the east of the dramatic cliffs formed by the Magħlaq Fault, a series of side fractures occur, which increase in the southeast direction (Pedley et al., 1976).

The third region is Gozo Island, slightly inclined to the NE. The southern west coast is characterized by cliffs reaching heights over 120 m. However, the northern coast is beyond 20 m below the sea level. The two largest faults in Gozo, the Sannat and Qala Faults, are centered around the locality of Mġarr ix-Xini. The Sannat fault extends in the W-NW whilst the Qala fault extends in the NE. The latter fault has a maximum throw of approximately 120 m to the south of Nadur, decreasing in height toward the east and west. Numerous smaller faults intersect the southern coast south of both fault systems, as documented by Pedley et al. (1976).

4.3 Seismicity

The Maltese islands lie on a relatively stable plateau within the pelagian platform (Figure 1). They are located at 200 km southwards from the Euro-African plate collision margin, which runs across Sicily, and 100 km west from the seismically active Malta Escarpment. The latter, together with the Pantelleria Graben and the Linosa Graben, form part of the Sicily Channel Rift Zone (SCRZ), a system which characterizes these three grabens from the Miocene-Pliocene age (Civile et al., 2010). The grabens are governed by a fault system that runs across the Sicily Channel from Southern Sicily to Tunisia and is responsible for the major tectonic and geomorphological development of the Maltese Islands. Knowledge regarding the seismicity that takes place on the Sicily Channel Rift Zone has always suffered from a degree of accuracy in locating the epicentre of the earthquakes (Agius & Galea, 2011)(Figure 1). This is partially due to the inadequate network coverage but also due to the generally small magnitude of the events, which peak at about 3.0 on the Richter scale. The largest earthquakes are potentially generated by the more dangerous area of the northern end of the Malta escarpment, which is believed to have generated the earthquake that caused maximum damage on the Maltese Islands during the 11 January 1693 event. Despite Malta's location near seismically active zones, the Maltese Islands rarely suffered from strong earthquakes that brought about severe damages. The earthquakes which occur on the islands are mild and infrequent (Figure 1). As a result of this, there is culturally no public awareness about seismic activity, as safety is an automatic assumption (Galea, 2007).

4.4 Geomorphology

Tectonic activity plays a key role in the land formation of the island and relates to the faulting, up-arching, and subsidence.

The formation of the island's landscape is significantly influenced by tectonic activity, which involves faulting, up-arching, and subsidence. According to House et al. (1961), the primary physical geomorphological landscape of the Maltese Islands can be categorized as follows:

Coralline Plateaus: these are uplands composed of coralline limestone which can be found in a variety of sizes. Large plateaus are located towards the west of Malta, with heights reaching 245 m, whilst smaller mesas can be found in Gozo.

Blue clay slopes: mainly present on coastal areas and in valleys that divide the plateau uplands from the sur-

Figure 7: Cliffs of Upper Coralline Limestone Formation on islands at the western end of Comino.

Figure 8: Quaternary deposits found in Pembroke.

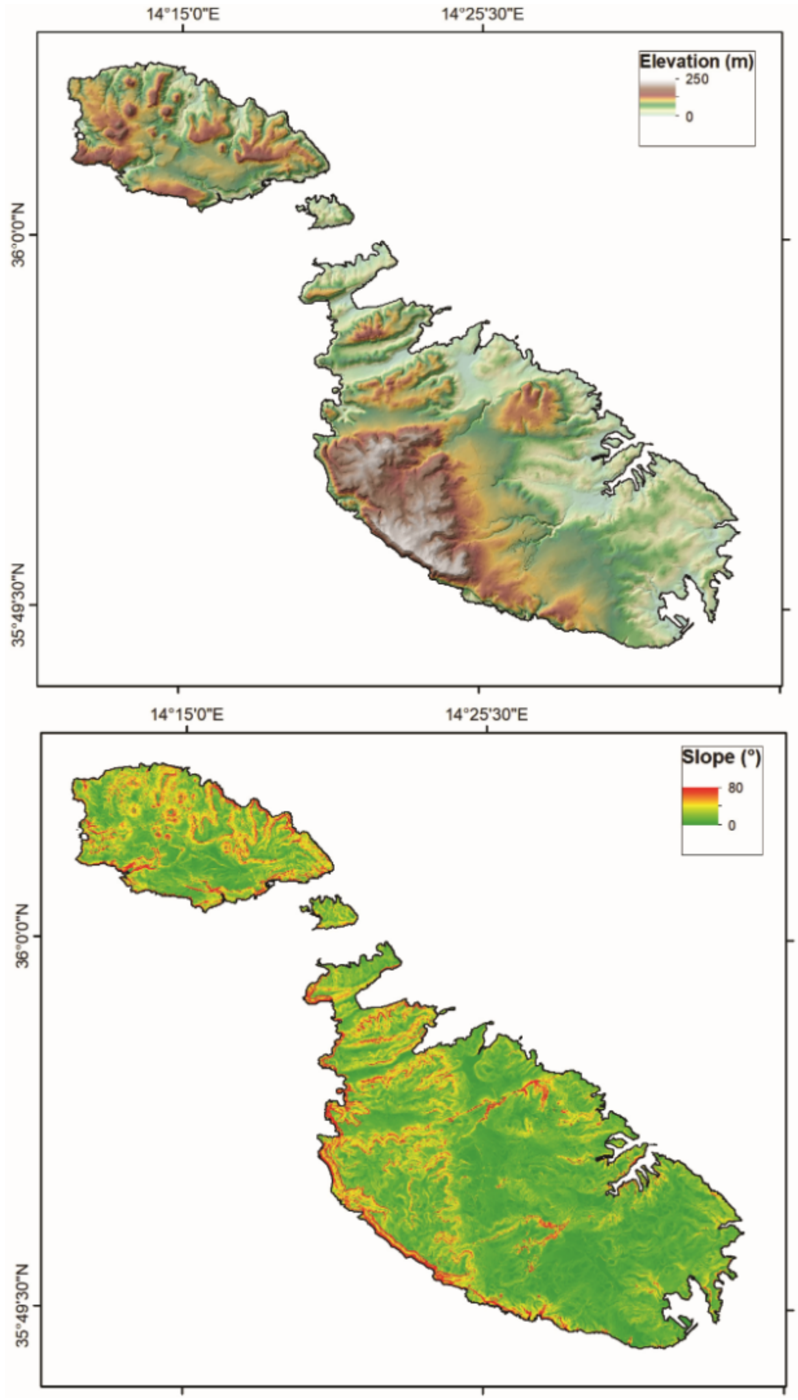

Figure 9: a) Topographic map showing the general elevation of the Maltese Islands. b) Slope Map of Malta.

Epoch	Stage (Years BP)	Formation	Maximum Thickness (m)
U.Miocene	Tortonian (12–7.5 MA)	Upper coralline Limestone	104–175
M.Miocene		Greensand	0–16
M.Miocene	Serravallian (13–12 MA)	Blue Clay	0–75
M.Miocene	Langhian (15–13 MA)	Upper Globigerina Limestone	5–20
L. Miocene	Burdigalian	Middle Globigerina Limestone	0–110
L. Miocene		Lower Globigerina Limestone	5–110
U. Oligocene	Chattian	Lower Coralline Limestone	140 (visible)
			236 (boreholes)

Table 1: Summary description of the general stratigraphy of Maltese archipelago.

rounding areas. Along the Maltese coastline, these slopes are situated at the base of the UCL plateau. Moving inland, Blue Clay can be found in dry valleys that feature seasonal watercourses (only during the wet season) and in some areas with perennial springs that flow throughout the year (Schembri, 1993), owing to the permeability of Blue Clay. In Gozo, it is present in coastal and valley slopes and floors that cut through Coralline plateaus and Globigerina Limestone plains.

Undercliffs: cliffs, locally known as 'Rdum' where steep blue clay slopes form. They are characterized by rockfalls of the UCL onto the Blue Clay slopes. Most undercliffs are situated on the western coast of Malta and on the Eastern coast in Gozo.

Flat-floored basins: these geomorphological formations are typically formed as a result of faulting and erosion (Magri, 2006). Examples of flat floored valleys include Pwales valley, Binġemma Basin and Wied il-Għasel.

Globigerina limestone hills: these are vast regions of gently sloping land. In Malta, these areas are linked to a sequence of low ridges and shallow valleys, with minimal flat land available, mainly found in places like the Marsa Creek in the east, Ta' Qali in the center, and the Luqa airfield in the south. In contrast, the Globigerina Limestone hills and plains in Gozo display more diverse topography.

4.5 Hydrology and Hydrogeology

On the Maltese islands, precipitation is primarily lost through water runoff and evapotranspiration. The remaining water is collected in underground freshwater reservoirs, as it flows through fissures in the rock layers. The Miżieb and Binġemma basins are sealed off by a soft blue clay layer and function as perched synclines, allowing for water collection. The top layer of water, which has the lowest salinity, is extracted and utilized for irrigation and public water supply, as noted by Stuart et al. (2010).

The geological features of the Maltese Islands give rise to two distinct types of aquifers: sea-level aquifers (freshwater lenses within the LCL) and perched aquifers. The most significant aquifer in Malta is the Mean Sea-Level Aquifer (MSLA), which covers an area of 216 km^2 south of the Victoria fault. The MSLA is in contact with seawater and has an outflow gradient towards the sea, with galleries excavated in the saturated zone serving as a crucial source of drinking water. Conversely, perched aquifers are smaller aquifers located in the UCL with a low permeability and porosity ranging between 41% and 45%. These aquifers discharge through springs, but due to heavy pollution, they are only suitable for irrigation purposes. The aquifers are primarily recharged through fissures, cracks, rock porosity, and a thin soil coverage, with the MSLA being approximately 50–100 m thick, while perched aquifers range between 20–50 m in thickness (Bakalowicz & Mangion, 2003).

5 The Area of Influence

The study area considered for this report is the urban area of Sliema (Figure 11). Sliema, one of the largest towns in the north-eastern section of Malta, offers a diverse lifestyle and is a main tourist attraction in the summertime with its numerous rocky beaches. It is a peninsula characterized by a low rocky coast, surrounded by the Mediterranean. The geomorphology, geology and structure of the area reflects its dense population and urbanization it underwent during the past few years. The area's geomorphology, hydrology, lithostratigraphy and structure are reviewed in greater detail.

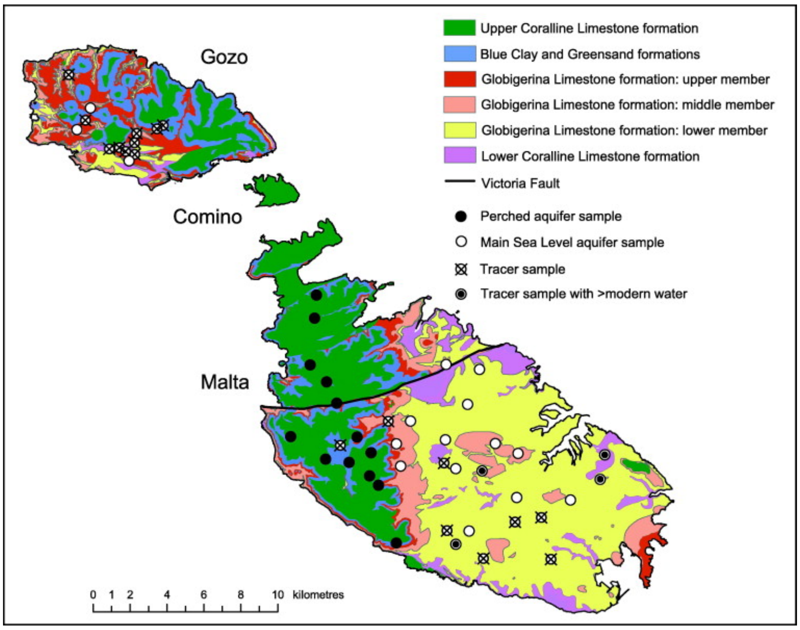

Figure 10: a) Map showing locations of the mean sea level aquifers and perched aquifers taken from (modified from Stuart et al. (2010)).

Figure 11: Aerial image of the area of Sliema taken from Google Earth.

5.1 Stratigraphy

Sliema is mainly composed of two rock members which can be found at the surface. The majority of surface is covered by the lower member of the Globigerina Limestone Formation. This Globigerina rock outcrop varies from an elevation of around 33 m all the way towards the coast at sea level. Globigerina limestone can be seen as pale-yellow rock and contains great amounts of planktonic foraminifera. The second rock member found in Sliema is the older Xlendi member which makes part of the LCL formation. The Xlendi member is a harder and more resistant rock in comparison to the overlying Globigerina Limestone member and has a greyish colour. This member is found mostly towards the upper part of Sliema (near St. Julians) and is the third oldest member of the formation from the total of four. This indicated a zone of unconformity as the uppermost, youngest member of the LCL formation which formed between the Xlendi member and the Lower globigerina member is not present. This is possibly due to erosion and weathering as result of the heavy wind and wave action present in the coast of Sliema.

Another geological feature present in the study area of Sliema are Quaternary Rocks (Figure 12). Quaternary rocks are discontinuous rocks containing high amounts of fossils such as land shells and extinct marine quaternary gasteropoda. This rock type can be found at Surfside, a known location along the Siema Coast.

5.2 Structures

The Sliema shore platform's distinctive structure is characterized by numerous fault and joint systems that vary in both size and orientation (see figure 13). Most of the faults are situated on the western side of the coast, with fewer on the eastern side, resulting in an uneven platform surface. The faults present in the rocks contribute to the alteration and erosion of the shoreline by weakening the bedrock and making certain parts of the shoreline more vulnerable to wave quarrying.

Joints have been identified throughout the study area and are depicted in figure 16. The mapped joints generally trend in an ENE-WSE and NW-SE direction, and it is suggested that their genesis and evolution are linked to the main fault systems, namely the Victoria and Magħlaq Faults. Some of the observed faults on the ground were also found to contain infill material, likely due to their large-scale size and width. This infill material typically consists of silt, sand, and gravel, although some were found to be filled with sea water, algae, and fauna.

5.3 Geomorphology

The geomorphology of Sliema includes landforms and coastal geomorphology features such as potholes, pools which exist within the rocky coast as well as depositional material. The geomorphology of area, being an urban and densely populated city, is highly affected by human activities, such as tourism, therefore displays a number of human impacts (Figure 13).

The area contains many geomorphological features, such as bays and valleys (Figures 13 and 17). Examples of such bays include Balluta Bay, St. Julian's Bay as well as St. George's. The valleys located in the Sliema area include Wied Mejxu and Wied il-Kbir.

Since the area is mainly characterized by the presence of Lower Globigerina Limestone, it is easily eroded by wave action due to its soft nature, resulting in the formation of a number of features. The wind forces which vary throughout the year give rise to the formation of potholes distributed along the coast, which are then normally filled with infill material which acts as an abrasive tool. This gives the potholes a characteristic circular shape with steep sides and are found in the same areas that are also occupied by pools. Pools are formed by solution and characterized by pitted beds and can extend for distances ranging 5 to 30 m in length. The depth of the pools increases moving towards the shoreline and can reach depths that range 20–25 cm deep.

The topographic profiles along three linear locations in Sliema were generated and analysed for a better understanding of the geomorphological components. Topographic profiles help visualise the topography as seen from a cross-sectional perspective and hence help describe and observe the geomorphology, elevations and inclinations present along the area (Figure 16). The three lines are labelled as AB, CD and EF, where AB is the longest. The lines CD and EF are slightly shorter of a different orientation. This is shown in figures 16 to 18.

AB profile: This is the longest topographic profile out of all three topographic profiles considered. The topographic profile was plotted along a line with an NNW-SSE orientation. A number of highs and lows are observed within the topography along line AB. This is an indication of ridges and valleys. The valleys have a V-shape suggesting that water is transported along these valleys and results in erosion of the rock.

The elevation decreases from a maximum elevation of 45 m at Point A, which is the maximum elevation, to 0 m at Point B, which is the point closer to the coast and 500 m away from Point A (Figure 16).

CD profile: This topographic profile depicts the area of St. Julians, with a SW to NE orientation. The flat surface is seen to reach a maximum of 45 m above the sea level and a rather steep inclination towards the coast with a dip, down to 15 m height before a slight increase to 20 m above sea level. This is followed by another decrease.

Figure 12: Quaternary deposit mapped in the study area.

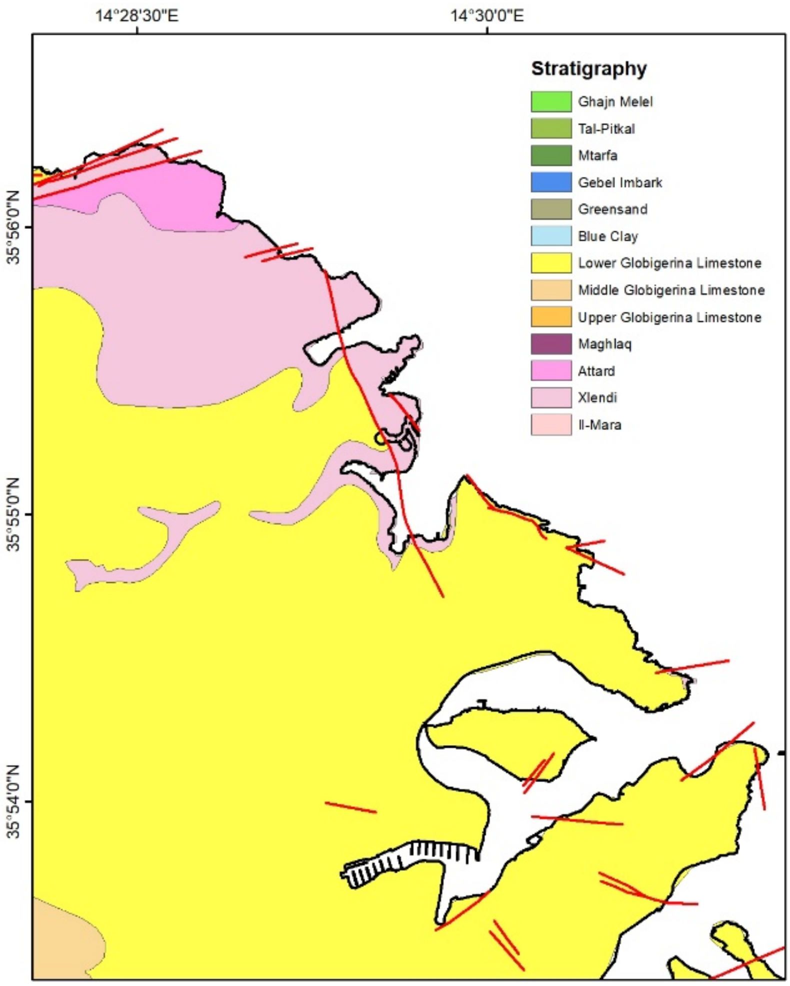

Figure 13: Geological map of the area of Sliema showing the lithostratigraphy and the main faults affecting the study area.

Figure 14: Aerial image of the area of Sliema taken from Google Earth showing several fractures affecting the study area.

The topographic map indicates a V shaped water course (Figure 17).

EF profile: The two points form a line 1,800 m long across the SW-NE direction. The initial elevation at point E is around 26 m, shown to initially increase to around 45 m. This is followed by a dip to 25 m and a sharp rise back to an elevation of around 45 m, displaying a V-shaped valley. At the distance of 1600 m, the topographic profile shows the presence of slope break forming an escarpment whose genesis is linked to the occurrence of a small normal fault (Figure 18). The final elevation at point F is of 0 m, as once again this point is located very close to the coast.

5.4 Hydrology

The hydrological characteristics of the Maltese Islands are influenced by various factors, including climate, geology, soils, and vegetation cover. The semi-arid climate of Malta, characterized by high-intensity rainfall over short periods of time, has resulted in minimal vegetation and soil in the area of Sliema. However, surrounding areas have xerorendsina soils that develop in semi-arid climates, with varying structures and textures. The absence of soil and vegetation in Sliema today does not necessarily indicate that the area was always barren. It is possible that farming or agriculture may have taken place in the past when the area had more favorable conditions.

Sliema is also characterized by watercourses that collect inland water and transport it as runoff to the coast and into the sea (Figure 19). Although Sliema currently does not have any rivers, the presence of watercourses suggests a different, more humid climate in the past that could have supported the formation of rivers about 10,000 years ago.

6 Conclusion

Small islands such as Maltese Islands are suited for geological investigations. This study has shown that the geology of the islands, including that in Sliema is quite young. This is evident through the simple lithostratigraphy and the effect of lateral movements. With close reference to the densely populated and urbanized study area of Sliema, the geology of the area consists mainly of the Lower Globigerina Limestone and ix-Xlendi member of the LCL. Sections of quaternary rock were also visible in the area close to Surfside, Sliema. Along the study area, multiple fractures in the rocks are likely linked to the main fault systems affecting the Maltese islands. Moreover, the rocks closer to the coast are seen to be heavily eroded and discoloured by the sea.

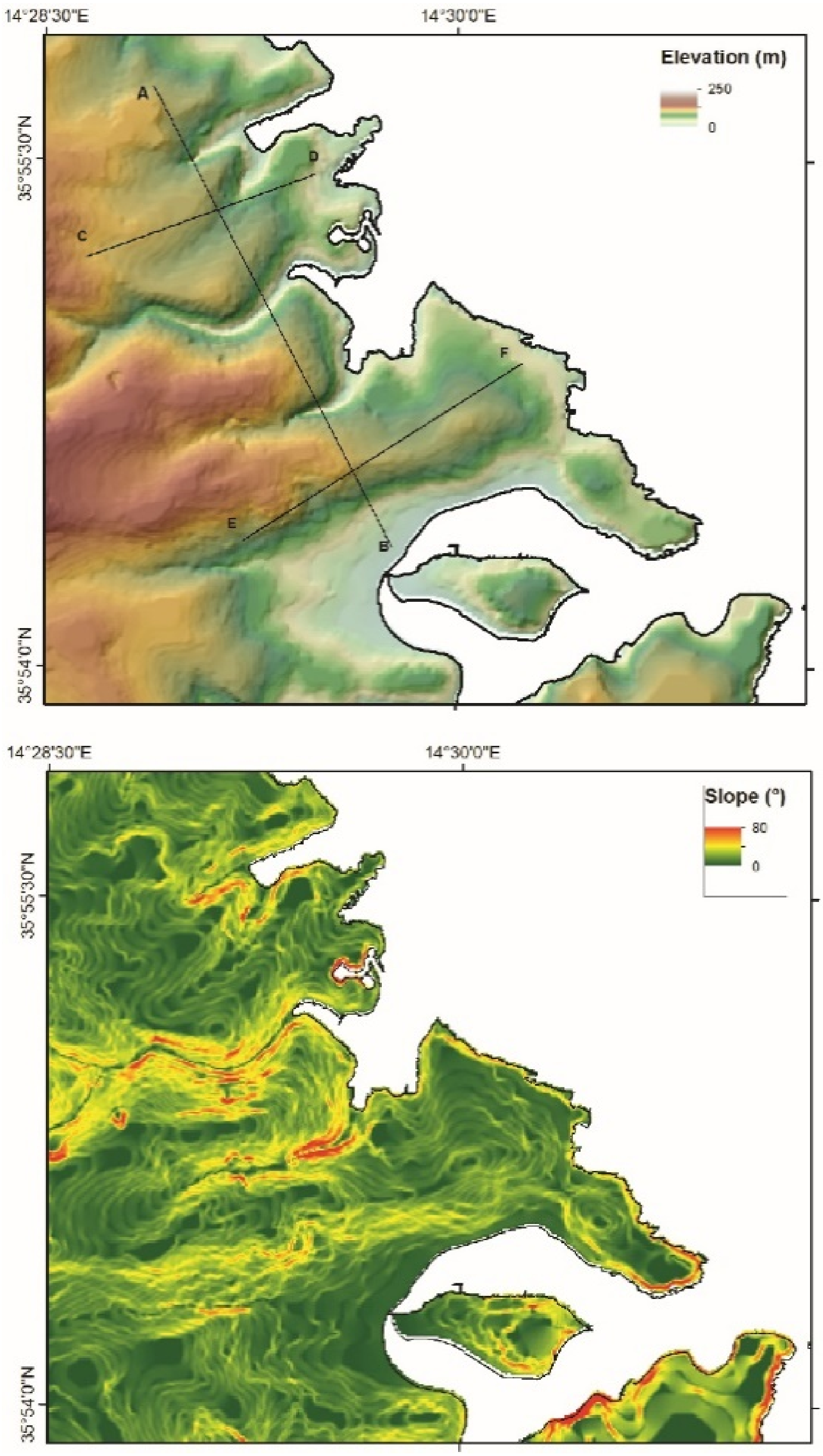

Figure 15: a) Topographic map showing the general elevation of the Maltese Islands. B) Slope Map of the area of interest.

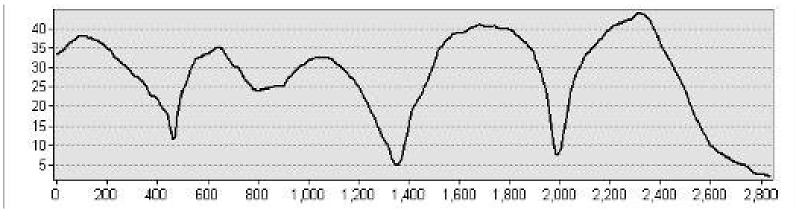

Figure 16: Topographic profile depiction from point A to B.

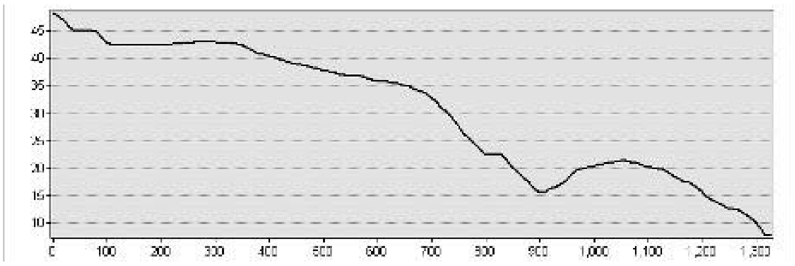

Figure 17: Topographic profile depiction from point C to D.

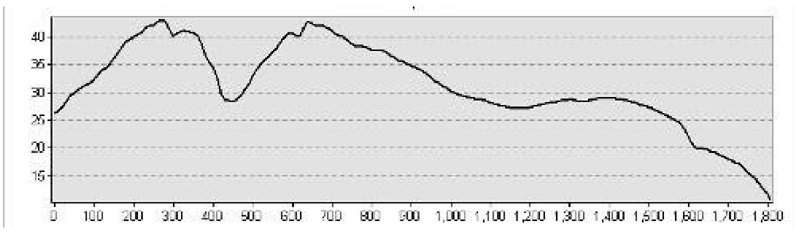

Figure 18: Topographic profile depiction from point E to F.

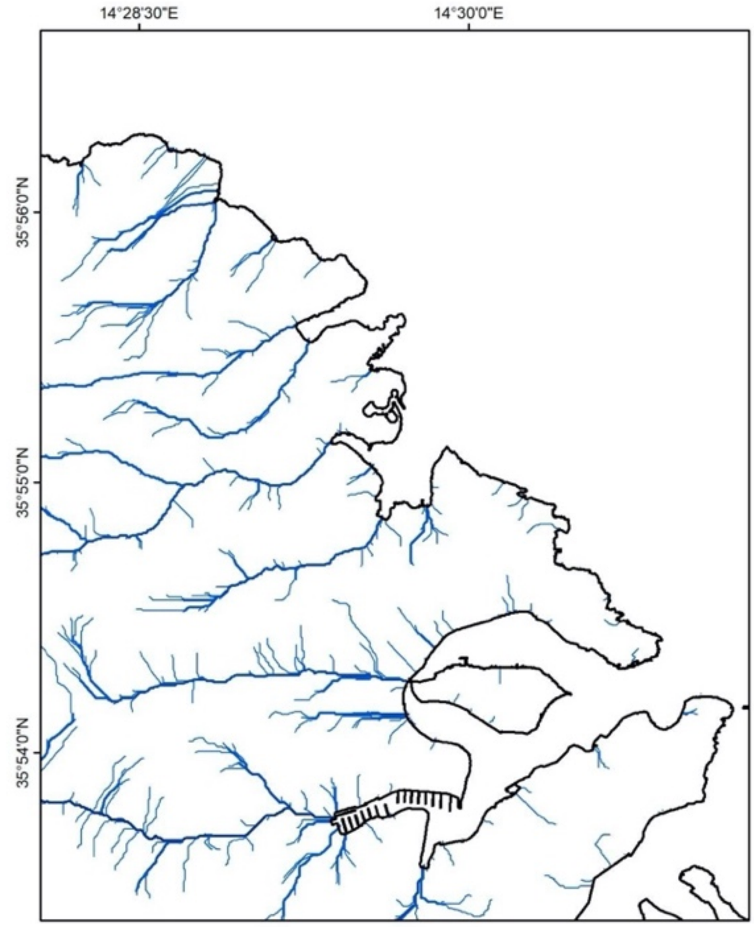

Figure 19: Reconstruction of the hydrology of the area using the digital elevation model coming from continental shelf website and using a specific tool with ARCGIS.

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