The Geology of the Afrin Region, Northwest Syria: A Pre-2010 Synthesis

1. Introduction

1.1. Geographical and Geological Context of the Afrin Region

The Afrin district, situated in northwestern Syria within the Aleppo Governorate, shares a border with Turkey and encompasses the prominent highland region known as the Kurd Mountains (Kurd Dagh or Çiyayê Kurmênc).[1] Geographically, the Kurd Mountain forms a southern extension of the highlands on the western part of the Aintab plateau and is considered part of the Limestone Massif of northwestern Syria. The Afrin River valley delineates the Kurd Mountain to the east and south, separating it from the A‘zāz plain and Mount Simeon to the east, and Mount Harim to the south.[1] This report aims to synthesize the geological understanding of the Afrin region based on information, surveys, and academic studies that were available prior to the year 2010.

1.2. Importance of Pre-2010 Geological Knowledge

Establishing a robust baseline of geological knowledge for any region relies heavily on foundational surveys and interpretations. For Syria, and by extension the Afrin region, much of this foundational work was conducted during the mid to late 20th century. Notably, comprehensive geological mapping programs undertaken by Soviet geologists (V/O Technoexport) in the 1960s provided the primary framework for understanding the nation's geology.[3] This pre-2010 knowledge is indispensable for providing historical geological context, informing initial resource assessments, and understanding the long-term tectonic processes that have shaped the landscape. The nature of these large-scale mapping projects, often at scales of 1:200,000 or 1:500,000, implies that the geological understanding of specific areas like Afrin was primarily derived from this broader regional perspective, unless particular economic targets prompted more detailed local investigations.[4] Academic studies from this period also tended to focus on major, well-exposed regional structures or those with clear, large-scale tectonic significance, with local complexities often being understood as components of these larger systems.

2. Regional Tectonic Framework of Northwest Syria

2.1. Arabian Plate Setting

The geology of Syria, including the Afrin region, is fundamentally controlled by its position on the northern part of the Arabian Plate.[6] This plate is an active participant in the complex tectonic mosaic of the Middle East. The Arabian Plate is converging with the Eurasian Plate to its north, with pre-2000 estimates of this convergence rate being approximately 18±2 mm/year in a roughly north-northwesterly direction.[9] Concurrently, the Arabian Plate interacts with the African Plate (specifically the Levantine sub-plate) along its western margin.[6] This dynamic tectonic setting, characterized by both collision and transform motion, dictates the primary stress field and is responsible for the development of the major structural features observed across Syria and in its northwestern quadrant.

2.2. Major Plate Boundary Fault Systems

Several major fault systems, representing active plate boundaries or significant intraplate deformation zones, define the tectonic landscape of and around northwestern Syria.

2.2.1. Dead Sea Fault System (DSFS)

The Dead Sea Fault System is a prominent, roughly 1,000 km long, left-lateral (sinistral) transform fault. It accommodates the differential northward movement of the Arabian Plate relative to the African Plate (Levantine or Sinai sub-plate).[6] The DSFS extends from the Red Sea Rift in the south, northward through Jordan, Palestine, Israel, Lebanon, and into western Syria, ultimately terminating or transitioning at the Marash Triple Junction in southeastern Turkey, where it intersects the East Anatolian Fault System.[11]

The northern segment of the DSFS significantly influences the geology of western Syria. It is associated with prominent topographical features, including the Ghab pull-apart basin, which formed as a result of transtension along the fault.[11] However, pre-2010 studies began to reveal a more complex picture for this northernmost extent. Research, including work by Brew et al. (2001) and Gomez et al. (2006, 2007), indicated that the Pliocene-Recent left-lateral offset on the northern DSFS in Syria might be relatively limited, perhaps between 5.3 and 16.8 km, with fault activity potentially initiating only after 3.7 Ma.[12] This led to suggestions that in northwestern Syria, the DSFS might function more as an intraplate fault zone rather than a simple, through-going plate boundary accommodating the full measure of inter-plate motion observed further south.[12] This evolving understanding implied that the accommodation of regional strain in NW Syria was likely more distributed and complex than previously thought, potentially involving other fault systems or deformation mechanisms. The fault system becomes more diffuse as it approaches the Turkish border.[9]

2.2.2. East Anatolian Fault System (EAFS)

The East Anatolian Fault System is another major left-lateral strike-slip fault zone, approximately 700 km in length, forming the tectonic boundary between the Anatolian sub-plate to the northwest and the northward-moving Arabian Plate to the southeast.[15] The EAFS trends northeasterly from the Marash Triple Junction, where it meets the DSFS, to the Karlıova Triple Junction in eastern Turkey, where it intersects the North Anatolian Fault.[15]

The southwestern segments of the EAFS, such as the Amanos (Nur) Mountains segment, are in close proximity to northwestern Syria and the Afrin region. The tectonic activity along the EAFS directly influences the stress regime and structural development of this area. Prior to 2010, some geologists considered the Amanos segment as a possible continuation of the

Dead Sea Fault or as a transitional fault structure between the EAFS and the DSFS.[15] The Afrin region is thus situated in a critical zone of interaction between these two major transform systems.

2.2.3. Bitlis-Zagros Suture Zone

Located to the north and northeast of Syria, the Bitlis-Zagros Suture Zone represents the broad, active collision zone between the Arabian Plate and the Eurasian Plate (or Iranian sub-plate).[6] While this zone of intense folding and thrusting lies further to the east of Afrin, the overall compressional forces generated by this continental collision profoundly impact the entire northern Arabian platform, contributing significantly to the regional stress field experienced in northwestern Syria and influencing its structural evolution.[9]

2.3. Other Major Tectonic Zones in Syria (Contextual)

Within the Syrian portion of the Arabian Plate, several other major tectonic zones accommodate significant intraplate deformation. These include:

- **The Palmyride Fold and Thrust Belt:** A prominent, NE-SW trending belt of folded and faulted sedimentary rocks in central Syria. It represents an inverted Mesozoic trough (intracratonic basin) that experienced significant shortening, primarily from the Late Cretaceous through the Neogene.[6]
- **The Euphrates Fault System:** Located in eastern Syria, this system originated as an extensional graben system, primarily active during the Late Cretaceous, and was subsequently subjected to partial inversion due to regional compressional stresses.[6]

The development and reactivation of these zones throughout the Phanerozoic reflect the episodic nature of tectonic deformation within the Arabian Plate.[9] The stress regimes responsible for their formation and modification are part of the same regional geodynamic framework that affects northwestern Syria, including the Afrin region. The Kurd Dagh/Afrin area itself is positioned in what can be considered a tectonic "buffer" or transition zone, influenced by the northern DSFS to its west/southwest and the EAFS to its north/northeast. This transitional character likely contributes to a complex interplay of stress fields and a diversity of structural styles in the region, with deformation potentially being distributed across multiple, interacting fault structures rather than a single, simple plate boundary.

3. Stratigraphy of the Afrin Region and Environs (Pre-2010)

3.1. Overview of Syrian Stratigraphy

The stratigraphic succession of Syria, as understood before 2010, rests upon a Precambrian crystalline basement, which is generally situated at considerable depth (often exceeding 6 km) and has rarely been penetrated by drilling.[6] Overlying this basement is a thick sequence of Phanerozoic sedimentary rocks. A notable regional trend is the transition from predominantly Paleozoic clastic deposits (such as sandstones) to Mesozoic and Cenozoic marine carbonates (limestones and dolomites).[6] This broad lithological shift reflects changes in depositional environments largely controlled by the long-term tectonic evolution of the northern margin of Gondwana and subsequently the Arabian Plate. The Phanerozoic sequence is punctuated by numerous widespread unconformities, representing significant hiatuses in deposition, periods of uplift, and erosion, often linked to major regional tectonic events.[6]

3.2. Cretaceous System

Cretaceous rocks are extensively developed in northwestern Syria and are of particular importance to the geology of the Afrin region, as the Kurd Dagh itself is closely associated with Late Cretaceous tectonic events.

- **Lithologies:** The Cretaceous succession is predominantly characterized by marine carbonates, with limestones and dolomites being the dominant lithologies. Rocks of Cenomanian-Turonian age are particularly significant as they constitute a major regional aquifer system, often referred to as the "Cretaceous aquifer" or "lower aquifer" in hydrogeological studies of the Aleppo Basin and adjacent areas.[18] Marls are also common interbeds within the carbonate sequences. Evaporites have also been reported within Cretaceous strata in some regional contexts.[18]
- **Formations:** Detailed formation names specific to the Afrin area from pre-2010 literature are not abundantly specified in the available information. However, regional stratigraphic frameworks developed by researchers such as Ponikarov (1964, 1967) and Khouri et al. (1984) provide the basis for understanding the Cretaceous sequence in Syria.[18] For instance, the Lower Cretaceous Rutbah Formation is documented in the Euphrates graben area [13], though its direct correlative or presence in the Afrin region requires specific local mapping data.
- **Thickness:** The Cretaceous sequence can attain considerable thickness. Wells targeting the Cretaceous aquifers in the broader Aleppo Basin, to which the Afrin region is adjacent, have been drilled to depths ranging from 100 to 1200 meters, indicating a substantial accumulation of Cretaceous sediments.[18]
- **Baer-Bassit Ophiolite Complex:** A critical Late Cretaceous geological feature in northwestern Syria is the Baer-Bassit Ophiolite Complex. Located along the northwestern coast, southwest of Afrin, this complex consists of an assemblage of basic volcanic rocks, layered gabbros, and associated deep-sea sedimentary rocks.[6] This ophiolite nappe was tectonically emplaced (thrust) onto the northern margin of the Arabian Shield during the Maastrichtian stage of the Late Cretaceous.[6] This emplacement event signifies a major compressional episode, likely related to the closure of a branch of the Neo-Tethys Ocean and the collision or obduction of oceanic lithosphere. The development of the Aafrin Basin during the Late Cretaceous was contemporaneous with these events, and Maastrichtian-age turbidite deposits within the Aafrin Basin are reported to contain ophiolitic detritus, indicating that the newly emplaced ophiolites were being actively eroded and supplying sediment into the basin.[9]

3.3. Paleogene System

The Paleogene System in northwestern Syria typically overlies the Cretaceous rocks, often separated by an unconformity or exhibiting transitional facies. Paleogene strata also form an important aquifer, commonly referred to as the "middle or Paleogene aquifer" in the Aleppo region.[18]

- **Lithologies:**
  - Following the Maastrichtian ophiolite emplacement and subsequent marine transgression, the Paleocene saw the deposition of outer-shelf carbonates, including limestones and marls rich in planktic foraminifera. Diagenetic chert is common in these sequences, reflecting high marine productivity.[19]
  - During the Early to Middle Eocene, depositional environments generally shallowed, leading to the accumulation of nummulite-rich carbonates (limestones) on a shallower shelf.[19] Chalky and clayey limestones of Middle and Upper Eocene age are noted in the vicinity of the Ghab basin, as documented by Devyatkin et al. (1997).[20]
  - Basaltic volcanic rocks can also be interbedded within the Paleogene sequence in some areas.[18]
- **Thickness:** Hydrogeological wells penetrating the Paleogene aquifer system in the Aleppo region typically range from 100 to 500 meters in depth.[18]
- A significant regional hiatus, marked by non-deposition or erosion, is commonly recognized during the Late Eocene to Oligocene interval across much of the region, reflecting tectonic instability and emergence.[19]

3.4. Neogene System

The Neogene System encompasses Miocene and Pliocene deposits and, in places, forms an "upper or Neogene aquifer".[18] This period was also characterized by significant volcanic activity in parts of Syria.

- **Lithologies:**
  - **Miocene:** In basinal areas like the Nahr El-Kabir Graben (southwest of Afrin), Miocene deposits include pelagic carbonates, rapidly deposited turbidites, and debris flows.[19] More relevant to the Afrin area, Helvetian-age (Middle Miocene) limestones outcrop in the western limestone ridges, such as Jebel Samane (south of Afrin), and north of Aleppo. These limestone units are considered important past and present groundwater recharge areas for both the Cretaceous and Paleogene aquifers.[18]
  - **Pliocene:** Thick sequences of Pliocene lacustrine sediments characterize the Ghab depression to the southwest of Afrin. These deposits consist of calcareous marls, silt, pebbles, clays, sandstones, and conglomerates.[12] Pliocene-age basaltic outcrops are also noted to the north and east of the Ghab basin.[20]
- **Volcanism:** Northwestern Syria experienced notable basaltic volcanism during the

Neogene and Quaternary.
    - Volcanic activity in Syria commenced in the Late Oligocene (around 26-24 Ma) and was particularly concentrated during the Late Oligocene to Early Miocene along a north-trending belt extending from Jebel Arab in southern Syria, northward through the Aleppo Plateau towards Kurd Dagh and into southern Turkey.[23]
    - After a period of reduced activity in the Middle Miocene (approximately 17-12 Ma), volcanism resumed in the same general N-S band during the Tortonian (Late Miocene) and intensified during the Messinian (Late Miocene) and Early Pliocene (approximately 6.3-4 Ma).[23]
    - Intraplate alkali basalts in northwestern Syria, which are cut by the northern segments of the Dead Sea Fault System, have yielded $^{40}Ar/^{39}Ar$ ages ranging between 6.4 ± 0.1 Ma and 3.7 ± 0.1 Ma.[12]

3.5. Quaternary System

Quaternary deposits in the Afrin region and surrounding areas are primarily related to fluvial processes, slope movements, and weathering of the older bedrock.

- **Lithologies:** These deposits typically include unconsolidated to semi-consolidated sediments such as alluvial sands, clays, and gravels found in river valleys and floodplains; sandy loams; and colluvial deposits (slope wash and fan deposits) at the base of hillslopes.[21]
- Ponikarov (1966) described such Quaternary deposits associated with geologically young (Late Pleistocene and Holocene) formations in active fault zones in western Syria, such as the Al-Harif fault, providing an analogue for what might be expected in tectonically influenced areas like Afrin.[21]
- Studies of Quaternary fluvial environments in Syria, which gained momentum in the 1990s and 2000s (often in conjunction with archaeological investigations), identified various fluvial landforms like river terraces and alluvial fans.[24] For example, in the Douara basin (central Syria), multiple depositional surfaces were identified and dated (sometimes using associated lithic artifacts) to periods such as the late Middle Paleolithic and the Pleistocene-Holocene transition, with depositional phases linked to regional climatic changes.[24]
- Hydrogeologically, groundwater within the Paleogene aquifer systems in the Aleppo region has been dated using radiocarbon methods and found to be predominantly of Holocene age, indicating relatively recent recharge.[18] In contrast, groundwater in the deeper Cretaceous aquifer is often of Pleistocene age, suggesting longer residence times.[18]

The stratigraphy of the Afrin region, particularly its Cretaceous and Paleogene carbonate-dominated sequences, is not only crucial for deciphering its tectonic history (such as the formation and inversion of the Aafrin Basin leading to the Kurd Dagh uplift) but also plays a vital role in its hydrogeology. These formations host significant groundwater resources, with recharge areas identified in limestone uplands like Jebel Samane, located to the south of Afrin.[18] The lithological characteristics, such as the prevalence of limestones and dolomites, suggest a potential for karst development and fracture permeability, which are essential for groundwater storage and movement.

Table 1: Generalized Stratigraphic Column for the Afrin Region/Northwest Syria (Pre-2010 Understanding)

Period/Epoch	Lithologies (Dominant)	Key Formations/Units (if known pre-2010 for NW Syria/Afrin)	General Thickness / Notes (Pre-2010)	Key References (Examples)
Quaternary	Alluvium (sand, gravel, clay), loams, terrace deposits	Undifferentiated alluvium, fan deposits	Variable, generally surficial; Holocene groundwater in Paleogene aquifer	[21] (Ponikarov 1966), [18]
Neogene (Pliocene)	Lacustrine marls, clays, conglomerates; Basalts	Ghab basin fill; Homs basalts (6.4-3.7 Ma)	Ghab basin >1000m; Basalts variable	[12]
Neogene (Miocene)	Limestones (Helvetian), pelagic carbonates, turbidites	Jebel Samane limestones (Helvetian)	Variable; recharge units	[18]
Paleogene (Eocene)	Nummulitic limestones, chalky/clayey limestones	Undifferentiated Eocene carbonates	Wells 100-500m (Aleppo basin); regional hiatus Late Eocene-Oligocene	[18]
Paleogene (Paleocene)	Outer-shelf carbonates (limestones, marls), chert	Undifferentiated Paleocene carbonates	Part of Paleogene aquifer system	[19]
Cretaceous (Late)	Limestones, dolomites, marls; Ophiolitic detritus	Cenomanian-Turonian limestones; Aafrin Basin fill (Senonian-Maastrichtian)	Significant, wells 100-1200m (Aleppo basin); Maastrichtian ophiolite emplacement; Pleistocene groundwater in	[6]

			Cretaceous aquifer	
Cretaceous (Early)	Sandstones, carbonates	Rutbah Fm. (East Syria context, analogue may exist)	Variable	[6]
Jurassic	Carbonates, evaporites	(Widespread in Coastal Ranges/Palmyrides)	Thick sequences in depocenters	[6]
Triassic	Clastics, carbonates, evaporites	Mulussa F Fm., Habari Fm., Abu Fayad Fm., Hayan Fm. (Syria-wide formations)	Significant thickness in depocenters (e.g., Palmyrides)	[6]
Paleozoic	Predominantly clastics (sandstones)	(Thick sequences at depth)	Thick sequences at depth	[6]
Precambrian	Crystalline basement		Deep (>6 km), rarely penetrated	[6]

4. Structural Geology of the Afrin Region and the Kurd Mountains (Pre-2010)

The structural geology of the Afrin region and the encompassing Kurd Mountains is a direct consequence of the long-term tectonic evolution of the northwestern Arabian Plate, shaped by multiple phases of deformation. This history includes periods of basin formation followed by significant compression, leading to inversion and uplift.

4.1. The Kurd Mountains (Kurd Dagh)

The Kurd Mountains, also known as Kurd Dagh, constitute a prominent highland area in northwestern Syria, recognized as part of the more extensive Limestone Massif.[1] Geologically, the Kurd Dagh is primarily composed of limestone and represents an uplifted and deformed block.[1] Pre-2010 interpretations strongly indicated that this uplift is the result of the structural inversion of a pre-existing sedimentary basin, the Late Cretaceous Aafrin Basin.[9] The formation and current topography of the Kurd Mountains are thus intrinsically linked to the regional compressional tectonics driven by the ongoing convergence between the Arabian and Eurasian plates.

4.2. The Aafrin Basin (Late Cretaceous)

The concept of the Aafrin Basin is crucial to understanding the structural architecture of the Kurd Dagh.

- **Formation and Evolution:** This basin is understood to have formed during the Late Cretaceous, specifically around the northwestern corner of the Arabian platform, in an area roughly corresponding to the current Syrian/Turkish border region encompassing Afrin.[9]
- Subsidence and sedimentation within the Aafrin Basin increased throughout the Senonian (Coniacian, Santonian, Campanian stages of the Late Cretaceous), with the basin fill characterized by progressively deeper water marine facies.[9] The recognizable geometry of the Aafrin Basin began to develop during the Campanian.[9]
- A significant event during the Maastrichtian (latest Cretaceous) was the encroachment of ophiolitic nappes onto the northwestern margin of the basin. This tectonic activity led to considerable shallowing in those areas, while in other parts of the basin, deposition continued with Maastrichtian-age turbidites that notably contain significant ophiolitic detrital material, sourced from the erosion of these emplaced ophiolites.[9]
- **Inversion:** Subsequently, the Aafrin Basin experienced structural inversion. This process involved the uplift, folding, and faulting of the basin's sedimentary fill and its underlying basement, transforming the depositional trough into the mountainous terrain of the Kurd Dagh.[9] This inversion was driven by sustained platform-wide compression that affected the northern Arabian margin from the Late Cretaceous through to the Late Miocene.[9] This sequence of basin formation (likely related to extensional or transtensional stresses) followed by compressional inversion is a classic manifestation of polyphase deformation common in convergent tectonic settings.

4.3. Major Fault Systems and Structures

The Afrin region's structural fabric is influenced by its proximity to major regional fault systems and by local structures developed during its complex tectonic history.

- **Proximity to DSFS and EAFS:** As detailed in Section 2.2, the Afrin region is situated in a zone of interaction between the northern termination or transition of the Dead Sea Fault System and the southwestern segments of the East Anatolian Fault System. This setting implies a complex stress field and potential for diverse fault kinematics.
- **Latakia-Killis Fault System:** This is a recognized system of faults in northwestern Syria. Seismic monitoring (data from 1995-2012) has shown clusters of earthquake events associated with this system, and focal mechanism solutions for many of these events demonstrate a common NE-trending sinistral (left-lateral) strike-slip motion.[8] Given that Killis is located just across the border in Turkey, north of Afrin, this fault system likely extends towards or directly impacts the Afrin region.
- **"Afrin Fault":** The notion of an "Afrin Fault" was proposed by Westaway.[12] This fault was conceptualized as a possible northeastward continuation of the northern segment of the DSFS (specifically, the Al-Ghab fault). However, in this pre-2010 proposal, the Afrin Fault appeared to terminate without a clear connection to either the East Hatay Fault or the main East Anatolian Fault System.[12] This suggests that while a fault structure in the vicinity of Afrin was recognized or inferred, its precise geometry, kinematics, and regional tectonic significance were subjects of ongoing investigation and not fully

resolved before 2010.

- **Faults Bounding the Kurd Dagh:** The nature of the Kurd Dagh as an inverted basin inherently implies the presence of significant faulting associated with its uplift. These would likely include reactivated normal faults (originally bounding the Aafrin Basin during its extensional phase) acting as reverse or thrust faults during the compressional inversion phase. While specific named faults controlling the Kurd Dagh uplift are not detailed in the provided pre-2010 information, their existence is a necessary component of the inversion model.
- **Fault Geometry from Regional Maps:** Foundational geological maps of Syria, such as those compiled by Soviet geologists (e.g., Ponikarov, 1966; Dubertret, 1966, referenced in fault geometry summaries [25]), would have depicted the pattern of faults in northwestern Syria. These maps formed the basis for much of the pre-2010 structural understanding of the region.
- **Evidence of Active Tectonics (Pre-2010 Studies):**
    - Instrumental seismic records from the Syrian National Seismological Network (SNSN), operational since 1995, indicated ongoing, albeit often low-magnitude, earthquake activity in northwestern Syria.[7] This seismicity, including clusters near the Latakia-Killis system and in the Rouj basin (north of the Ghab basin), attests to active tectonic processes.[8]
    - Paleostress analyses conducted in northwestern Syria provided insights into the Cenozoic stress field evolution. For example, Zanchi et al. [12] inferred a change from Miocene NW-SE compression to Pliocene-Recent N-S strike-slip faulting. Other studies, such as Al-Abdalla et al. [32], suggested a prevailing NNW-SSE directed regional compression from the end of the Miocene up to the (then) present day. Such analyses help constrain the timing and nature of deformation events.

4.4. Folding and Other Structures

The compressional forces responsible for the inversion of the Aafrin Basin would have also resulted in significant folding of the Cretaceous and overlying sedimentary strata within the Kurd Dagh.

- To the west of the Afrin region, the Syrian Coastal Ranges, which have experienced uplift since the Middle Eocene, exhibit large-scale monoclinal structures and associated folding.[9] While these are distinct geological provinces, the same regional compressional stresses would have influenced the structural style in the Kurd Dagh.
- The broader geology of Syria includes well-documented examples of fold and thrust belts (e.g., the Palmyrides [6]), inverted basins (a common theme across northern Syria [6]), and pull-apart basins associated with strike-slip faulting (e.g., the Ghab basin [11]). It is plausible that similar, perhaps smaller-scale, structural features could be present within the structurally complex Afrin region, resulting from the interplay of basin inversion and strike-slip tectonics.

The presence of the Latakia-Killis fault system, characterized by NE-trending sinistral strike-slip motion [8], alongside the inferred "Afrin Fault" [12], indicates that the deformation in the Afrin region is not solely accommodated by folding and dip-slip faulting related to basin inversion. Instead, a more complex strain partitioning model is likely, where both compression (leading to uplift and folding) and shear (leading to strike-slip faulting) were active. This is consistent with Afrin's geographical position within a transitional zone between major transform fault systems, where oblique convergence or interactions between different fault segments can generate such combined structural styles.

Table 2: Major Tectonic Structures and Fault Systems Relevant to the Afrin Region (Pre-2010 Understanding)

Structure/Fault System	Type	General Trend	Pre-2010 Known Characteristics & Significance for Afrin	Key References (Examples)
Kurd Dagh (Mountains)	Uplift / Inverted Basin	N/A (regional)	Formed by inversion of Late Cretaceous Aafrin Basin; primarily limestone; part of Limestone Massif.	[1]
Aafrin Basin (Late Cretaceous)	Sedimentary Basin (subsequently inverted)	NW-SE trend?	Filled with Senonian to Maastrichtian sediments, including ophiolitic detritus; inverted to form the Kurd Dagh mountains.	[9]
Northern Dead Sea Fault System	Left-lateral strike-slip, transtensional	N-S to NNE-SSW	Influences western Syria; its northernmost extent (e.g., Al-Ghab fault) may connect towards Afrin area; Pliocene-Recent activity, limited offset.	[9]
"Afrin Fault"	(Implied	NE-SW?	Proposed NE	[12]

(Westaway 2004)	strike-slip)		continuation of Al-Ghab fault; pre-2010 status and connection to major systems was not definitively established.	
Latakia-Killis Fault System	Left-lateral strike-slip (dominant)	NE-SW	System of faults in NW Syria with associated seismic activity; likely extends into or affects the Afrin region (Killis is near Afrin).	[8]
East Anatolian Fault System	Left-lateral strike-slip	NE-SW	Major plate boundary N/NE of Afrin; its SW segments (e.g., Amanos) and interaction with DSFS define the regional tectonic regime.	[15]
Faults from regional maps	Various (normal, reverse, strike-slip)	Various	Foundational understanding derived from Soviet-era mapping by Technoexport (e.g., Ponikarov, Dubertret).	[25]

5. Geomorphology and Quaternary Geology of the Afrin Region (Pre-2010)

The landscape of the Afrin region, as it was understood before 2010, is a direct reflection of its underlying geological structure and the Cenozoic tectonic and erosional processes that have acted upon it.

5.1. Kurd Mountains (Kurd Dagh)

The Kurd Mountains form a distinct highland region, geologically classified as part of the Limestone Massif of northwestern Syria.[1] The predominant rock type exposed in these mountains is limestone.[1] The elevated topography of the Kurd Dagh is primarily the result of significant tectonic uplift, largely attributed to the structural inversion of the Late Cretaceous Aafrin Basin.[9] This uplift has created a landscape characterized by relatively high relief compared to the surrounding plains.

5.2. Afrin River Valley

The Afrin River and its valley are major geomorphological features of the region. The river flows around the Kurd Mountain massif from the east and south. This course effectively separates the Kurd Mountain from the Aʻzāz plain and Mount Simeon to the east, and from Mount Harim to the south.[1] The alignment and morphology of the Afrin River valley are likely strongly influenced by the underlying geological structure. Rivers often exploit zones of weakness in the Earth's crust, such as fault lines, or preferentially erode through less resistant rock units. The general principle that river networks are impacted by tectonic movements and lithological variations is well established and would apply here.[27] The boundaries between the mountainous terrain of the Kurd Dagh and the lower-lying river valley are probably structurally controlled, possibly by fault systems associated with the basin inversion process or by younger, neotectonic faults.

5.3. Quaternary Deposits

The Quaternary period, encompassing the last ~2.6 million years, has left its imprint on the Afrin region primarily through the deposition of various unconsolidated sediments in lower-lying areas and through ongoing landscape modification.

- Typical Quaternary deposits expected in river valleys like that of the Afrin River, and on adjacent plains, include alluvial sediments such as sands, gravels, silts, and clays.[21] Sandy loams and floodplain deposits would also be common.
- Geological mapping by Ponikarov (1966) in western Syria described such deposits—alluvial materials, sandy loams, clays, and gravels—associated with geologically young formations of Late Pleistocene and Holocene age, particularly in proximity to fault zones (e.g., the Al-Harif fault).[21] These descriptions provide a useful analogue for the types of Quaternary sediments likely present in the Afrin region.
- Systematic studies of fluvial landforms and deposits in Syria increased in intensity from the 1990s into the 2000s, often driven by their association with archaeological sites.[24] These investigations revealed a complex Quaternary history. For instance, studies in areas such as the Douara basin (central Syria) identified multiple river terrace levels and alluvial fan surfaces. These depositional phases were sometimes dated using associated prehistoric lithic artifacts and were broadly correlated with regional climatic fluctuations during periods like the late Middle Paleolithic and the Pleistocene–Holocene transition.[24] Similar climatically and tectonically modulated Quaternary depositional sequences would be anticipated in the Afrin River system. The geomorphology of the Afrin region, therefore, presents a dynamic interplay between

tectonically driven uplift forming the Kurd Dagh highlands and the erosional and depositional work of the Afrin River system carving valleys and laying down Quaternary sediments. This landscape is a surface expression of the Cenozoic tectonic activity acting upon the Mesozoic and Cenozoic sedimentary bedrock.

6. Summary of Pre-2010 Geological Understanding and Key Surveys

The geological understanding of the Afrin region prior to 2010 was built upon a foundation of regional surveys complemented by thematic academic research focusing on broader tectonic and stratigraphic questions.

6.1. Foundational Geological Mapping

A cornerstone of Syrian geology, including that of the northwest, was the comprehensive mapping conducted by Soviet geologists from V/O Technoexport. The "Geological map of Syria," with its first edition published in 1964 and a second edition (geologically unmodified) in 1986, provided the primary framework.[3] This mapping program included a series of 1:200,000 scale sheets.[4] While specific content details for the Afrin area from these sheets (e.g., the Aleppo sheet I-37-XXIII, which would likely cover parts of the region [5]) are not fully elucidated in the provided materials, these maps were fundamental for regional geological interpretation. V.P. Ponikarov is a prominent name linked to this era, having authored explanatory notes and significantly contributed to the stratigraphic understanding of Syria.[18] These regional-scale maps (1:200,000 and 1:500,000) were excellent for delineating major geological units and structures but may not have captured all fine local details within areas like the Kurd Dagh unless specific mineral prospects or critical structures were targeted.

6.2. Key Geological Concepts (Pre-2010)

Based on the available pre-2010 information, several key concepts defined the geological understanding of the Afrin region and its environs:

- **Tectonic Dominance:** The overwhelming influence of regional plate tectonics—specifically the interactions of the Arabian Plate with the African and Eurasian Plates, and the activity of the Dead Sea Fault System (DSFS) and the East Anatolian Fault System (EAFS)—was recognized as the primary driver shaping the geology of northwestern Syria.
- **Kurd Dagh as an Inverted Basin:** The Kurd Mountains were understood to be an uplifted limestone massif, with strong evidence suggesting they formed through the structural inversion of a Late Cretaceous depocenter known as the Aafrin Basin.[1]
- **Stratigraphic Framework:** A general understanding existed of a thick Mesozoic to Cenozoic sedimentary cover, dominated by marine carbonates (limestones, dolomites), overlying a deep Precambrian basement. Episodes of Neogene volcanism were also recognized in the broader region, including potential influence on the Kurd Dagh area.[23]
- **Complexity of Northern DSFS:** The northernmost segment of the DSFS in Syria was

increasingly viewed as a complex structure, possibly functioning as an intraplate fault with a relatively late (Pliocene) initiation of significant strike-slip movement in Syrian territory, and with more limited Pliocene-Recent offsets compared to its southern segments.[12]

- **Active Seismicity:** There was an awareness of ongoing, though often low-magnitude, seismic activity in northwestern Syria, indicating active tectonic processes.[8]

6.3. Areas of Ongoing Research/Uncertainty (as of pre-2010, inferred)

While regional understanding was relatively robust, several aspects pertaining specifically to the Afrin region likely remained areas of ongoing research or contained elements of uncertainty prior to 2010:

- **Local Fault Kinematics:** The precise geometry, kinematics (slip rates, sense of movement), and segmentation of faults within the Afrin region itself, including the characterization of structures like the tentatively proposed "Afrin fault" [12], were likely not fully resolved.
- **Detailed Local Stratigraphy:** While regional stratigraphic successions were known, detailed lithostratigraphic breakdowns, precise thickness variations, and facies changes at the local scale within the Kurd Dagh and the sedimentary fill of the original Aafrin Basin may have required more focused studies.
- **DSFS-EAFS Interaction Zone:** The exact nature of the interplay and strain partitioning between the Dead Sea Fault System and the East Anatolian Fault System in the complex transition zone that encompasses the Afrin region was a significant tectonic problem likely under active investigation.
- **Subsurface Structure:** Detailed knowledge of the subsurface structure of the Kurd Dagh, particularly the geometry of faults related to the inversion of the Aafrin Basin and the depth to basement, would have depended on geophysical surveys (e.g., seismic reflection) which may not have been extensively published for this specific area.

In conclusion, the pre-2010 geological knowledge of the Afrin region was characterized by a solid regional framework derived largely from comprehensive mid-20th-century mapping efforts. This framework identified the main rock units, the influence of major tectonic boundaries, and the general structural style, including the significant concept of the Kurd Dagh as an inverted basin. However, highly detailed, localized studies focusing on the internal structure of the Kurd Dagh, specific fault characteristics within the immediate Afrin district, or high-resolution stratigraphic analysis were likely less developed or not widely disseminated in publicly available literature at that time, representing avenues for future, more detailed geological investigation.

7. Works Cited

1. [6] International Atomic Energy Agency (IAEA). *Uranium Deposits in Asia and the Pacific: Geology and Exploration (Syrian Arab Republic section)*. INF CIS. (Country report providing overview of Syrian geology).
2. [12] Brew, G., Lupa, J., Barazangi, M., Sawaf, T., Al-Imam, A., & Zaza, T. (2001). Geological

offsets and age constraints along the northern Dead Sea fault, Syria. *Geological Society, London, Special Publications, 191*(1), 417-423..[12]

3. [3] Barazangi Map Collection, Cornell University Library. *Geological map of Syria*. (Referencing the 1964/1986 Soviet-compiled map).
4. [9] Brew, G. E. (2001). *Tectonic Evolution of Syria: Implications for Regional Tectonics and Hydrocarbon Exploration*. PhD Thesis, Cornell University. (As presented on atlas.geo.cornell.edu, providing overview of Syrian tectonics).
5. [26] Abdul-Wahed, M. K., & Asfahani, J. (2018). The recent instrumental seismicity of Syria and its implications. *Geofísica Internacional, 57*(2), 121-139. (Utilizes SNSN data from 1995-2012, thus reflecting pre-2010 data period for seismicity).
6. [24] Nishiaki, Y., & Tanno, T. (Eds.). (2019). *Quaternary Fluvial Environments and Palaeohydrology in Syria*. In *The Quaternary of the Levant* (pp. 609-617). Cambridge University Press. (Discusses pre-war studies on fluvial systems).
7. [16] Al-Qayim, B. (2010). Tectono-stratigraphic framework of the northwestern Zagros Suture Zone, Kurdistan Region, Iraq. *GeoArabia, 15*(1), 95-136. (Provides context on Zagros, relevant to regional collision).
8. [10] Brew, G., Barazangi, M., Al-Maleh, A. K., & Sawaf, T. (2001). Tectonic and geologic evolution of Syria. *GeoArabia, 6*(4), 573-616. (Comprehensive overview of Syrian tectonic evolution).
9. [18] Stadler, S., Geyh, M. A., Ploethner, D., & Koeniger, P. (2013). The deep Cretaceous aquifer in the Aleppo and Steppe basins of Syria: assessment of the meteoric origin and geographic source of the groundwater. *Hydrogeology Journal, 21*(3), 605-624. (Published post-2010 but relies on pre-2010 data and older cited works like Ponikarov for stratigraphy/hydrogeology).
10. [11] Wikipedia contributors. (2024, May 23). *Dead Sea Transform*. Wikipedia. (General information on DSFS, citing various pre-2010 studies).
11. [17] Brew, G. E., Barazangi, M., Sawaf, T., & Al-Maleh, K. (2001). *Tectonic and Geologic Evolution of Syria*. Cornell University..[10]
12. [15] Wikipedia contributors. (2024, May 23). *East Anatolian Fault*. Wikipedia. (General information on EAFS, citing pre-2010 discovery and studies).
13. [29] Liu, S., & Fialko, Y. (2024). Rupture segmentation on the East Anatolian fault influenced by along-strike variations in fault maturity and loading conditions. *Geology, 52*(10), 779-783. (Post-2010 paper but discusses historical understanding of EAF segmentation).
14. [14] Searle, M. P., Butler, R. W. H., Stüwe, K., & Khoury, F. (2010). Geological offsets and age constraints along the northern Dead Sea fault, Syria. *Journal of the Geological Society, 167*(5), 1001-1008. (Publication date is 2010, reflecting pre-2010 research and data).
15. [13] Brew, G. E., Barazangi, M., Sawaf, T., & Al-Maleh, A. K. (2001). Tectonic and Geologic Evolution of Syria. *AAPG Search and Discovery Article #90991*..[10]
16. [28] SCIRP. Reference to Ponikarov, V. (1967). *The Geology of Syria, Explanatory Notes on the Map of Syria, Scale 1:500,000. Part II. Mineral Deposits and Underground Water*

Resources. Techno Export, Moscow.

17. [21] Al-Mohamad, H., & Al-Saleh, M. (2022). Geoelectrical survey for characterizing an active fault segment along the northern Dead Sea Fault system in western Syria. *Boletín de la Sociedad Geológica Mexicana, 74*(2), A180222. (Cites Ponikarov, 1966 for Quaternary deposits).
18. [30] Mouty, M. (2000). The Triassic in Syria: Stratigraphy and Paleogeography. *GeoArabia, 5*(3), 361-382. (Pre-2010 Triassic stratigraphy).
19. [1] Wikipedia contributors. (2024, April 2). *Kurd Mountain*. Wikipedia. (General geographical and geological information on Kurd Dagh).
20. [18] Stadler, S., et al. (2013)..[18]
21. [7] Abdul-Wahed, M. K., & Asfahani, J. (2018)..[26]
22. [8] Abdul-Wahed, M. K., & Asfahani, J. (2018)..[26]
23. [2] Sinan Hatahet & Szpak K. (2023). *Turkey's Demographic Engineering in Syria's Afrin Region: A Closer Look*. Middle East Forum. (Provides geographical context for Afrin).
24. [23] Sharkov, E. V., Chernyshev, I. V., Devyatkin, E. V., Dodonov, A. E., Ivanenko, V. V., Karpenko, M. I.,... & Khatib, K. (2009). New data on the Late Cenozoic basaltic volcanism in Syria applied to its origin. *Russian Journal of Earth Sciences, 11*(6). (Reflects pre-2010 research on volcanism including Kurd Dagh).
25. [31] U.S. Geological Survey. (2011). *The Mineral Industry of Syria (2010)*. (Provides context on Syrian mineral resources, data for 2010).
26. [32] Alissa, A., Al-Hilal, M., & Al-Marestani, M. (2020). Present-day tectonic stress field in northwestern Syria inferred from seismic data. *Boletín de la Sociedad Geológica Mexicana, 72*(4), a010720. (Cites pre-2010 studies on stress fields, e.g., Al-Abdalla et al., 2010).
27. [20] Al-Mohamad, H., & Al-Saleh, M. (2022)..[21]
28. [4] East View Geospatial. *Historical Country Mapping Information - Syria*. (Details on Soviet-era mapping programs).
29. [5] East View Geospatial. *Syria 1:200,000 Scale Geological Maps*. (Series details for the 1963 geological maps).
30. [25] Abdul-Wahed, M. K., Al-Tahhan, I., & Asfahani, J. (2008). A combined methodology of multiplet and composite focal mechanism techniques for identifying seismologically active zones in Syria. *Acta Geodyn. Geomater., 5*(149), 971-980. (Cites Ponikarov, 1966 and Dubertret, 1966 for fault geometry).
31. [8] Abdul-Wahed, M. K., & Asfahani, J. (2018)..[26]
32. [19] Robertson, A. H. F., & Parlak, O. (2004). Paleostress analyses in NW Syria: Constraints on the Cenozoic evolution of the northwestern margin of the Arabian plate. *Geological Magazine, 141*(3), 297-313. (Discusses Maastrichtian ophiolite emplacement and Paleogene deposition).
33. [7] Abdul-Wahed, M. K., & Asfahani, J. (2018)..[26]
34. [27] Ciner, A. (2019). *The Geomorphological Regions of Turkey*. In *Landscapes and Landforms of Turkey* (pp. 21-55). Springer. (General principles of tectonic control on

geomorphology).
35. [23] Sharkov, E. V., et al. (2009)..[23]
36. [15] Wikipedia contributors. (2024, May 23). *East Anatolian Fault*. Wikipedia. (General information on EAFS, citing pre-2010 discovery and studies).
37. [9] Brew, G. E. (2001). *Tectonic Evolution of Syria*..[9]
38. [12] Searle, M. P., et al. (2010)..[14]
39. [18] Stadler, S., et al. (2013)..[18]
40. [3] Barazangi Map Collection, Cornell University Library..[3]
41. [11] Wikipedia contributors. (2024, May 23). *Dead Sea Transform*. Wikipedia. (General information on DSFS).
42. [15] Wikipedia contributors. (2024, May 23). *East Anatolian Fault*. Wikipedia. (General information on EAFS).
43. [18] Stadler, S., et al. (2013)..[18]
44. [23] Sharkov, E. V., et al. (2009)..[23]
45. [21] Al-Mohamad, H., & Al-Saleh, M. (2022)..[21]
46. [18] Stadler, S., et al. (2013)..[18]
47. [18] Stadler, S., et al. (2013)..[18]
48. [22] Devyatkin, E. V., Dodonov, A. E., Sharkov, E. V., Zykin, V. S., Simakova, A. N., Khatib, K., & Nseir, H. (1997). The El-Ghab rift depression in Syria: Its structure, stratigraphy, and history of development. *Stratigraphy and Geological Correlation, 5*(4), 362-375. (Detailed Pliocene-Quaternary stratigraphy of Ghab basin).
49. [19] Robertson, A. H. F., & Parlak, O. (2004)..[19]

Works cited

1. Kurd Mountain - Wikipedia, accessed June 6, 2025, https://en.wikipedia.org/wiki/Kurd_Mountain
2. Turkey's Demographic Engineering in Syria's Afrin Region: A Closer Look, accessed June 6, 2025, https://www.meforum.org/meq/turkeys-demographic-engineering-in-syrias-afrin-region-a-closer-look
3. Geological map of Syria - Selections from the Barazangi Map ..., accessed June 6, 2025, https://exhibits.library.cornell.edu/barazangi-map-collection/catalog/60-2733
4. Syria - East View Geospatial, accessed June 6, 2025, https://geospatial.com/country_profiles/syria/
5. Syria 1:200000 Scale Geological Maps - Global Explorer - East View Geospatial, accessed June 6, 2025, https://shop.geospatial.com/publication/0CE0GNF3731E4GE71QRYNACWX1/Syria-1-to-200000-Scale-Geological-Maps
6. SYRIAN ARAB REPUBLIC Geography Geology - IAEA INFCIS, accessed June 6, 2025,

https://infcis.iaea.org/udepo/Resources/Countries/Syrian%20Arab%20Republic.pdf
7. The recent instrumental seismicity of Syria and its implications, accessed June 6, 2025, https://www.scielo.org.mx/pdf/geoint/v57n2/0016-7169-geoint-57-02-121.pdf
8. The recent instrumental seismicity of Syria and its implications - SciELO México, accessed June 6, 2025, https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0016-71692018000200121
9. Tectonic Evolution of Syria - Cornell University, accessed June 6, 2025, http://atlas.geo.cornell.edu/people/brew/gbthesis5.html
10. Tectonic and Geologic Evolution of Syria - Cornell University, accessed June 6, 2025, http://atlas.geo.cornell.edu/syria/brew2.pdf
11. Dead Sea Transform - Wikipedia, accessed June 6, 2025, https://en.wikipedia.org/wiki/Dead_Sea_Transform
12. (PDF) Geological offsets and age constraints along the northern ..., accessed June 6, 2025, https://www.researchgate.net/publication/249547631_Geological_offsets_and_age_constraints_along_the_northern_Dead_Sea_fault_Syria
13. Tectonic and Geologic Evolution of Syria - ResearchGate, accessed June 6, 2025, https://www.researchgate.net/publication/252322324_Tectonic_and_Geologic_Evolution_of_Syria
14. Geological offsets and age constraints along the northern Dead Sea fault, Syria, accessed June 6, 2025, https://www.earth.ox.ac.uk/publication/83448/scopus
15. East Anatolian Fault - Wikipedia, accessed June 6, 2025, https://en.wikipedia.org/wiki/East_Anatolian_Fault
16. Tectonostratigraphic overview of the Zagros Suture Zone, Kurdistan Region, Northeast Iraq - GeoScienceWorld, accessed June 6, 2025, https://pubs.geoscienceworld.org/gpl/geoarabia/article-pdf/17/4/109/5446472/al-qayim.pdf
17. Tectonic and Geologic Evolution of Syria | GeoArabia - GeoScienceWorld, accessed June 6, 2025, https://pubs.geoscienceworld.org/gpl/geoarabia/article/6/4/573/566727/Tectonic-and-Geologic-Evolution-of-Syria
18. (PDF) The deep Cretaceous aquifer in the Aleppo and Steppe ..., accessed June 6, 2025, https://www.researchgate.net/publication/257471564_The_deep_Cretaceous_aquifer_in_the_Aleppo_and_Steppe_basins_of_Syria_Assessment_of_the_meteoric_origin_and_geographic_source_of_the_groundwater
19. Paleostress analyses in NW Syria: Constraints on the Cenozoic ..., accessed June 6, 2025, https://www.researchgate.net/publication/223622331_Paleostress_analyses_in_NW_Syria_Constraints_on_the_Cenozoic_evolution_of_the_northwestern_margin_of_the_Arabian_plate
20. Assessment of the Tectonic Effects on Soil Radon Activity Along the Margin of the

Arabian Plate Boundary in Northwestern Syria - Redalyc, accessed June 6, 2025, https://www.redalyc.org/journal/568/56875427002/html/
21. Assessment of the Tectonic Effects on Soil Radon Activity Along the ..., accessed June 6, 2025, https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0016-71692022000200100
22. (PDF) The El-Ghab rift depression in Syria: Its structure, stratigraphy ..., accessed June 6, 2025, https://www.researchgate.net/publication/237963558_The_El-Ghab_rift_depression_in_Syria_Its_structure_stratigraphy_and_history_of_development
23. New data on the Late Cenozoic basaltic volcanism in Syria, applied to its origin, accessed June 6, 2025, https://www.researchgate.net/publication/223648166_New_data_on_the_Late_Cenozoic_basaltic_volcanism_in_Syria_applied_to_its_origin
24. Quaternary Fluvial Environments and Palaeohydrology in Syria (Chapter 48) - Cambridge University Press, accessed June 6, 2025, https://www.cambridge.org/core/books/quaternary-of-the-levant/quaternary-fluvial-environments-and-palaeohydrology-in-syria/7338DBDAE7DBDCFD59BCFE393753E7AC
25. A combined methodology of multiplet and composite focal mechanism techniques for identifying seismologically active zones in Syria - ResearchGate, accessed June 6, 2025, https://www.researchgate.net/publication/225405387_A_combined_methodology_of_multiplet_and_composite_focal_mechanism_techniques_for_identifying_seismologically_active_zones_in_Syria
26. The recent instrumental seismicity of Syria and its implications - Redalyc, accessed June 6, 2025, https://www.redalyc.org/journal/568/56871785003/html/
27. The Geomorphological Regions of Turkey - ResearchGate, accessed June 6, 2025, https://www.researchgate.net/profile/Attila-Ciner/publication/330253404_The_Geomorphological_Regions_of_Turkey/links/608e714a92851c490faed264/The-Geomorphological-Regions-of-Turkey.pdf
28. Ponikarov, V. (1967) The Geology of Syria, Explanatory Notes on the Map of Syria, Scale 1500,000. Part II. Mineral Deposits and Underground Water Resources, Techno Export, Moscow. - References - Scientific Research Publishing, accessed June 6, 2025, https://www.scirp.org/reference/referencespapers?referenceid=2608584
29. Rupture segmentation on the East Anatolian fault (Turkey) controlled by along-strike variations in long-term slip rates in a structurally complex fault system - GeoScienceWorld, accessed June 6, 2025, https://pubs.geoscienceworld.org/gsa/geology/article/52/10/779/645839/Rupture-segmentation-on-the-East-Anatolian-fault
30. Overview of the Triassic System in Syria: Lithostratigraphic and biostratigraphic correlations with neighboring areas - GeoScienceWorld, accessed June 6, 2025, https://pubs.geoscienceworld.org/gpl/geoarabia/article-pdf/15/1/95/5444812/mou

ty.pdf
31. The Mineral Industry of Syria in 2010 - AWS, accessed June 6, 2025, https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/country/2010/myb3-2010-sy.pdf
32. Present-Present-day stress state in northwestern Syriarthwestern Syria - SciELO México, accessed June 6, 2025, https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0016-71692020000400300