

Late Proterozoic – Paleozoic Geology of the Golan Heights and Its Relation to the Surrounding Arabian Platform

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1. Introduction

1.1 Study area

The Golan Heights (GH) is an elevated basalt-covered plateau located at the south-western tip of the Palmyrides, rising above the Sea of Galilee on the eastern side of the Jordan River (Figures 1a & 1b, Meiler, 2011; Meiler *et al.*, 2011). The Golan Plateau is covered by tens of volcanic cones and comprises the western continuation of an extensive Hauran region – a broad and flat Plio-Pleistocene volcanic province that extends eastward into Syria.

The study area is framed by prominent tectonic and geo-morphological elements (Figures 1a & 1b). To the north, the GH is bounded by the Mt. Hermon Anticline, which comprises a south-western continuation of the Palmyrides transpressive fold belt (Picard, 1943), as well as the right bend of the Dead Sea Fault System (DSFS) (Freund, 1965; 1980). To the west, the GH is delimited by the DSFS and the Jordan Rift Valley (JRV) which in this area extends along nearly 60km from the Yarmouk River in the south to the Mt. Hermon Structure in the north. The DSFS is an active plate boundary separating the Arabian plate to the east from the African plate (Sinai sub-plate) to the west (Garfunkel *et al.*, 1981). To the south, the GH is bordered by the Yarmouk River and the adjacent Jordanian Highlands, which comprises at this area an international border between Israel and Jordan. To the east, the GH is bordered by the Hauran-Jebel Druze depression, which exhibits similar morphology of an elevated plateau with prominent volcanic cones and numerous basaltic sheets. The Hauran - Jebel Druze Plateau comprises the most north-western part of the wide-scaled Harrat-Ash-Shaam volcanic field, which extends from southern Syria, across Jordan and into Saudi Arabia (Figure 1a).

The cumulative stratigraphic column and the general structure of the rocks underlying the Plio-Pleistocene basalt cover were studied by various authors. The syncline nature of the Golan Plateau was pointed out by Michelson (1979), Mor (1985), Hirsch *et al.* (2001) and Shulman *et al.* (2004). Meiler *et al.* (2011) presented first results of an extensive depth-domain seismic analysis according to which the Golan Plateau covers a large structural depression that constitutes the northern and deeper part of the extensive Irbid-Golan Syncline (Figure 2). The syncline has evolved during the Late Cretaceous - Cenozoic amid the Hermon Structure to the north and the Ajlun anticline to the south.

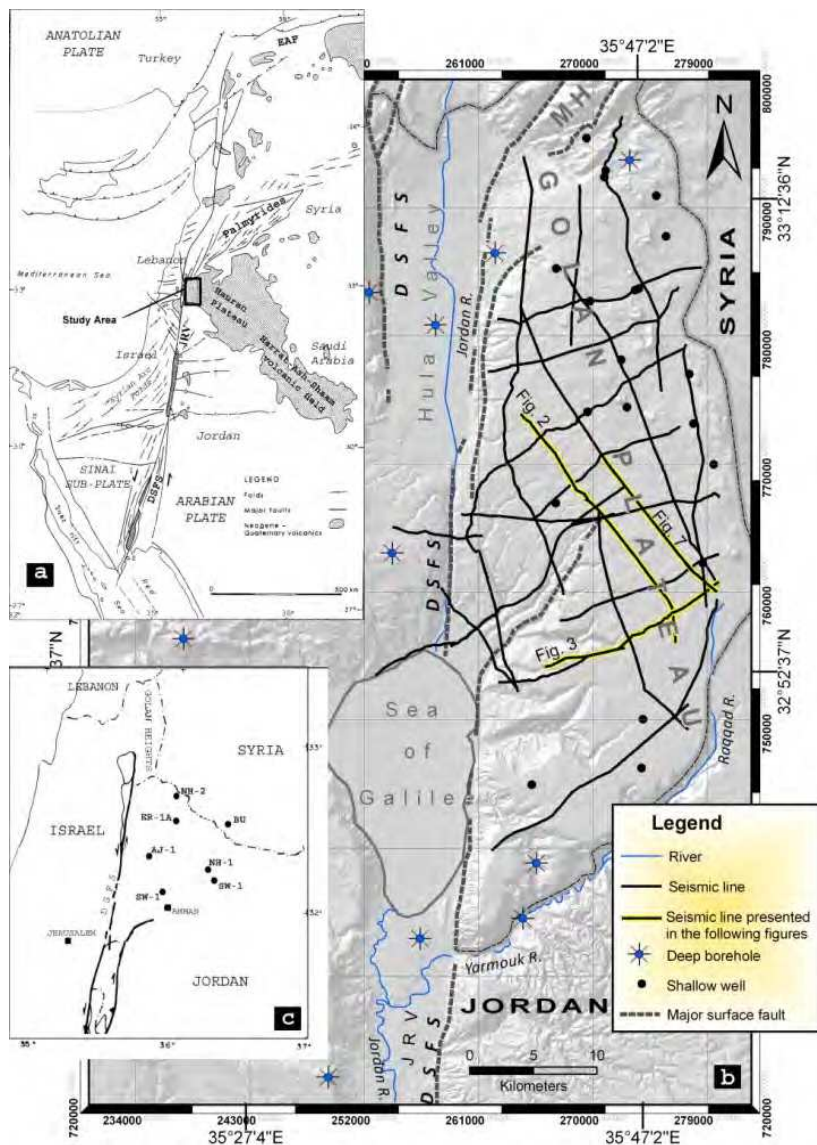


Fig. 1. **a.** Regional setting of the study area. Modified after Garfunkel *et al.*, 1981. DSFS - Dead Sea Fault System; EAF - East Anatolian Fault; JRV - Jordan Rift Valley; **b.** Location map of the seismic lines, deep boreholes and shallow water wells in the GH and the adjacent areas (Israeli side only), overlaying Digital Terrain Model (DTM). DTM after Hall, 1993. MH - Mount Hermon. The map is given in WGS-1984 and Israel-TM-grid coordinate systems. **c.** Location map of the deep boreholes drilled in the Northern Jordan and SW Syria areas. Thickness information on the principle stratigraphic units penetrated by these boreholes is presented in Table 1.

The sedimentary succession accumulated within the Golan part of the depression extends from the Late Proterozoic at the bottom to the Pleistocene basalts at the top of the section, attaining a thickness of at least 8.5km in the northern part of the plateau. The stratigraphic column beneath the basalt cover consists of up to 3,500m of Infracambrian – Paleozoic succession; up to 5,000m of Mesozoic rocks and about 1,500m of Cenozoic section (Meiler *et al.*, 2011). The thickness of the basaltic layer covering the Golan depression attains at the central Golan 1,100m (Reshef *et al.*, 2003; Meiler *et al.*, 2011).

1.2 Regional background

During Late Proterozoic – Paleozoic the areas surrounding the Golan Plateau, i.e. Levant, Arabian Platform and North Africa, constituted a part of the Gondwana continent. Following the Pan-African orogenic event and the subsequent cratonization, the region behaved typically as a stable platform during this time span. An extensive sedimentary cover of marine and continental origin has accumulated over the area in several deposition cycles. Sedimentation of mostly siliciclastic deposits has continued on the stable subsiding passive margin shelf of the Gondwanaland until Permian, when a series of rifting events related to the Neo-Tethys opening set on a new episode in the regional geological history (Garfunkel and Derin, 1984; Garfunkel, 1988; Weissbrod, 2005).

The Late Precambrian – Early Cambrian clastic cycle consists of immature, polymictic and poorly sorted conglomerates and arkose that were mostly derived from the Pan-African metamorphic and Plutonic terrain in the Arabo-Nubian Shield, to the west and south of the study area. The detrital sediments of the conglomeratic facies accumulated due to rapid and repeated subsidence episodes along major fault scarps and tectonic depressions, whereas the arcose facies was deposited in a broad pericratonic basin, which extended from the Arabo-Nubian Shield in the south to the passive margin and the Paleo-Tethys in the north. Today, these clastics are discontinuously exposed throughout Saudi-Arabia, Egypt, Jordan and Israel, separated by erosion gaps on the elevated igneous rocks of the Arabo-Nubian Shield. The thickness of the conglomeratic facies preserved within the rift-related depressions in Northern Arabia and Eastern Desert of Egypt locally attains 5,000m, whereas the thickness of arcose facies in Israel and Jordan attains at least 2,500m (Weissbrod, 2005).

The Paleozoic sediments are very wide spread in the north-eastern part of the Arabo-African continent, comprising one of the most voluminous bodies of sediments in the region (Garfunkel, 1988). This second sedimentary cycle continued from the Middle Cambrian to Permian, incorporating mostly siliciclastic deposits, with mixed carbonate-shale intercalations throughout the sequence. The sediments were accumulated in the fluvial environment and shallow epicontinental shelf, attaining a thickness of almost 5,000m.

Overall, the Late Precambrian – Paleozoic sequence attains thickness of more than 10,000m. However, due at least three major uplift-and-erosion events ((1) end of Silurian; (2) end Devonian to Early Carboniferous; (3) Late Carboniferous to Early Permian) a complete time sequence is hardly found at any locality in the northern part of the Arabo-African continent (Garfunkel and Derin, 1984; Weissbrod, 2005).

1.3 The scope of the study

The purpose of the current work is to present the deepest stratigraphic section identified beneath the volcanic cover of the Golan Plateau, based on the extensive depth-domain seismic analysis, and to discuss the geological evolution of the study area during the Late Precambrian – Paleozoic time span in the light of the available information from the surrounding north-western parts of the Arabian Platform.

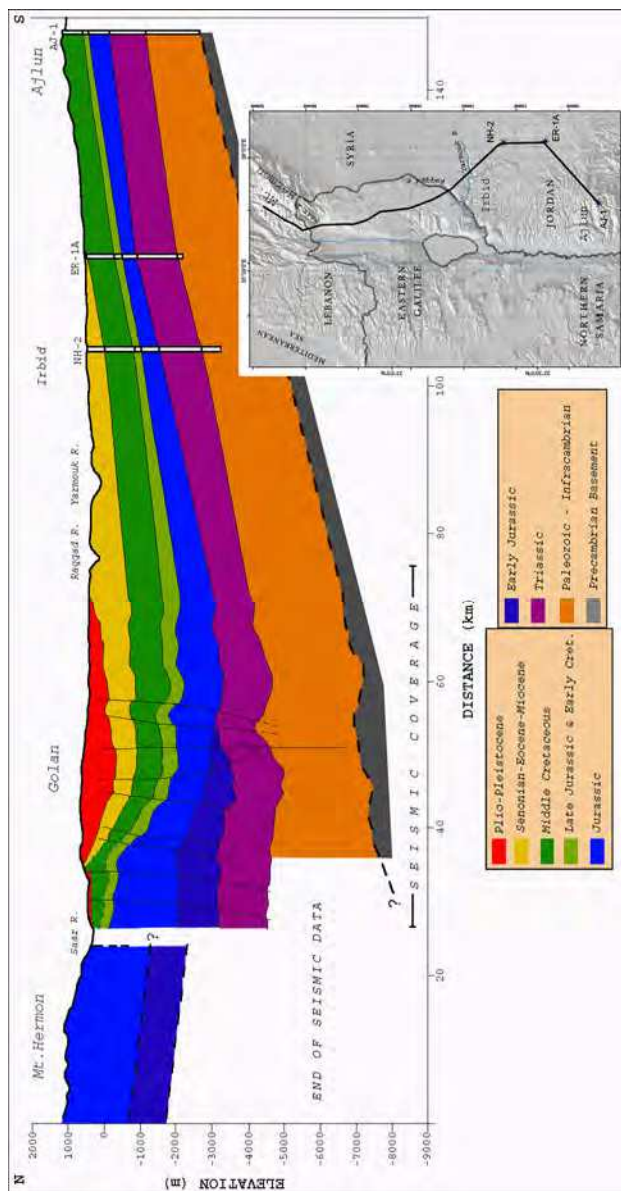


Fig. 2. Generalized cross-section showing the regional geological structure and the Late Proterozoic - Phanerozoic stratigraphic column in the area laying in between the Ajlun anticline at the south and the Mt. Hermon at the north (Modified after Meiler, 2011; Meiler *et al.*, 2011). The cross-section is based on analysis of three deep boreholes located in the Northern Jordan (AJ-1, ER-1A and NH-2) and depth-domain interpretation of seismic data that covers the GH area (Figure 1b). The cross-section outlines the syncline nature of the study area, confined by the Ajlun and Hermon anticlines. Note the similarity with respect to

the thickness of the Infracambrian - Paleozoic sections revealed in the subsurface of Northern Jordan and Golan Heights areas, suggesting analogous geological history during this time-span. On the contrary, the thickened Jurassic succession interpreted in the central and northern parts of the GH implies that significantly different geological environment prevailed in the GH with respect to that of the Jordanian Highlands during the Early - Middle Mesozoic.

2. Methods

2.1 Database (Figures 1b & 1c)

- A set of twenty five 2-D seismic reflection lines covering the GH area
- Formation tops from eighteen deep oil-exploration boreholes located in the Golan Heights area, Eastern Galilee, Northern Jordan and SW Syria. Table 1 presents the thickness information from the Jordanian and Syrian wells which penetrated the Paleozoic succession. Figure 1c indicates the location of these drillings.
- Formation tops from twenty shallow water and research wells drilled in the Golan Heights area
- Geological and topographical maps in different levels of resolution and geological cross-sections in local and regional scales

2.2 Seismic data processing

In the course of the present study, the Pre-Stack Depth Migration (PSDM) technique was utilized as the main seismic processing tool. PSDM was carried out from the surface topography, enabling an enhanced imaging of the Base-of-Basalt interface. The seismic data processing and analysis were accompanied by examination of stratigraphic information derived from the deep boreholes of Jordanian Highlands and SW Syria (Figure 1c), which penetrated the Mesozoic-Paleozoic successions, and in one case - the Precambrian basement (Ajlun-1 borehole).

Interval velocity analysis consisted of two steps:

1. 2-D velocity function construction for each of the 25 seismic lines was based on the Constant Velocity Half Space technique (Reshef, 1997).
2. 3-D interval velocity model construction, utilizing a MULTI 2-D approach. The procedure resulted in a comprehensive 3-D interval velocity model that covers the entire study area, including the subsurface parts which lay in between the seismic lines. The velocity model was then smoothed in the 3-D domain, resulting in a global interval velocity model of the study area.

The final depth sections were obtained by the Pre-Stack Explicit Finite-Difference Shot Migration and Post-stack Explicit Finite-Difference Depth Migration algorithms, employing extracted 2-D velocity functions from the global 3-D model.

2.3 Seismic data quality

Despite the thick basaltic layer entirely covering the Golan Plateau, the final depth sections show surprisingly good quality of seismic data. The final depth sections show reflections from 7 – 8 km below the datum (Figure 3) in the southern and central parts of the study area. There is a considerable deterioration of the seismic quality towards the Northern Golan.

2.4 Seismic interpretation

Eleven seismic markers were identified and mapped in the subsurface of the GH (Figure 3). Since the borehole information in the GH area is restricted to the upper 1,400 meters, direct correlation between the seismic data and the borehole stratigraphic information is limited to the upper two horizons only: the Base-of-Basalt (H1) and the Near Top Turonian (H2). Stratigraphic identification of the deeper seismic horizons became possible due to the fact that the seismic data was Pre-Stack depth migrated and the entire interpretation procedure took place in the geological (i.e. depth) domain. This enabled to perform an instantaneous correlation of the prominent seismic markers with the exposures of the Mesozoic section outcropping on the adjacent Mt. Hermon Anticline and to compare the intervals between the horizons with the thickness information derived from the deep boreholes of Northern Jordan. Hence, stratigraphic ascription of the LC-3 horizon (H3, electric log marker within the Lower Cretaceous) and the Near Top Jurassic horizon (H4) relies mainly on the correlation of the seismic data with the exposures of the Lower Cretaceous and the Jurassic strata outcropping on the Mt. Hermon Structure. Identification of the Near Top Triassic (H5) and the three Paleozoic – Infracambrian horizons (H6 - H8) is based on the concept that the thickness of the principle stratigraphic units in the Southern Golan should be comparable to the thickness reported in the Jordanian Highlands, across the Yarmouk River, where it is controlled by a series of deep oil-exploration boreholes. Three additional reflections with limited spatial distribution were identified in different parts of the study area; they were designated as: within the Tertiary (H1b), within the Early Jurassic (H4b) and the Near Top Precambrian basement (H9).

	AJ-1	ER-1A	KH-1	NH-1	NH-2	SW-1	BU-1
Cenozoic Basalts	-	-	-	-	-	-	507
Ajlun Group (M. Cretaceous)	546	769	427	340	801	-	418
Kurnub Group (Aptian-Albian)	159	210	235	238	217	115	228
Azab Group (Jurassic)	598	389	-	-	488	131	252
Ramtha Group (Triassic)	1043	1137	668+	542	1239	687	1119
Hudayb Group (Permian)	226	114+	-	-	439+	-	151
Amud Formation (U. Cambr.-Ordov.)	-	-	-	813	-	-	63+
Ajram Formation (M-U Cambrian)	-	-	-	253	-	213	-
Burj Formation (L-M Cambrian)	-	-	-	201	-	252	-
Salib Formation (L. Cambrian)	580	-	-	571	-	931+	-
Unassigned units + Saramuj (L. Cambrian)	634	-	-	1052	-	-	-
Total Depth	3800	2754	1333	4017	3722	2329	2938

Table 1. Thicknesses (m) of principle stratigraphic units measured within the boreholes of the Northern Jordan and Syrian Busra-1. (Summarized after Abu-Saad and Andrews, 1993 and other sources. The figures referring to Busra-1 approximately correspond to the lithostratigraphic nomenclature used for the GH and the Northern Jordan areas)

The lowest four horizons (H6 - H9) are within the scope of current study.

A detailed description of various seismic processing and interpretation aspects implemented during the study was presented by Meiler *et al.*, 2011.

3. Results

3.1 Lithostratigraphic identification

Near top basement (Horizon 9)

The deepest reflection recognizable on the depth sections was tentatively assigned as the Near Top Precambrian basement (Horizon 9). The horizon was identified on several profiles, mostly in the eastern parts of the GH. It is generally absent in the western and northern parts (Figure 3), although patches of it can be scarcely observed on some lines in these areas.

Horizon 9 is stratigraphically identified relying on the assumption that a smooth and gradual transition of the basement is expected between the Jordanian Highlands and the Southern Golan in the Yarmouk River area. The base of the sedimentary cover was penetrated by the AJ-1 borehole (Figures 1c & 2; Table 1), 50km south to the study area, reaching the basement at depth of nearly 3,800 meters beneath the surface. The closest boreholes to the study area drilled in the Northern Jordan and SW Syria, i.e. ER-1A, NH-2 and BU-1 (Figure 1c), did not penetrate below the upper Paleozoic. However, NH-1 well, located about 70km south-east to the GH, penetrated ~1,000m of the Saramuj and an unassigned clastic units, which overlay the basement. Thus, it is assumed that on the most southern profiles of the GH the basement should be found about 1km below the Near Top Saramuj horizon (H8), the penetrated figure of the Saramuj clastics within NH-1 (Figures 3 & 4).

Sarmuj formation and the unassigned clastic unit (Horizon 8)

Horizon 8 is interpreted as the near top of the Late Precambrian – Early Cambrian sedimentary succession, known as the Saramuj Formation and the unassigned clastic unit (Figure 5). The sequence is known in the Arabian Platform region as the oldest non-metamorphosed sedimentary sequence, consisting of polymict conglomerate and poorly sorted coarse to fine grained arkose, accompanied by magmatic intrusions and extrusions (Weissbrod, 2005).

Near top burj formation (Horizon 7) and the near top paleozoic (Horizon 6)

In four, out of seven deep boreholes of Northern Jordan and Syrian Busra-1, the Paleozoic succession is topped by the Permian strata, usually limited to several hundred meters in thickness (Table 1). Therefore, it seems reasonable to assume that in the Southern GH some few tens to several hundred meters of Permian section rest at the top of the Paleozoic succession and Horizon 6 may roughly represent the Near Top Permian. The thickness of the Permian in the subsurface is expected to increase towards north, as up to 600-700m of Permian deposits were reported within the Palmyra Trough (Leonov, 2000).

Beneath the Permian section, beds of different Upper Paleozoic units are residing in the deep boreholes south to the GH (Table 1). In NH-1 and BU-1 the Permian Hudayb Group overlays the Ordovician Amud Formation (in Syrian BU-1 it is defined as "Afandy Formation"), whilst in SW-1 and AJ-1 it overlays Middle - Upper Cambrian Ajram and Lower Cambrian Salib Formations respectively. The other deep boreholes located in the vicinity of the GH did not penetrate beneath the Permian strata. However, the Middle Cambrian Burj Formation is widely distributed in the subsurface of Northern Jordan and

Syria and is known as a prominent regional seismic interface, designated as "D-reflector" (McBride *et al.*, 1990). Therefore Horizon 7 was lithostratigraphically assigned as the Near Top Burj Formation.

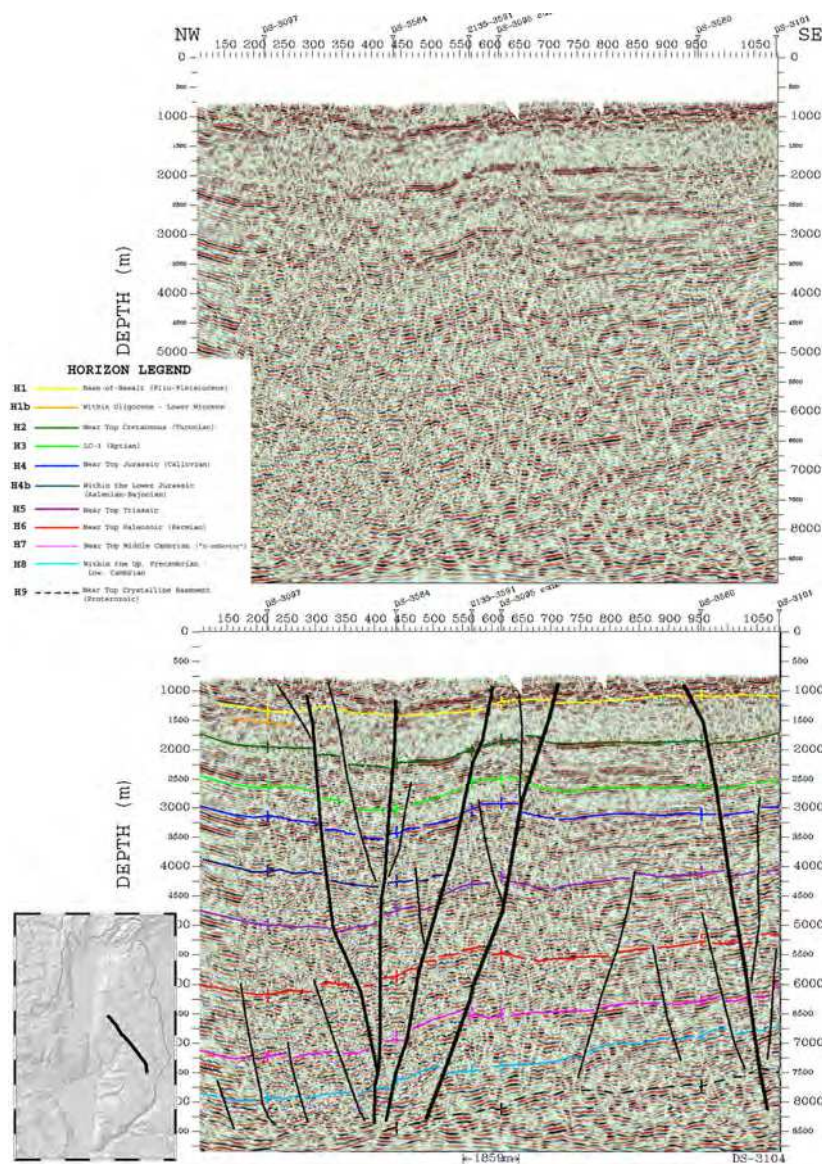


Fig. 3. DS-3104 depth section. Datum +1,150m. Note the good quality of seismic data, showing reflections from depths of 7 - 8 km below the datum. The gentle northward dipping of the Near Top Basement Horizon (H9), along with the overlying Paleozoic succession (H6 - H8), is observable.

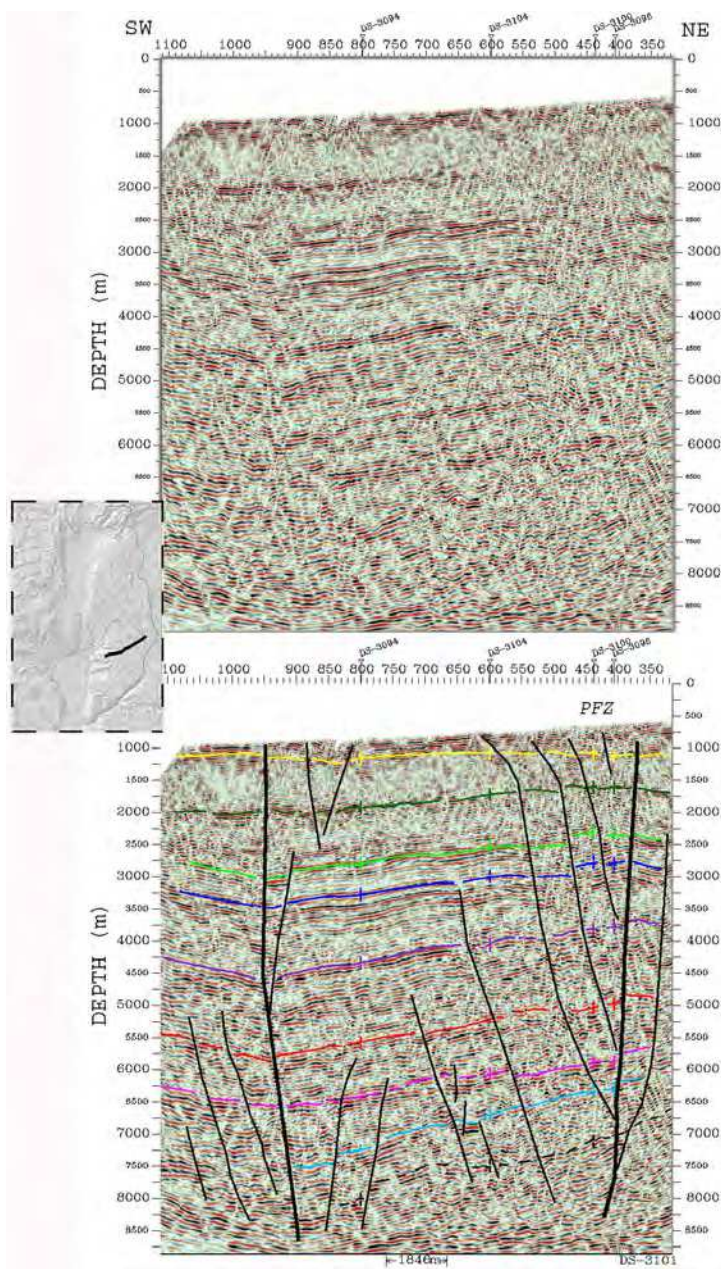


Fig. 4. DS-3101 depth section Datum +1,150m.; PFZ – Pezura Fault Zone. The Near Top Basement Horizon (H9) is assumed to lay ~1,000m below the Saramuj Fm (H8). Note the rising of the basement and the Saramuj Formation towards the PFZ on the eastern part of the profile. The western dip of the entire sedimentary column is clearly observable.

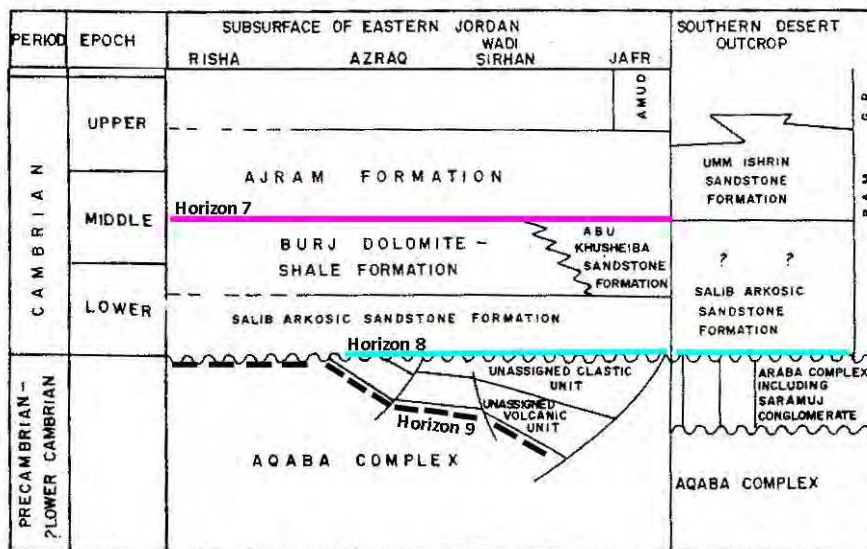


Fig. 5. Lithostratigraphy of the Lower Paleozoic (Cambrian) and the Precambrian of Jordan (Modified after Andrews, 1991). Horizons 7, 8 and 9 are tentatively assigned to the Near Top Burj Fm.; the Near Top Saramuj Fm. and/or the unassigned clastic unit; and to the Near Top Precambrian Basement, respectively (marked by the corresponding colors as presented in horizon legend on figure 3). Note the half-graben structure within the Infracambrian section.

3.2 Structural and isopach maps

Several structural and isopach maps were compiled in order to outline the geological evolution of the GH during the Late Proterozoic - Paleozoic time span. Figure 6 presents the structural map of the Near Top Basement Horizon (H9) and the isopach map compiled for the entire Infracambrian - Phanerozoic sedimentary cover.

Due to its limited appearance on the seismic sections, Horizon 9 was only partly interpreted in the subsurface of the GH area and therefore the structural and the isopach maps presented in figure 6 are restricted to the eastern and central parts of the study area. Nevertheless, the general structure and the architecture of the crystalline basement can be inferred from the maps.

The depth to the Near Top Basement Horizon, given its restricted seismic appearance and the uncertainty with respect to its stratigraphic correlation, ranges in the GH area between 5,700 to 7,700m beneath the sea level (Figure 6a) or between 6,150 - 8,500m beneath the surface topography (Figure 6b). The depth to the top of the crystalline basement in the Southern Golan is estimated to be 6 - 6.5km. The depth to the base of the sedimentary cover increases towards the Northern Golan and the Hermon Structure, where the sedimentary succession is outlined by its thickened Mesozoic sequence (Figure 2).

The thickness of the Infracambrian interval (i.e. Saramuj Formation and the unassigned clastic units of the Upper Proterozoic) in the study area varies in range from several hundred to 1,500 meters (Figure 7).

The structural map of Horizon 6 is presented in figure 8. The map displays the contemporary configuration of the Near Top Paleozoic (Permian?). The structural setting is dominated by the notable westward dipping from -3,5km in the east to -7km in the west, in the proximity of the DSFS.

Overall, based on the information derived from the deep boreholes of Northern Jordan and Syrian Busra-1, it is reasonable to assume that the seismic interval interpreted in the GH between the Near Top Paleozoic (Horizon 6) and the Middle Cambrian Burj Formation (Horizon 7) incorporates few tens to several hundred meters of Permian, overlaying additional several hundred meters of Ordovician to Middle - Upper Cambrian strata. The thickness of this interval varies between 500 - 1,100m for most of the GH area, locally attaining 1,300m (Figure 9).

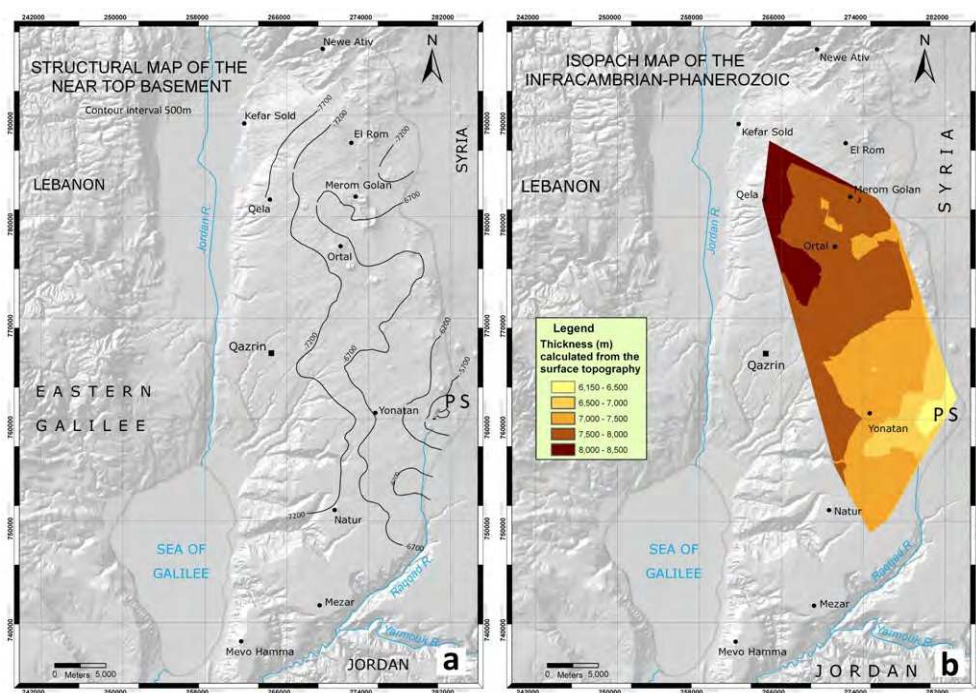


Fig. 6. **a.** Generalized structural map of the Near Top Basement Horizon (Horizon 9; faults are omitted). *PS* – Pezura Structure. Note the north-western dipping of the basement. (Modified after Meiler *et al.*, 2011). **b.** Isopach map showing the thickness of the seismic interval calculated between the Digital Terrain Model and H9. The map presents the thickness of the entire Infracambrian - Phanerozoic sedimentary cover in the central and eastern parts of the GH and indicates the depth to the crystalline basement calculated from the surface topography. (Modified after Meiler *et al.*, 2011).

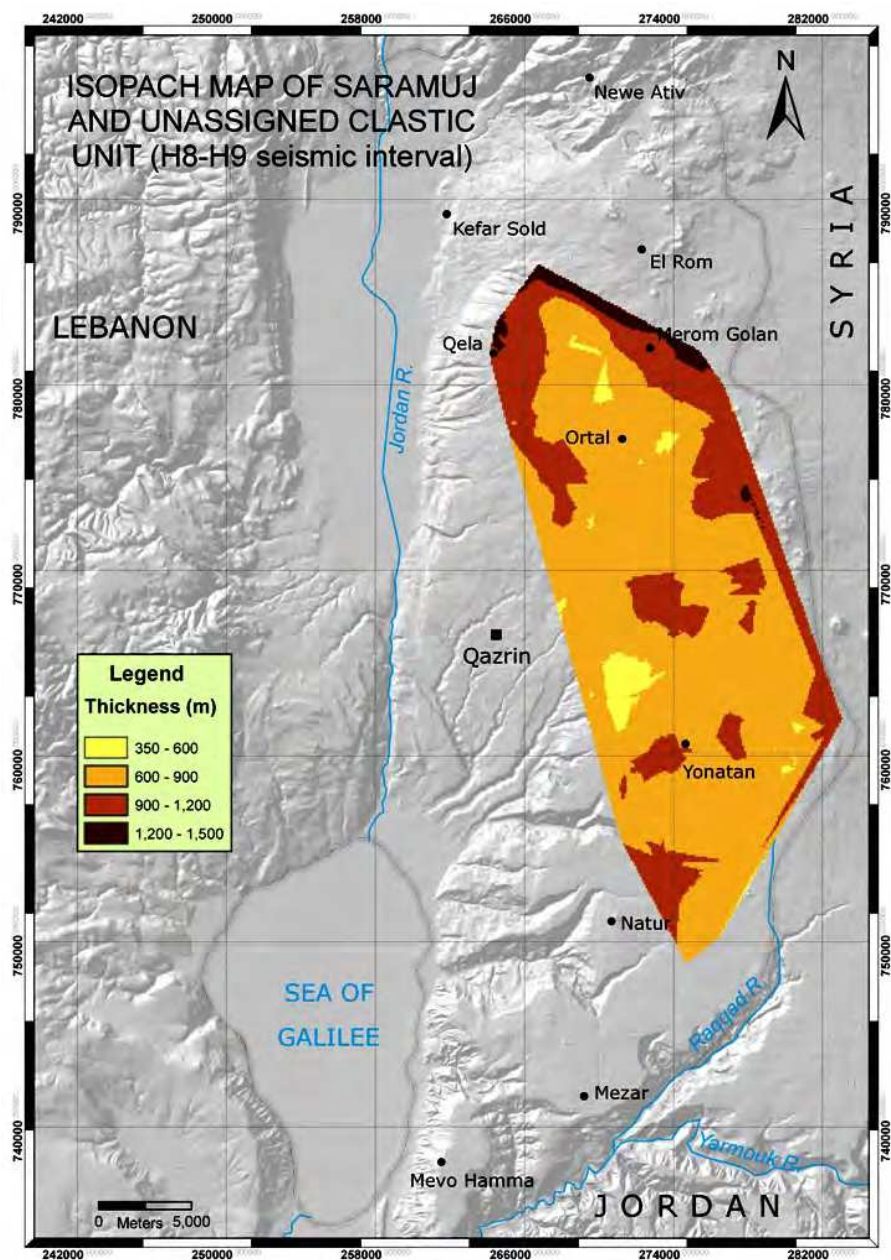


Fig. 7. Isopach map of the Saramuj and the unassigned clastic units within the Infracambrian time span. The map represents the seismic interval calculated between H8 and H9.

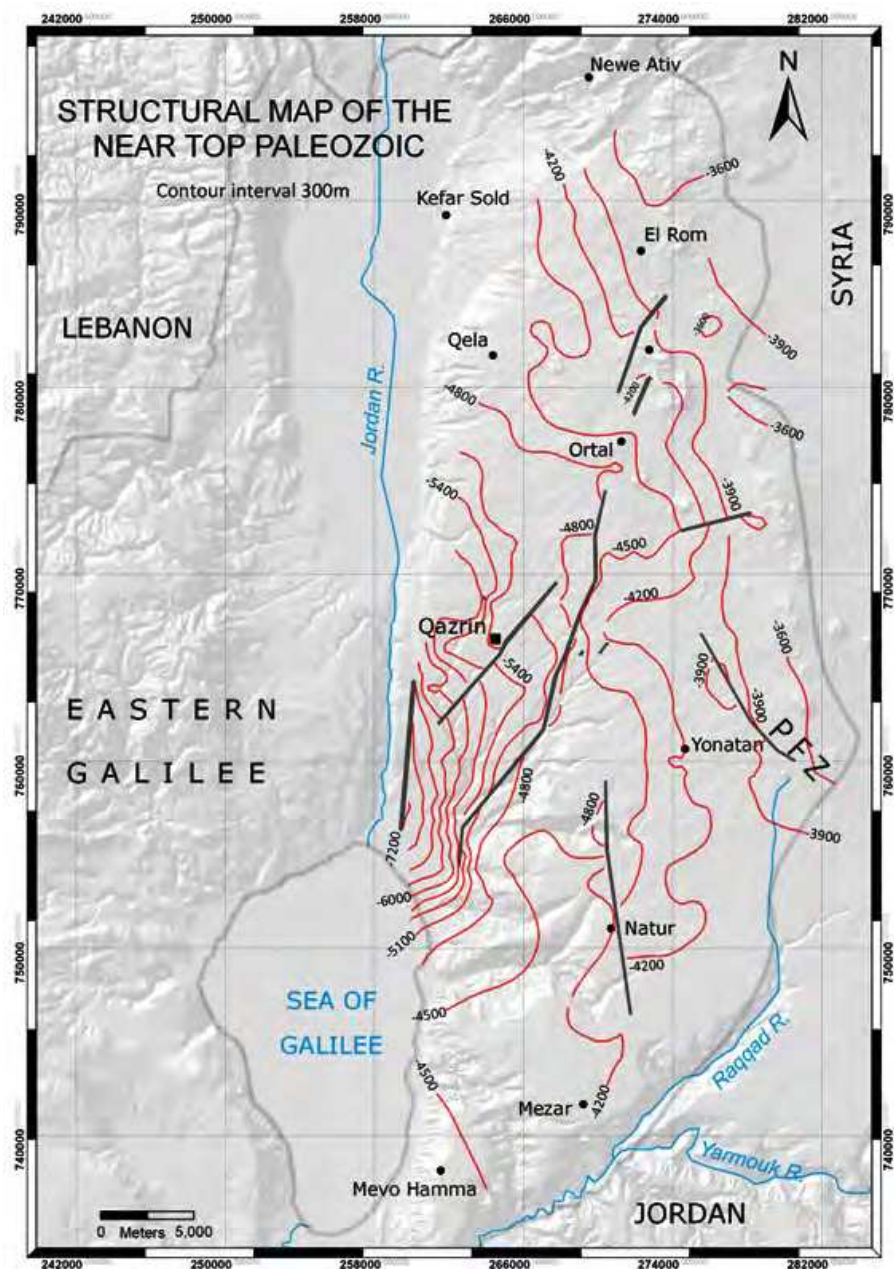


Fig. 8. Structural map of the Near Top Paleozoic Horizon (H6). After Meiler *et al.*, 2011. Note the western dip of the horizon from ~-3600m at the Syrian border in the east to about -7200m at the Sea of Galilee area in the west. Major fault zones are indicated.

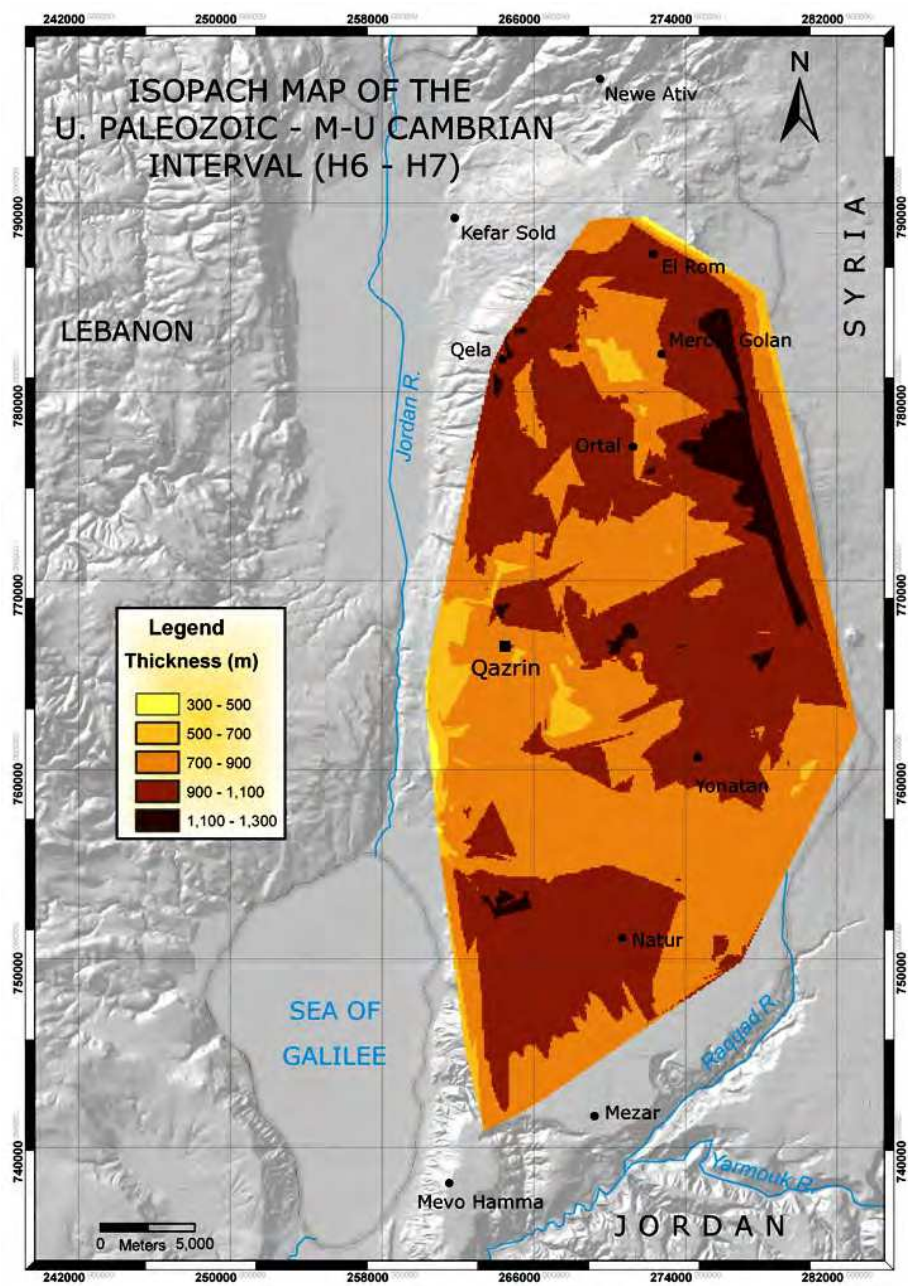


Fig. 9. Isopach map of the Upper Paleozoic (Permian?) to Middle-Upper Cambrian time span. The map represents the seismic interval calculated between H6 and H7.

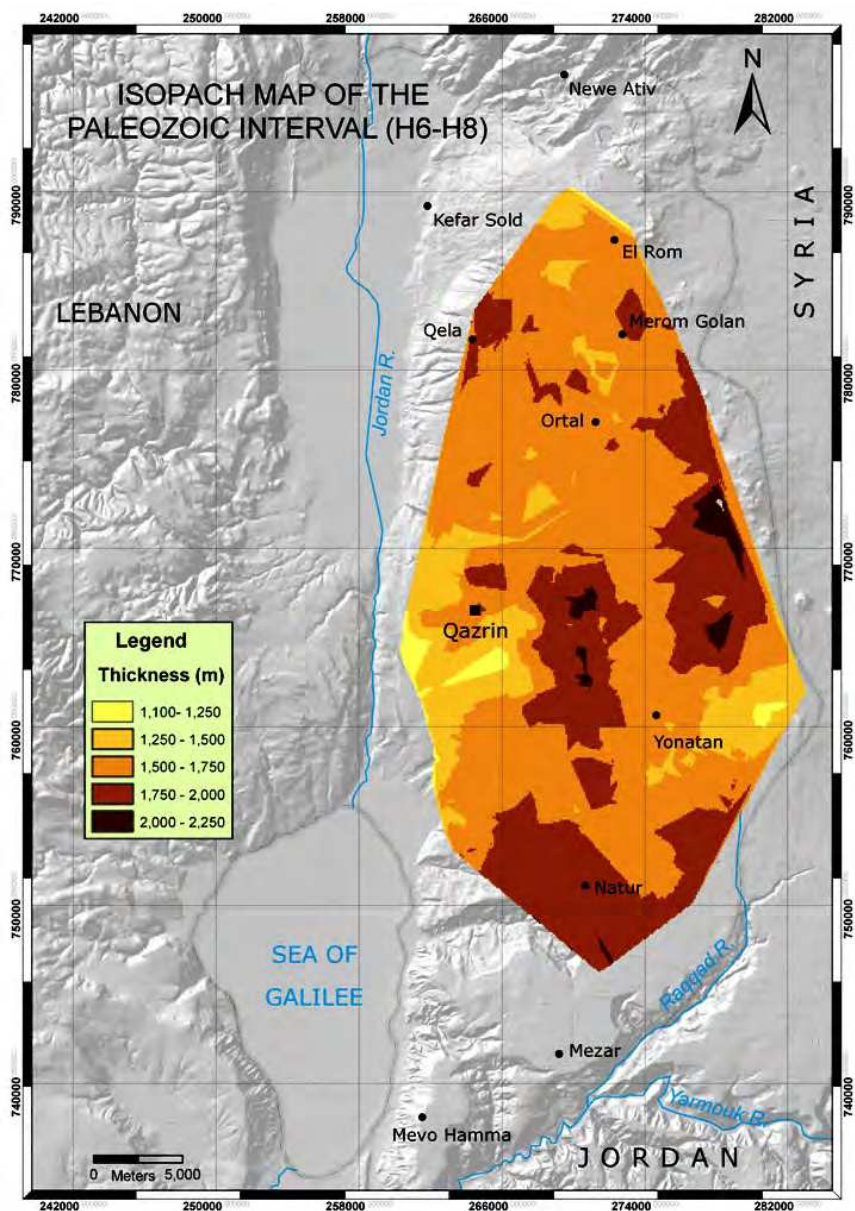


Fig. 10. Isopach map of the Paleozoic succession. The map represents the seismic interval calculated between H6 and H8.

A cumulative thickness of the Paleozoic succession is presented in isopach map calculated between the seismic intervals H6 – H8 (Figure 10). The interpreted thickness of this interval ranges from 1,100 to 2,250m.

4. Discussion

4.1 Near top basement (Horizon 9)

The depth to the base of the crystalline basement in the study area ranges between ~6km in the Southern GH to ~8.5km in the Northern Golan (beneath the surface topography). The basement dips northwards towards the Hermon Structure (Figure 2 & 3). At the foot of Mt. Hermon the thickness of the sedimentary cover is not known, but assumed to exceed the 8,500m calculated in between the Qela and the El-Rom area (Figure 6), the most northern area where the horizon is traceable and could be interpreted. In the south-western part of the Palmyride fold belt the depth to the basement was estimated to 11km within the Palmyra Trough (Seber *et al.*, 1993). East of the GH, outside of the Palmyrides, the depth to basement was estimated at 8 - 10km (Rybakov and Segev, 2004). To the west of the GH, across the DSFS in the Galilee region, the thickness of the sedimentary cover attains its regular figures of 6 - 8km (Ginzburg and Folkman, 1981). Thus, considering the northward dip of Horizon 9, it is suggested that the basement continues to deepen in the Northern Golan and the Mt. Hermon areas, whilst its depth beneath the Hermon Structure may attain 10 - 11km, as was estimated by Seber *et al.* (1993) in the south-western parts of the Syrian Palmyrides.

At the south-eastern part of the Golan the basement morphology is outlined by the significant structural uplift, referred here as the Pezura Structure (Figures 4, 6 & 8). It rises for several hundred meters above its surrounding and its structural influence can be traced upwards within the Paleozoic, Mesozoic and also Cenozoic sedimentary units. Reconstruction of seismic data to the Mid-Cambrian level (Horizon 7) indicates that this structure existed as a local high already in the Late Proterozoic - Early Cambrian (Figure 11, see).

4.2 Sarmuj formation and the unassigned clastic unit (Horizon 8)

The Late Precambrian - Early Cambrian sedimentary succession in the Arabian Platform comprises the oldest non-metamorphosed sedimentary sequence in the region, consisting of polymict conglomerate and poorly sorted coarse to fine grained arkose, accompanied by magmatic intrusions and extrusions (Weissbrod, 2005). The term "Infracambrian" describes this non-metamorphosed, mostly clastic sequence (Wolfart, 1967; Horowitz, 2001). Horizon 8 is interpreted as the near top of this sedimentary sequence in the subsurface of the Golan Heights.

In the Negev area of Southern Israel, a large Infracambrian sedimentary depression was reported overlaying the Precambrian basement (Weissbrod, 1980). It comprises a part of a broad marginal basin known as the Arabian-Mesopotamian Basin, which extends from the Arabo-Nubian Shield across Arabia, Levant and Mesopotamia to the edge of the Arabian Plate along the Bitlis Suture (Weissbrod and Sneh, 2002). The basin was filled with several kilometers of immature clastics and volcanics, defined in the Southern Israel as Zenifim and Elat Conglomerate Formations.

Sarmuj Formation and the unassigned clastic unit of Northern Jordan (Figure 5) consist both of clastic sediments, mainly coarse conglomerate and arkosic sandstones as well as some volcanic components (Andrews, 1991). These units are considered both as time and lithological equivalents of the Infracambrian Elat Conglomerate and the Zenifim sandstones reported from the Southern Israel (Garfunkel, 2002; Hirsch and Flexer, 2005; Weissbrod, 2005). The overlaying Salib Formation is very similar in composition and corresponds to the Lower Cambrian Amudei Shelomo and Timna Formations (Southern Israel) composed of predominantly clastic units. Horizon 8 is hypothesized to represent the near top of this

Infracambrian sequence which is characterized by the immature clastics of Saramuj conglomerate followed by the Salib arcose sandstones, similar to their southern contemporaneous known as Zenifim Formation and the Lower Cambrian Amudei Shelomo and Timna Formations; all units comprising a part of the above mentioned Arabian-Mesopotamian Basin.

The thickness of the Infracambrian interval (i.e. Saramuj Formation and the unassigned clastic units of the Upper Proterozoic) in the study area varies in range from several hundred to 1,500 meters (Figure 7). These Infracambrian units unconformably overlay the Near Top Basement Horizon (H9), filling the locally fault-bounded blocks (Figures 4 & 11a). These interpreted figures of the Infracambrian succession in the GH are comparable thickness figures to ~2,500m of Zenifim Formation estimated by Weissbrod and Sneh (2002) to overlay the basement on the regional scale.

The Infracambrian sedimentary section recognized in Jordan and Saudi Arabia is considered as a syn-rifting succession accumulated during the extensional phase of the Late Proterozoic – Early Cambrian time span (Abed, 1985; Huesseini, 1989; Best *et al.*, 1990). The period was dominated by the intra-continental rifting and wrenching (Husseini and Husseini, 1990), resulting in a series of asymmetric half-grabens with occasionally rotated basement blocks and immature syn-rift clastic deposition (Andrews, 1991; Figures 5 & 11a).

The thick Infracambrian section (Figure 7) which fills the underlying faulted blocks observable in the subsurface of the GH (Figure 11) is in agreement with the idea of possible pre-Cambrian or Early Paleozoic rifting episode that took place in the North-Western Gondwanian Arabia, as suggested by the above mentioned authors.

4.3 Pezura structure

A complex basin-and-swell configuration was proposed to prevail throughout the northern parts of the Gondwanaland during the Paleozoic (Garfunkel, 1998). Several large up-doming elements related to this Paleozoic configuration were reported in the Eastern Mediterranean region: the Hercynian Geoanticline of Helez, centred in the coastal plane of Israel (Gvirtzman and Weissbrod, 1984); Hazro structure extending across the Turkish-Syrian border (Rigo de Righi and Cortesini, 1964); Riyadh swell in central Saudi Arabia (Weissbrod, 2005).

The elevated feature interpreted in the south-eastern corner of the GH, referred here as the Pezura Structure (Figures 4 & 6), may represent one of the uplifted features which constituted a part of this basin-and-swell configuration, although in considerably smaller scale. The uplift, followed by the notable tilting and on-lapping sedimentation of younger Paleozoic strata (Figure 11c), can be related to the Hercynian Orogenic episode, which is dated in Jordan as mid-Carboniferous (Andrews, 1991) and Pre-Carboniferous or Pre-Permian (Gvirtzman and Weissbrod, 1984) event in Israel. However, figure 11b shows that the structure preceded the Middle Cambrian Burj Formation (H7) deposits, originating already in the upper Proterozoic and affecting the subsequent Paleozoic sedimentation.

This is evidenced by the on-lapping stratigraphic relations between H7 and H8. Thus, it seems that the Pezura structure was established as a tectonically active area already in the upper Proterozoic and it continued to act periodically throughout the Paleozoic, as part of the Hercynian Orogenic episode. The location of the presently elevated Pezura structure coincides with the formerly well developed fault-bounded depression (Figure 11a). This overlapping pattern in which the Upper Proterozoic rifting zones became a regional uplifts during the Early Paleozoic characterize additional regional highs, such as Rutba swell (Seber *et al.*, 1993).

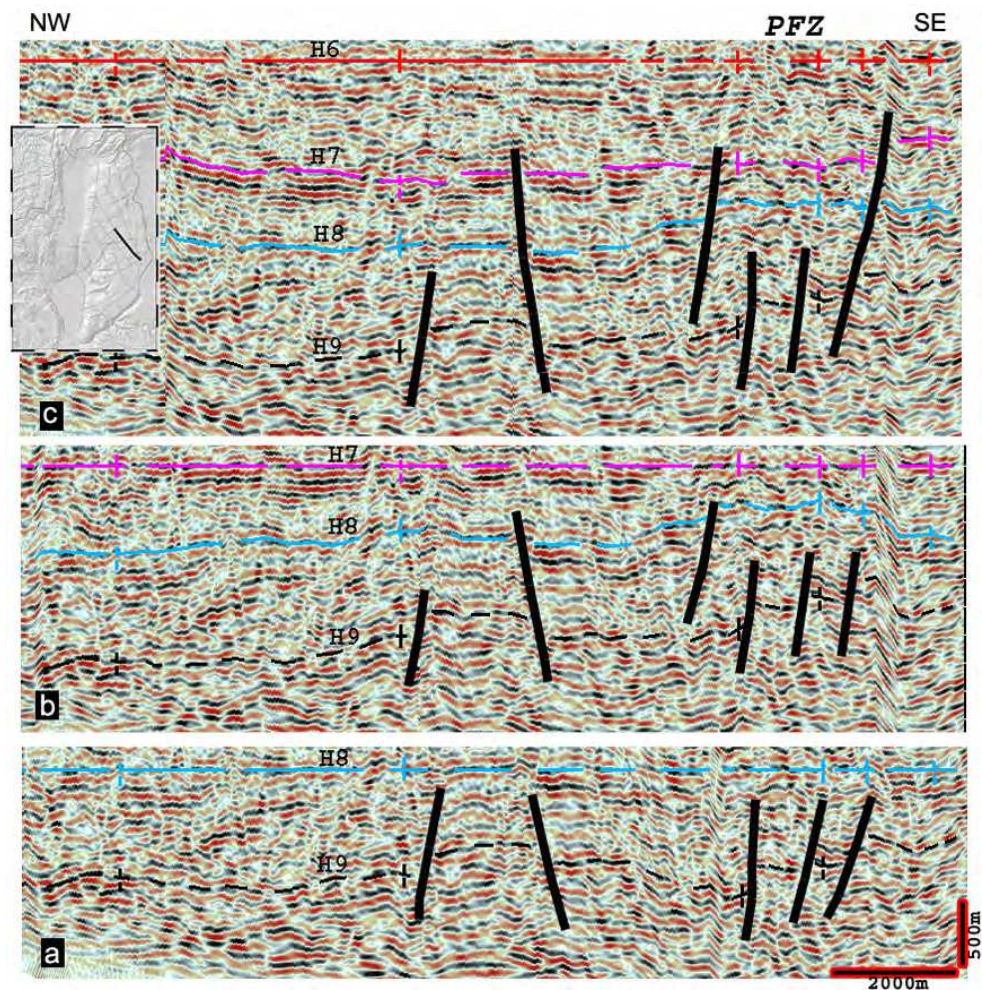


Fig. 11. Reconstruction of the Infracambrian - Paleozoic structural evolution in the Pezura Fault Zone (PFZ) area, south-eastern GH. The Early Cambrian (a), Mid-Cambrian (b) and Late Paleozoic (c) stages are presented, through flattening the southern section of DS-3096 profile to H8, H7 and H6 seismic markers, respectively. (Horizon legend as in figure 3). a. The reconstruction presents the Infracambrian section overlaying the crystalline basement, as appeared at the end of the deposition of Saramuj Formation (H8). Note that in the Pezura structure area the Infracambrian Saramuj section fills the faulted blocks of the basement. b. The reconstruction presents the Late Proterozoic - Early Cambrian sections overlaying the crystalline basement, as appeared at the end of the deposition of Burj Formation (H7). Note the uplifted Pezura structure in the area formerly outlined by a series of down-faulted blocks. c. The reconstruction presents the Late Proterozoic - Late Paleozoic sections overlaying the crystalline basement, as appeared at the end of the Paleozoic (H6). Note additional faulting in the Pezura area, suggesting for an alternating tectonic activity throughout Paleozoic.

4.4 Near top burj formation (Horizon 7) and the near top paleozoic (Horizon 6)

Since in most of the deep drillings adjacent to the GH the Paleozoic succession is topped by the Permian strata, it is assumed here that in the Southern Golan some few tens to several hundred meters of Permian section rest at the top of the Paleozoic succession and Horizon 6 roughly represents the Near Top Permian.

On the regional scale the Paleozoic sediments are very widespread in the north-eastern part of the Arabo-African continent (Alsharhan and Nairn, 1997; Garfunkel, 2002; Weissbrod, 2005). Large Paleozoic basin was reported in Syria, where more than 5,000m of Cambrian – Carboniferous section was documented in the subsurface. Total thickness of the Paleozoic section in Syria locally attains 7,000m (Krashennikov, 2005; Leonov, 2000). In Northern Jordan, the thickness of the Paleozoic succession reaches nearly 2,000m in NH-1 borehole (Table 1). In Southern and Central Israel the Paleozoic succession is highly reduced and attains thickness of several hundred meters only (Weissbrod, 1980; Ginzburg and Folkman, 1981). Thus, the thickness of the sedimentary section interpreted in the GH within the seismic interval Horizon 6 - Horizon 8 (Figure 10) appears to be comparable to the thickness of the coeval units reported in the Northern Jordan area.

It's worth noting that the eastern regional dip of the Paleozoic strata well-documented throughout the Eastern Mediterranean (Figure 11; Gvirtzman and Weissbrod, 1984; Andrews, 1991) was not observed in the subsurface of the GH.

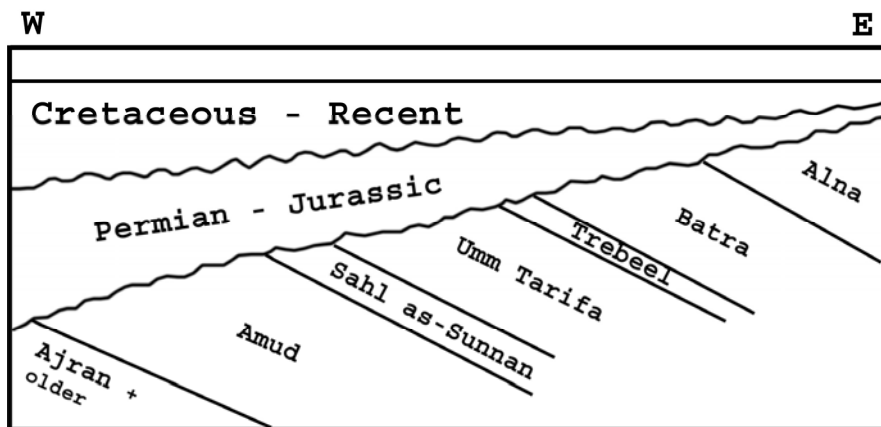


Fig. 12. Schematic stratigraphic relations between Paleozoic and Mesozoic sections in Jordan (Andrews, 1991). The sedimentary succession is outlined by the notable eastern dipping of the Paleozoic section, uncomfortably overlain by the Mesozoic units tilted towards west.

Moreover, on some profiles (Figures 3, 4 & 8) horizons attributed to the Paleozoic and Infracambrian sections (i.e. Horizons 6, 7 and 8) clearly show inclination to the opposite direction, i.e. due west, whilst a slight angular unconformity appears between the Mesozoic and the Paleozoic stratigraphic packages. A possible explanation would be an existence of an uplifted structure, like the above mentioned Pezura Structure, which locally tilted the sedimentary section to the west. However, this western inclination is clearly visible also on the northern profiles, away from the Pezura area; therefore it seems more reasonable to relate the inclination to a regional tectonic tilting which, according to the seismic data, took place during the Late Paleozoic – Early Mesozoic.

On the isopach map presenting the H6 - H7 seismic interval (Figure 9), figures of up to 1,300m are observable at the eastern edge of the GH, partly overlapping the line of the Pezura Fault Zone (The main fault plain is marked on figure 8; a number of unassigned individual fault segments related to the Pezura Fault Zone were not mapped). This increased H6 - H7 interval corresponds to the line of the volcanic cones covering the Golan Plateau and may suggest that plutonic intrusions occupy the lower parts of the Paleozoic succession. However, no definite seismic indications were observed on the depth sections to support this suggestion.

5. Summary

A series of structural and isopach maps compiled based on an extensive depth-domain seismic analysis displays the Late Proterozoic - Paleozoic evolution of the GH.

The depth to the base of the crystalline basement within the study area varies in range from 6km at the Southern Golan to 8.5km at the Northern GH (beneath the surface). As the Near Top Basement Horizon dips northward, it may attain 10 - 11km beneath the Hermon Structure, as was estimated in other parts of the Palmyrides.

The deepest sedimentary section interpreted in the subsurface of GH consists of two primary sequences:

1. Infracambrian (Late Precambrian - Early Cambrian) Saramuj Formation and unassigned clastic units which comprise the oldest non-metamorphosed sedimentary sequence in the region.
2. Paleozoic section, consisting of various units attributed to Lower Cambrian - Permian time span.

A total estimated thickness of the Infracambrian - Paleozoic succession interpreted in the subsurface of the GH varies in range of 1,800 to 3,500m (Figure 13).

About 1,000 - 1,500m of this figure corresponds to the Infracambrian deposits; its lower part (i.e. Saramuj Fm.) is interpreted as a syn-tectonic sequence, accumulated within the fault-related depressions, such as the Pezura Structure.

There is a notable contrast between the Paleozoic and the subsequent Mesozoic thickness distribution patterns within the GH. The thickness map of the Paleozoic (Figure 8) does not show the typical Mesozoic zoning and north-western thickening (Meiler, 2011), but rather characterized by a mosaic and irregular thickness distribution. This supports the findings in Syria, Jordan and Israel according to which it can be concluded that the Paleozoic structure of the northern Arabo-African Platform had very little in common with the structure that persisted during the following periods, which by the Early Mesozoic time was already greatly influenced by the establishment of the passive continental margin to the north of the Arabia shores.

Overall, it can be concluded that the stratigraphic column and the major sedimentary cycles of the Upper Proterozoic - Paleozoic interpreted in the GH closely resemble the corresponding geologic history of the adjacent Northern Jordan area. In both areas a 3 - 3.5km thick sedimentary succession of this period is preserved in the subsurface. The Paleozoic succession found in these areas attains more than 2,000m and differs significantly from the reduced Paleozoic succession exposed in the Southern Israel area, to the west and south of the GH.

This configuration has changed during the subsequent Mesozoic Era, when the deposition environment of the GH became closely affiliated to the Syrian and Israeli geologic history rather to that of the Northern Jordan.

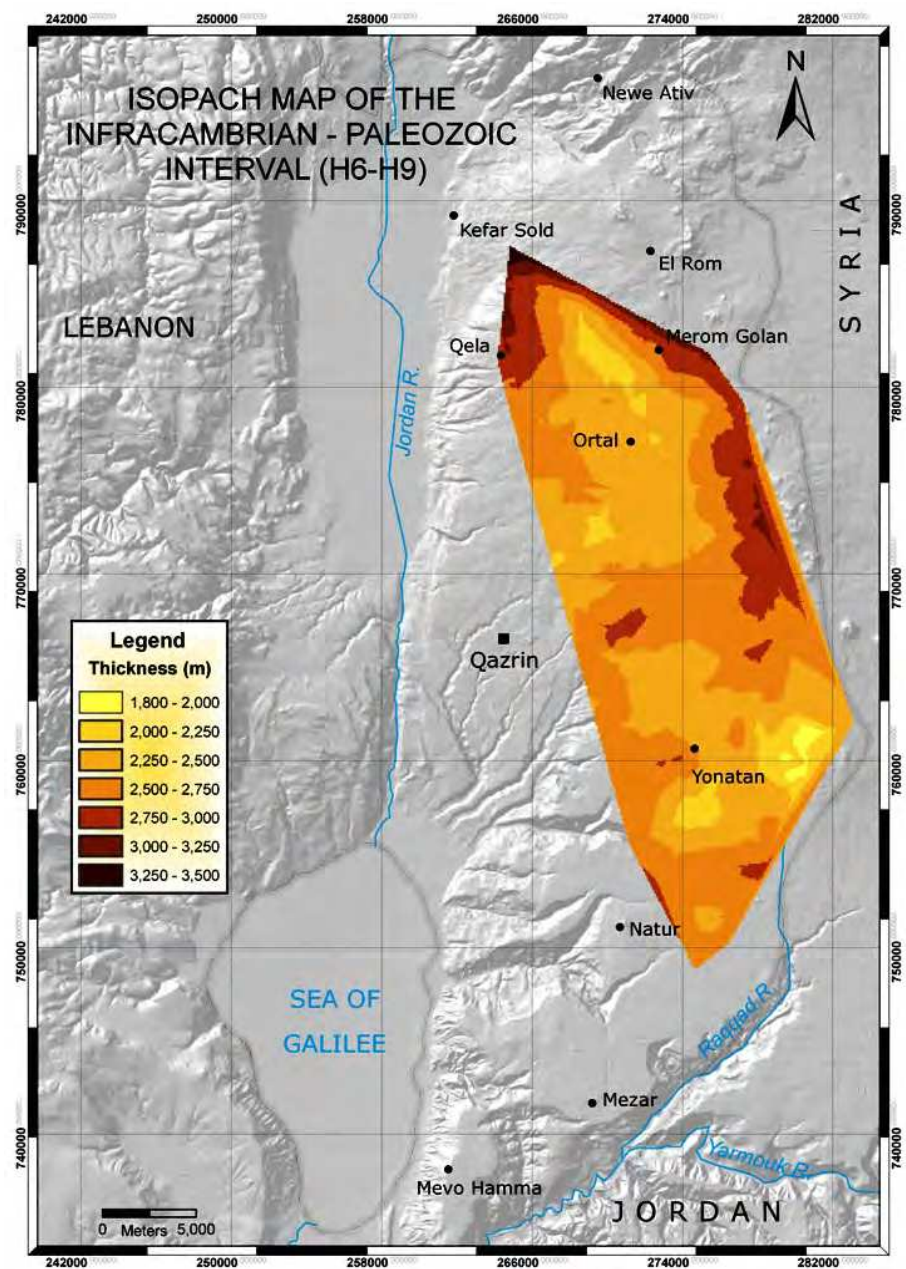


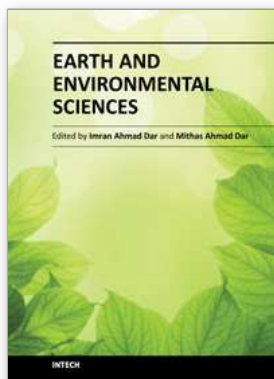
Fig. 13. Isopach map of the Infracambrian – Paleozoic succession. The map represents the seismic interval calculated between H6 – H9.

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We are increasingly faced with environmental problems and required to make important decisions. In many cases an understanding of one or more geologic processes is essential to finding the appropriate solution. Earth and Environmental Sciences are by their very nature a dynamic field in which new issues continue to arise and old ones often evolve. The principal aim of this book is to present the reader with a broad overview of Earth and Environmental Sciences. Hopefully, this recent research will provide the reader with a useful foundation for discussing and evaluating specific environmental issues, as well as for developing ideas for problem solving. The book has been divided into nine sections; Geology, Geochemistry, Seismology, Hydrology, Hydrogeology, Mineralogy, Soil, Remote Sensing and Environmental Sciences.

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