Morphometric and geomorphic approaches for assessment of tectonic activity, Dead Sea Rift (Israel)

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ABSTRACT

A series of 31 short, parallel, steep channels, mostly of first or second order, occur at intervals of 300–500 m along 16 km of the western margin of the northern Dead Sea Rift (Israel). The analysis of tectonic and geomorphic activity along the marginal faults between the various segments is based on morphometric parameters, such as sinuosity of the mountain front, channel gradients, drainage basin elongation ratio, planimetric ratio, facet areas, hypsometric curves, and integrals. Longitudinal profiles of the channels were studied in relation to the underlying lithology and the presence of marginal faults. Despite the great differences in climatic and geomorphologic settings, comparison with other studies worldwide showed morphometric values similar to other tectonically active regions.

The southern segments of the study area, which face the Hula deep depression, indicate enhanced geomorphic and tectonic activity. The northern segment proved dissimilar to the others, and is explained by its different tectonic setting.

Six sedimentary, fan-like units composed of polymictic conglomerates were deposited along the mountain piedmont at the channel mouths. The units were dated by OSL, K–Ar, and archaeology to <1.1 Ma (Q1 and Q1–2), <0.56 Ma (Unit Q3), ~1.20 ka (Unit Q4), and <10 ka (Units Q4 and Q5). The morphology and structure of the sedimentary units indicate pulses of depositional activity, followed by periods of quiescence and calcic-soil development. No major faulting occurred along the Naftali escarpment during the Upper Pleistocene, despite the high tectonic morphometric values obtained for the study area. The marginal faults displaced Unit Q4 during the Mid-Pleistocene, and since then tectonic activity has shifted from the western marginal faults eastward to younger faults deeply buried in the center of the graben. The field data calibrate the morphometric analysis: carbonate (limestone and dolomite) hillslopes developed in the Mediterranean climate have maintained ‘active tectonic class’ morphology since the last major faulting events during the Mid-Pleistocene.

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1. Introduction

During the Oligocene and Miocene, northern Israel was part of a wide peneplain dipping slightly westward toward the Mediterranean Sea (Picard, 1963; Garfunkel, 1988; Zilberman, 1992; Begin and Zilberman, 1997; Matmon et al., 1999). The rapid tectonic activity of the Pliocene and Pleistocene acted upon a region that was previously developed as an erosional surface, thus causing major changes in the landscape. The Dead Sea rift valley (DSR) was formed as a deep, elongated, inland depression that served as a new base level for the landscape. The Dead Sea rift valley (DSR) was formed as a deep, elongated, inland depression that served as a new base level for the landscape. Therefore, the evolution of the present morphology is a result of tectonics, climate and geomorphological processes.

In northern Israel, the DSR is characterized by the deep depression of the Hula valley (Fig. 1). Its western margin is represented by the Naftali Mountain range, an 880 m high escarpment, formed by regional faulting. The mountain front is exposed to channel weathering, fluvial erosion and intensive gravitational debris movements. Therefore, the evolution of the present morphology is a result of tectonics, climate and geomorphological processes.

The Naftali mountain front, which forms the western margin of the Hula valley, is dissected by E–W trending, 1st–2nd order, straight, ephemeral channels perpendicular to the piedmont that are defined in this study as ‘slope channels’ because of their gradients and geometry.

The geomorphology of tectonically-related mountain fronts can be used to assess long-term tectonic history and, therefore, serves as an...
important indicator for estimating tectonic activity (Mayer, 1986; Keller and Pinter, 2002). The landscape time of response is of the order of 10^5 years, which means that the landscape retains information about causative factors that occur with a frequency of less than several hundred thousand years (Ellis et al., 1999).

The study aims at investigating the response of carbonate slopes and channels (mainly limestone, dolomite and marl) to tectonic activity, in order to acquire a relative time frame for the development of the Naftali mountain front. Also the study will establish an initial relation between the geometrical expression of the mountain front
and its age, and a temporal framework for the tectonic activity along the marginal faults will be proposed.

2. Study area

2.1. Geographical settings

The Naftali mountain front is approximately 16 km long, extending between Nahal Qadesh and Nahal Misgav (A1) (Fig. 2). It rises from 80–100 m at the piedmont to 900 m at the Shinan mountain peak. It is characterized by steep slopes (30%–60%), owing to the short horizontal distance of 1–2 km between the water divide and the Hula base level. The escarpment is dissected by 31 short, steep, straight and parallel slope channels, mostly of first and second order, that developed at recurring distances of 300–500 m perpendicular to the Hula valley. The incised channels dissipate and disappear adjacent to the base level, where young sediments are deposited at the channel mouths. The climate is continental Mediterranean, with two seasons: cold-wet winters and hot-dry summers. The average annual precipitation varies between 550 mm and 850 mm, depending mainly on the altitude.

2.2. Geological settings

The Naftali ridge is an N–S-trending half-anticline, bordering the Hula valley. Its eastern flank was cut since the Pliocene by major faults and is buried deep in the valley. A series of geological mapping projects have been carried out in the region, and provide detailed maps and sections (Dubertret, 1952; Picard, 1956; Vroman, 1958; Rosenberg, 1960; Picard, 1963; Glikson, 1966a,b; Flexer, 1968; Gerson, 1970; Kafri, 1991; Sneh and Weinberger, 2003). The exposed lithology includes soft and hard carbonate rocks, deposited from the lower Cretaceous up to the Neogene: ① Neocomian–Barremian soft
sandstone and marls; ② Lower to Middle Cretaceous (Albian and Aptian) marl and limestone; ③ Mid-Cretaceous limestone, chert and dolomite; ④ Senonian to Paleocene chert, chalk and marls; ⑤ Eocene limestone and chalk; ⑥ Neogene lacustrine conglomerate and freshwater chalks, which are exposed in the Qiryat Shemona and south, according to their location in each segment (Fig. 3).

Along the mountain piedmont, undifferentiated colluvial–alluvial deposits have been mapped with various geological definitions, such as “Slope fans” (Vroman, 1958), “Landslides” (Picard, 1956; Kafri, 1991), and “Tectonic breccia” (Rosenberg, 1960). Horowitz (1973) suggested that this complex of sediments was of Pliocene age, and Bar and Harash (1983) defined them as “alluvial fans” and patches of “pediment”. Sneh and Weinberger (2003), who conducted detailed geological mapping, identified a well-cemented, polymictic conglomerate – the “En–Awwazim Conglomerate” – of Plio–Pleistocene times, as well as an overlying basalt bed, the En Awwazim basalt.

### Table 1

<table>
<thead>
<tr>
<th>Segment</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Field estimate of strength</th>
<th>Schmidt hardness (Type L – hammer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5</td>
<td>&gt;250</td>
<td>Rock material only</td>
<td>50–60</td>
</tr>
<tr>
<td>Extremely strong</td>
<td></td>
<td>chipped under repeated hammer blows</td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>100–250</td>
<td>Requires many blows of a geological hammer to break intact rock specimens</td>
<td>40–50</td>
</tr>
<tr>
<td>Very strong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>50–100</td>
<td>Hand held specimens</td>
<td>30–40</td>
</tr>
<tr>
<td>Strong</td>
<td></td>
<td>broken by a single blow of a geological hammer</td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>25–50</td>
<td>Firm blow with geological pick indents rock to 5 mm, knife just scrapes surface</td>
<td>15–30</td>
</tr>
<tr>
<td>Medium strong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>5–25</td>
<td>Knife cuts material but too hard to shape into triaxial specimens</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Weak</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R0</td>
<td>1–5</td>
<td>Material crumbles under firm blows of geological pick, can be scraped with knife</td>
<td></td>
</tr>
<tr>
<td>Very weak</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely weak</td>
<td></td>
<td>Indented by thumbnail</td>
<td></td>
</tr>
</tbody>
</table>

3.1. Geomorphological field methods and mapping

Detailed geomorphological mapping along the mountain front was carried out at a scale of 1:5000. The sedimentological and pedological characteristics of the fan-like sedimentary units found at the channel mouths were documented, using conventional nomenclature (Machette, 1985; Dackorne and Gardiner, 1987; Birkeland et al., 1991).

In order to evaluate the strength of the various lithologies in the study area, the ‘unconformed (or uniaxial) compressive strength’ (UCS) of rocks was used. The field test was defined by five terms of strength, related to the rock characteristics (www.mininglife.com) (Table 1).

At each slope channel, field relationships were established, using contacts and properties of the sedimentary units. Each unit was characterized by its general morphology, geometry, sedimentology and soil development, and was dated by either OSL, K–Ar or archaeology. The type section was described and differentiated in slope channel D0, in which most of the units were best preserved.

### Table 2

<table>
<thead>
<tr>
<th>SEGMENT</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels (1)</td>
<td>3</td>
<td>7</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Segment area (m²) (2)</td>
<td>6.7</td>
<td>6.8</td>
<td>10.6</td>
<td>7.4</td>
</tr>
<tr>
<td>Segment length (km) (N–S direction) (2)</td>
<td>2.7</td>
<td>2.3</td>
<td>5.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Avg. drainage basin area (km²) (2)</td>
<td>1.99</td>
<td>0.4</td>
<td>0.54</td>
<td>0.66</td>
</tr>
<tr>
<td>Avg. drainage basin perimeter (km) (2)</td>
<td>6.73</td>
<td>2.98</td>
<td>4.25</td>
<td>4.11</td>
</tr>
<tr>
<td>Avg. max. drainage basin length (km) (2)</td>
<td>2.68</td>
<td>1.13</td>
<td>1.78</td>
<td>1.69</td>
</tr>
<tr>
<td>Avg. max. watershed width (km) (2)</td>
<td>0.78</td>
<td>0.41</td>
<td>0.33</td>
<td>0.41</td>
</tr>
<tr>
<td>Avg. channel length (km) (2)</td>
<td>2.8</td>
<td>0.77</td>
<td>1.67</td>
<td>1.42</td>
</tr>
<tr>
<td>Avg. first order streams (3) (2)</td>
<td>3.7</td>
<td>1.4</td>
<td>2.08</td>
<td>2.0</td>
</tr>
<tr>
<td>Avg. channel gradient (2)</td>
<td>18</td>
<td>26</td>
<td>38</td>
<td>27</td>
</tr>
<tr>
<td>Avg. planimetric index (R0) (4)</td>
<td>3.67</td>
<td>3.68</td>
<td>5.81</td>
<td>4.17</td>
</tr>
<tr>
<td>Avg. elongation ratio (Re) (4)</td>
<td>0.58</td>
<td>0.65</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>Channelized area (%) (5)</td>
<td>89</td>
<td>85</td>
<td>62</td>
<td>72</td>
</tr>
<tr>
<td>Facets area (%) (5)</td>
<td>11</td>
<td>15</td>
<td>38</td>
<td>28</td>
</tr>
<tr>
<td>Simplicity Index (Simp) of the piedmont (6)</td>
<td>2.09</td>
<td>1.24</td>
<td>1.06</td>
<td>1.05</td>
</tr>
<tr>
<td>Simplicity Index (Swd) of the regional water divide (7)</td>
<td>1.16</td>
<td>1.25</td>
<td>1.07</td>
<td>1.10</td>
</tr>
<tr>
<td>Relative qualitative tectonic activity (8)</td>
<td>▲ ▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
</tr>
</tbody>
</table>

* Morphometric parameters developed to quantify description of landscape (Keller and Pinter, 2002).
** Morphometric parameters developed as a basic reconnaissance tools to identify areas experiencing rapid tectonic deformation (Bull and McFadden, 1977; Ramirez-Herrera, 1998; Keller and Pinter, 2002).

(1) Excluding Nahal Margaliyot – between segments B and C.
(2) Basic morphometric parameters, provide a basic perspective referring to the channel’s nature, elucidating the differences between the segments.
(3) Planimetric basin shape is described by an elongation ratio that can be expressed as Bs/Bw. (Bs is the length of the basin measured from its mouth to the most distant drainage divide and Bw is the width of the basin.) Streams developed under an active tectonic regime show elongated drainage basins, which are apparently dominated by downcutting in response to local base-level subsidence (Ramirez-Herrera, 1998).
(4) Elongation ratio. The typical basin shape which develops in a tectonically active mountain range is elongate. The shape of the basin becomes progressively more circular with time after cessation of mountain uplift. The elongation ratio (Re) may be described as the relation between the diameter of a circle with the same area as the basin, to the distance between the two most distant points in basin (Cannon, 1976).
(5) Facets. A facet is a triangular to polygonal shaped hillside situated between two adjacent basins within a given escarpment. Tectonically active mountain fronts tend to be less dissected, ranging from laterally continuous undissected escarpments to a nearly continuous front with only few large and distinct facets with minimal internal dissection (Wells et al., 1988). Facet formation is clearly associated with periods of active fault displacement (Hamblin, 1976; Wallace, 1978) In this study we used the relative area of facets in each segment as an indicator of incision rate.
(6) Mountain front sinuosity (Smf) is the ratio of the length along the edge of the mountain–piedmont junction (Lmf) to the overall length of the mountain front (Ls); Smf=Lmf/Ls (Bull and McFadden, 1977). A straight mountain front might be indicative of an active fault, while an embayed, pedimented front is considered to be representative of tectonic quiescence.
(7) Water divide sinuosity (Swd) is the ratio of the length along the main water divide of each segment (Lwd) to the overall length of the ridge crest (Lrc); Swd=Lwd/Lrc. A straight crest might be indicative of an active ridge. (8) Relative qualitative weight of the various tectonic parameters; ranks I–IV. [I=the most active].

3. Methods

The study area was divided into four segments, based on topographic criteria of the drainage basins, such as drainage basin size and shape, channel length, gradient, stream order, orientation and topographical relief. The segments were labeled A to D from north to south, and the drainage basins in each segment were also numbered from north to south, according to their location in each segment (Fig. 3).
3.2. Geometrical analysis of landforms

The specific morphometric parameters used in this paper have been developed in previous works as basic tools to identify areas experiencing rapid tectonic deformation, or to quantify description of landscape (Table 2). Parameters representing the mountain front geometry (sinuosity index of the piedmont and of the water divide, slope cross-profiles and facets percentage) were assessed, together with morphometric indices indicative of tectonic activity (planimetric index, elongation ratio, hypsometric curve, hypsometric integral, and the longitudinal profiles of the channels) (Hamblin, 1976; Cannon, 1976; Bull and McFadden, 1977; Wallace, 1978; Ramirez-Herrera, 1998). (For detailed explanations of the various indices, see captions in Table 2.) Geographical and morphological data were obtained from compiling a digital orthophoto map at a resolution of 1.3 m/pixel and a digital elevation contour map, scaling 1:5000–1:50 000, with intervals of 5±2 m.

3.3. Optical and radiometric dating

Both OSL and K–Ar dating were processed in the laboratories of the Geological Survey of Israel (GSI). Five samples of fine sediment derived from the matrix of the sedimentary units were dated by OSL and operated on quartz grains. The age calculations followed Murray and Wintle (2000).

Basalt gravels were found incorporated into the well-cemented conglomerate Q1–1. Five samples (cobble size) were dated by the K–Ar method. The gravels were fresh, hard and compacted. The age calculation followed Steinitz et al. (1983) and Kotlarsky et al. (1992).

4. Geometrical analysis

4.1. Morphometry and characteristics of the various segments

All parameters used for the morphometric analysis are presented in Table 2. The channels of SEGMENT A (A1–A3 in Fig. 3) are cut into hard carbonate rocks of the Upper Cretaceous and Eocene. Flow directions toward the northeast, as well as various morphological aspects, are exceptional compared to other segments: drainage basin sizes are 3–4 times larger, channel gradients are less steep, the number of first-order streams is considerably higher, most of the area is drained by channels (89%), and only 11% is drained by facets. The elongated shape of the basins is characteristic of the study area, despite their relatively large size and relatively moderate channel gradients. The segment is characterized by high piedmont sinuosity (Smf = 2.09), and its relative...
qualitative tectonic activity ranks IV (out of 4 segments), indicating the lowest tectonic activity in the study area.

Most of the area of SEGMENT B (85%) is drained by seven small basins to the southeast. The channels are slightly incised into the underlying Neogene indurated conglomerates. The Nahal Margaliyyot basin borders the southern edge of Segment B (Fig. 3) and is not included in any of the segments, since it is essentially different from all other streams because of a different tectonic and geomorphic setting. The segment is characterized by less elongated basins, but a straight mountain front (Smf = 1.24). The total activity of Segment B is ranked III.

In SEGMENT C, the regional water divide rises up to 880 m, exposing the soft Lower Cretaceous units and the hard Cenomanian dolostones. This area is structurally uplifted northward by a series of E–W trending faults that determine the altitude of the highest part of the water divide. Thirteen drainage basins dissect the slopes, some of which have wide, well-incised channels upstream and funnel-shape outlets slightly cut into the colluvium that covers the mountain piedmont (Fig. 4). Therefore, the water divides downstream are adjacent to the active channel (less than 50 m), indicating young and continuous incision into the unstable slope (Shtober-Zisu et al., 2003). The segment is characterized by very low mountain-front sinuosity (Smf = 1.06), a very steep stream-channel gradient (38% on average, with a maximum of 45%), and an average planimetric index (Bv = 5.81) that is the highest in the study area. Only 62% of the area is drained by streams, whilst 38% is composed of facets, supporting the straight mountain front (Smf = 1.24). The total activity of Segment B is ranked III.

In SEGMENT D, the regional water divide rises rapidly from 400 m in the south to 740 m, following a NNE normal fault system. A second normal marginal fault system creates a long N–S tectonic valley and steps, which are exceptional in the study area (e.g., “Yesha faults” across channel D4). The segment is incised by eight short channels cut into the exposed Cenomanian dolostones. Most of the area (72%) is channelized, flowing eastward with gradients of 21–30%, and expressing high similarities with Segment C’s upper reaches. The segment is characterized by a very straight mountain front (Smf = 1.05). Its general tectonic activity was ranked II.

4.2. Topographical analysis of the piedmont and the water divide

Topographical analysis of the piedmont and the main water divide (Fig. 5) elucidates the differences in morphology among the four segments. Along Segments C and D, the piedmont is relatively straight and low (80–120 m). The alluvial fans along Segment D are prominent, whereas the Segment C piedmont is covered by colluvium down to the level of the Hula valley. The Qiryat Shemona area (Figs. 2 and 3) is characterized by an elevated piedmont because of the existence of a N–S-extending spur of tectonic origin that delimits the distribution of colluvial debris eastward to the Hula valley (Fig. 5).

The water divide rises northward, expressing a morphology of saddles and peaks. The sinuosity index (Swnd) of the regional water divide yielded values of 1.07–1.25, indicating a straight, slightly dissected mountain crest (Table 2) that, together with other morphometric parameters, might be characteristic of a young escarpment. Within the northern area of Segment D, a prominent NNE fault steeply raises the Mizpe Pe’er peak by approximately 200 m. The Margaliyyot valley, located between Segments C and B, is controlled by faulting, and interrupts the northward continuity of the water divide.

The N–S-trending slope profiles (Fig. 5) are indicative of the variability within the segments. The channels of Segment D are well incised at elevations of 200–300 m, creating alluvial fans near the base level. In Segment C, the slope-channels are well developed upstream at an elevation of 500–700 m, but poorly dissected in the middle, and they almost disappear at the lower reaches where they cut through the Lower Cretaceous soft units and the colluvium. Debris deposits and landslides cover the piedmont, thus restraining further incision and development of the valleys downstream (Fig. 4).
Segments C and D are dissected by a series of E–W-trending faults. These secondary faults show no evidence of steps or other associated neotectonic features, and thus are assumed to be inactive at present.

4.3. Longitudinal profiles of the channels

The longitudinal profiles of the channels are clearly associated with the lithology. In Fig. 6, four representative slope-channel profiles (of 31 studied) demonstrate the relationship among channel morphology, young faults and rock resistance. Each of these profiles represents a segment.

Segment A is characterized by long, convoluted profiles. Channel A3 demonstrates the longest, most complex profile, crossing three major faults that determine the location of knickpoints along the channel profiles (Fig. 6a). Accordingly, the gradients are controlled by the resistance of the various lithologies; e.g., the hard dolomitic “Kukam” formation creates steep gradients, clearly visible in all the segments.

The shortest, most homogenous channels occur in Segment B. Channel B3 (Fig. 6b) is cut into well-cemented Neogene conglomerate (Ngk), thus developing a relatively uniform profile. No major faults were observed in this area.

Along Segment C, the profiles adjust to the alternating soft and hard rocks (Klinh, Klr and Klh formations) of the Lower Cretaceous in the mid-reaches, and to the homogenous, resistant carbonate rocks of Upper Cretaceous (Kukam and Kudt formations) in the upper reaches (Fig. 1). The piedmont is covered by abundant colluvium, originating in the soft units exposed above, which fills the lower reaches of the channels by sliding and creeping downslope. These materials confine further incision and development of the channels (see also Fig. 4) and create concave-up profiles downstream (Fig. 6c). The older E–W faulting system at this segment has very little impact on the tectonic setting (Fig. 5). For example, along its upper reaches, channel C2 is developed along a normal fault, but there is no evidence of deeper incision or other associated morphology.

Segment D is characterized by hard lithology in general, over which the channels are cut relatively homogenously. The dominant factors controlling the channel profiles are the presence of two parallel N–S faults (Yesha and En Te’o), perpendicularly cut by the

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Table 3

<table>
<thead>
<tr>
<th>Generation</th>
<th>Unit</th>
<th>Description</th>
<th>Extension at elev.</th>
<th>Age determination and field relationship</th>
<th>Age (BP) Shober-Zisu (2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. (Low–Mid. Pleistocene) Q1,1</td>
<td>Indurated polymictic conglomerate cemented by CaCO3 (80–90%), reddish calcarenite. Unit Q1,1 contains also basalt clasts. (R5)</td>
<td>85–168 (m ASL)</td>
<td>K–Ar dating of basalt cobbles. The conglomerate was deposited post 1.1 Ma: age of the youngest cobbles.</td>
<td>Age of basalt cobbles: 1.1 ± 0.4–1.6 ± 0.0 Ma</td>
<td></td>
</tr>
<tr>
<td>I. (Low–Mid. Pleistocene) Q1</td>
<td>Polymictic conglomerate, contains large clasts up to boulder size of Q1 origin (Fig. 10). Includes calcic paleosols, of stages IV–V. (R3/R4)</td>
<td>80–380 (m ASL)</td>
<td>Q1,1 interfingers with Q1,2. They are similar in matrix color, hardness, rebound and gravel assemblage. Q1,2 underlies Q2.</td>
<td>Age of Q1 and Q1,1: &lt; 1.1 ± 0.4 Ma</td>
<td></td>
</tr>
<tr>
<td>II. (Mid–Pleistocene) Q2</td>
<td>Polymictic conglomerate, contains large clasts up to boulder size of Q1 origin (Fig. 10). Includes calcic paleosols, of stages IV–V. (R3/R4)</td>
<td>80–380 (m ASL)</td>
<td>The OSL age is estimated as a minimal age. The actual age is estimated to be older. Q2 usually overlies or is inserted into Q1,2 (R3/R4).</td>
<td>565 ± 106 Ka</td>
<td></td>
</tr>
<tr>
<td>III. (Upper Pleistocene) Q3</td>
<td>Abundance of fine sediments indicates matrix rich flows. Includes calcic paleosols, of stages I–II. (R2)</td>
<td>100–340 (m ASL)</td>
<td>OSL ages. The unit overlaps units Q2 and Q1.</td>
<td>117 ± 11 Ka</td>
<td></td>
</tr>
<tr>
<td>IV. (Holocene) Q4</td>
<td>Relatively low-angle fluvial deposition. Low degree carbonate soils. (stage I). Unit Q4 is also deposited eastward into the Hula valley, where it interfingers with unit Q3. Unit Q4 is composed of reddish clays derived from the slopes. (R1)</td>
<td>70–80 (m ASL)</td>
<td>OSL and archaeological (Natufian) ages. The unit overlaps Units Q2 and Q1 adjacent to present base level.</td>
<td>5.8 ± 3.0 Ka</td>
<td></td>
</tr>
<tr>
<td>IV. (Holocene) Q5</td>
<td>Unit Q5</td>
<td>70–80 (m ASL)</td>
<td>Archaeological age of Early Bronze age. The unit interfingers with unit Q4.</td>
<td>7.5–9.5 Ka</td>
<td></td>
</tr>
</tbody>
</table>

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At present, the base level is at 75 m ASL.
The Unconfined Compressive Strength Term (R1–R5) — following [www.mininglife.com]).

a Based on field relations and stratigraphy.
b Absolute ages: OSL samples taken from 1.5–2 m below the surface, K–Ar dating of basalt cobbles incorporated.
c Archaeological ages.

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Fig. 7. The hypsometric integral values and curves indicate an important proportion of the drainage basin surfaces located at high altitudes. Four channels are absent, as their profiles are exceptional, and associated with local morphologies. a) Convex-up curves — indicative of young landscapes and high tectonic activity. b) S-shape curves — indicative of young but further developed landscapes. As most of the basin areas are still found above the solid line, the tectonic tendency is apparent.
channels. Characteristic morphologies of steps and shallow tectonic valleys occur along the channel D₄ profile in Fig. 6d.

4.4. Hypsometric curves and integrals

Hypsometric curves of the drainage basins have been used as a tool to assess geomorphological development stages resulting from concurrent tectonic and denudation processes. The integral of these curves (Hypsometric integrals — HI) allows the resulting morphology of a drainage basin to be summarized in a single value (Strahler, 1952; Summerfield, 1991; Ohmori, 1993; Keller and Pinter, 2002; Riquelme et al., 2003). In this study, despite differences among the segment’s morphologies, the common denominator of the landscape is clearly visible from the convex-up-shape tendency of the hypsometric curves and the high values of the hypsometric integrals (Fig. 7). About 40% of the drainage basins are characterized by convex-up hypsometric curves with high HI values (0.54–0.78), reflecting the high altitudes of a significant proportion of their surface; i.e., incised drainage basins (Fig. 7a). Almost 50% are characterized by a nearly S-shape tendency, indicating that a high proportion of their surface is similarly located at high altitudes, whereas the high (0.4–0.71) HI values are characteristic of young landforms (Fig. 7b). No major differences were noted among the various segments.

5. Stratigraphy of the sedimentary units

In this study, the alluvial–colluvial complex along the Naftali mountain front was separated for the first time into four major sedimentary generations and six sedimentary units depending on their detailed morphology, sedimentary characteristics and relative (archaeological) or absolute (OSL, K–Ar) ages (Table 3, Figs. 8 and 9). These units were identified along the channels and mouths of the slope channels of Segments C and D. In Segments A and B, these relics are probably covered by young debris and slope deposits or by Hula valley soils (Shtober-Zisu, 2006).

The outcrops extend along the channels from their mouths up to an elevation of 300 m above base level. All sedimentary units are composed of polymictic conglomerate of angular, poorly sorted...
limestone, dolomite and chert gravel in a reddish clay matrix and cemented by carbonates. Carbonate soils and calcrite horizons up to Stage V (Machette, 1985) have developed into them.

Units Q1 and Q1–1 were dated by K–Ar to the lower Pleistocene (∓1 Ma). Unit Q1–1 also contains basalt clasts dated to 1.1–1.6 Ma; which determine the earliest age of deposition of the units to ∓1.1 Ma. The geometry and spatial distribution is unknown, as only a few relics have been preserved. The relics lie unconformably over the bedrock. The conglomerate, well cemented by carbonates (80%–90%), is similar in hardness to other rocks, such as the underlying dolomite. Unit Q1 is identified with the En–Awwazim conglomerate (Sneh and Weinberger, 2003), and is covered in places by the En Awwazim basalt flow dated to 0.88±0.06 Ma (Harlavan et al., in press).

The middle Pleistocene unit, Q2, overlaps or insets into Units Q1 and Q1–1. The morphology and structure indicate stages of deposition in lobes toward the Hula valley with gradients of 10%–20%. This polymictic conglomerate also contains boulders derived from Unit Q1 (Fig. 10). The soil profile includes three carbonate paleosols of Stages IV–V. The unit was OSL-dated to a minimum age of 565±106 ka (Table 3). Unit Q2 is faulted by the En Te'o fault with a vertical displacement of about 1–2 m (Fig. 11), and probably also by the Western Hula fault. The thickness of Unit Q2 on the downfaulted block is larger than on the uplifted block, indicating several phases of movement.

Unit Q3 overlaps Units Q2 and Q1 (Fig. 12), and was deposited during the upper Pleistocene. The sediments were OSL-dated at two sites to 122±16 ka and 117±11 ka (Table 3). The unit does not reach the base level, hanging some tens of meters above the Hula valley floor. It was deposited in a series of sedimentary pulses with gradients of about 30%, while calcic soils of Stages I–II (Machette, 1985) developed between them. The abundance of fine sediments indicates matrix-rich debris-flows, with a debris-cone morphology. These depositional bodies cover the En Te'o fault (Fig. 13).

Unit Q4 overlaps Units Q3, Q2, and is inset into Unit Q3. It covers the mountain piedmont in a fan-like geometry resembling alluvial fans. Unit Q4 was deposited during the Holocene, and was OSL-dated at two sites to 5.8±0.6 ka and 3.0±0.5 ka, and by Neolithic artifacts to 7.5–9 ka (Table 3). Its structure, sorting, and bedding indicate fluvial deposition. Unit Q4 is deposited within the Hula valley, where it interfingers with Unit Q5. Unit Q5 is composed of reddish clay sediments that originate in the Terra Rosa soils over the carbonate rocky slopes. These
6. Discussion

6.1. Morphometric analysis

Despite the climatic variability and the different geological settings, tectonically active regions all around the world are characterized by typical morphometric characteristics, such as straight mountain fronts and high values of hypsometric integrals, planimetric index, and facet percentage.

A comparison with other studies worldwide shows that the morphometric values obtained in this study are high and typical of the "active tectonic class" proposed by Bull and McFadden (1977) and demonstrated in other studies (Table 4).

Nevertheless, a comparison of the various segments reveals relatively wide differences among the four segments (Table 2). The morphometric values of Segment C are extremely high, and are characteristic of areas with relatively high tectonic activity. The soft sandy and marly units exposed trigger-slope movements of debris, which block the channels limit further incision, and cover the marginal faults. This process may explain the funnel-shape geometry of the basins: a shallow, bankless and narrow channel in the lower parts, in contrast to the deeply incised and wide upper reaches.

Segment D is also characterized by relatively high tectonic characteristics similar to Segment C. For example, the sinuosity index ($S_{mf}$), which is considered one of the most significant parameters (Table 4), shows that the values obtained for Segments C and D (1.05–1.06) are very low, indicating relatively high activity. These segments face the Hula depression. In contrast, Segment B (1.24) is considered an intermediate, and Segment A (2.09) the highest, which together with other parameters, indicate slower geomorphic activity — although this may also be related to the different tectonic setting of Segment A.

Most of the hypsometric index values for all segments were higher than 0.5, indicating an active tectonic regime (Keller and Pinter, 2002).

Fig. 12. Unit $Q_3$ overlaps Unit $Q_1$ (Channel C13, elevation 320 m ASL).

Fig. 13. Field relationship between the sedimentary units and the faults at channel D8: Unit $Q_3$ overlaps Unit $Q_2$, and the En Te'o fault. Unit $Q_2$ overlaps $Q_1$ and infills the fault morphology. Note the OSL ages of Units $Q_2$ and $Q_3$ and their locations.
Table 4
Ranges of morphometric parameters, indicative of high tectonic activity (active mountain fronts) with various climate, lithology and tectonic regimes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Study area</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sout siminity of the mountain front</td>
<td>1.0–1.6</td>
<td>Garlock fault, California</td>
<td>Rockwell et al. (1984)</td>
</tr>
<tr>
<td></td>
<td>&lt; 1.4</td>
<td>Ventura anticline, California</td>
<td>Rockwell et al. (1984)</td>
</tr>
<tr>
<td></td>
<td>1.0–1.5</td>
<td>Costa Rica, Mexico</td>
<td>Wels et al. (1988)</td>
</tr>
<tr>
<td></td>
<td>1.06–1.32</td>
<td>Acambay Graben, Jordan</td>
<td>Ramirez-Herrera (1998)</td>
</tr>
<tr>
<td></td>
<td>1.17–1.41</td>
<td>Edom Mt. front, DSIR, Jordan</td>
<td>Sagy (2001)</td>
</tr>
<tr>
<td></td>
<td>~1–2</td>
<td>Oak Ridge anticline, Ventura basin, Ca.</td>
<td>Azor et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>1.17–1.53</td>
<td>Southeast Spain</td>
<td>Silva et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>1.06</td>
<td>Eastern Carmel</td>
<td>Mashiah (2004)</td>
</tr>
<tr>
<td></td>
<td>1.4–1.5</td>
<td>The Sierra Nevada, Mt., California</td>
<td>Figueroa and Knott (2004)</td>
</tr>
<tr>
<td></td>
<td>1.09–1.34</td>
<td>Eliki fault, Corinth gulf, Greece</td>
<td>Verrios et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>1.05–1.24</td>
<td>Present study</td>
<td></td>
</tr>
<tr>
<td>HI hypsometric Integral</td>
<td>0.4–0.78</td>
<td>Oak Ridge anticline, Edom Mt. front, DSIR, Present study</td>
<td>Azor et al. (2002) Sagy (2001)</td>
</tr>
</tbody>
</table>

As the hypsometric values are scale-dependent (Willgoose and Hancock, 1998), the analysis also includes hypsometric curves. The convex-up tendency of about 40% of the drainage basins indicates that the present mountain front has not been significantly lowered since it was formed; and the S-shape tendency found in about 50% of the drainage basins indicates a transitional stage between ‘youth’ and ‘steady state’.

6.2 Stratigraphy of the sedimentary units and tectonics of the marginal faults

The sedimentary units were best preserved in Segment D, as the hard lithologies exposed on the slopes delimit landslides or other associated slope movements under the Mediterranean climate regime.

The oldest Quaternary units exposed along the Naftali Mountain front are units Units Q1 and Q1.3, which were deposited during the Early Pleistocene and were dated to < 1.1 Ma. Their similar characteristics and field relationships indicate that they were deposited in close temporal proximity and under similar conditions. They are both confined to the channels, where they were best preserved. In addition, the outcrops of both units were found adjacent to, and only 10 m above, the Hula valley floor. This indicates that the Hula valley has remained almost at the same base-level elevation along its western border since the end of the Early Pleistocene. Based on the present study, the calculated rate between subsidence and sediment accumulation in the Hula valley is of the order of 0.01 mm/yr. This low rate is consistent with various stages of soil development. The units, composed of polymictic conglomerates, include several paleosols and calcitic soils from the Middle Pleistocene.

The large amounts of fine reddish sediments suggest intensive erosion of soils from the nearby slopes. The last significant faulting phase along the En Te’o fault occurred probably during Mid–Pleistocene, later than ~0.56 Ma, as indicated by the age of Unit Q2. Unit Q2 may also be faulted by the Western Hula fault (Shtober-Zisu, 2006), as is also shown in the map by Sneh and Weinberger (2003). The En Te’o fault was covered by Unit Q3, indicating no major faulting since about 120 ka B.P. This age of faulting calibrates the tectonic activity represented by the morphometric analysis in Segments C and D.

The Holocene Units Q4 and Q5, dated as being less than 10 ka B.P., form a south–north sequence of steep-gradient fans, deposited by fluvial activity. The bedded structure of these units, the reddish clay matrix, and the interbedded calcic soils, indicate phases of stripping of the Terra Rosa soils from the carbonate rocky slopes. These sedimentary units cover the Western Hula fault, and show no evidence of deformation. In addition, the Holocene units converge downstream, pointing at climatic (and not base-level) controlled progression (Gerson, 1982b).

Periods of quiescence between the various episodes of deposition were characterized by karst solution, abundant slope movements, and pedogenic processes that created mainly carbonate soils and calcrite horizons.

In light of all the aforementioned, it appears that since the Mid–Pleistocene, tectonic activity has migrated from the marginal faults located west of the DSR towards younger faults buried deep in the graben. This conclusion is also sustained by Heimann’s findings (1990) that the Hula’s marginal faults were active mainly until 2.2 Ma, and the main subsidence activity has moved eastward to younger faults since then. In addition, Shamir and Feldman (1997) found a cluster of microseismic activity in the central area of the Hula graben between 1980 and 1996, showing that the main location of present seismic activity is concentrated in the middle of the Hula depression.

7. Conclusions

1. All morphometric values are concordant with young tectonism along the entire mountain front (Segments A to D). However, the southern segments (C and D) express the highest values, indicating the highest activity in the study area.

2. Segments C and D are dissected by a series of E–W-trending faults. These secondary faults are apparently inactive at present, based on the absence of steps or other associated neotectonic features.

3. Four generations of deposition were recognized along the mountain piedmont, including six sedimentary units. These units, composed of polymictic conglomerates, include several paleosols with various stages of soil development. The units were dated by OSL, K–Ar or archaeology, and indicate ages from the end of the Early–Pleistocene to the present.

4. The morphology and structure of the sedimentary units show pulses of activity, represented by a chronosequence of periods of deposition and periods of quiescence, during which calcic soils were developed up to Stage V.

5. The bed relationship between the sedimentary units and the marginal faults show that no major faulting phases occurred along the Naftali escarpment during the Upper Pleistocene, despite the active tectonic morphometric values obtained in the study area. The marginal faults were probably active until the end of the Mid–Pleistocene.
6. Since the Mid-Pleistocene, tectonic activity migrated from the marginal faults located west of the DSR toward younger faults buried eastward, deep in the Hula graben.

7. The field data calibrate the morphometric analysis: carbonate hillslopes developed under Mediterranean climate have maintained the "active class" morphology at least since the end of the Mid-Pleistocene and the last major faulting events along the Naftali mountain front.

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References


