Alluvial fan facies of the Qazvin Plain: paleoclimate and tectonic implications during Quaternary

Azam Davoudi, Saeed Khodabakhsh*, Behrouz Rafiei
Bu-Ali Sina University, Faculty of Sciences, Department of Geology, Hamedan, Iran
*Corresponding author, e–mail: skhodabakhsh@Yahoo.com
(received: 14/03/2019 ; accepted: 19/06/2019)

Abstract
The present study provides a detailed facies description and interpretation of five alluvial fans of the Qazvin Plain. In addition to tectonic activities, which lead to the localization of the alluvial fans on the northern margin of the Qazvin Plain, climate also plays a significant role in the occurrence of facies in these fans. The alluvial fans are divided into three facies groups: group 1 (alluvial fan 1), group 2 (alluvial fans 2, 4, and 5), and group 3 (alluvial fan 3). Alluvial fan 1 is dominated by the episodic matrix to clast-supported gravel (interbedded with a subordinate) and red matrix-supported gravel deposited by non-cohesive debris flow. Groups 2 and 3 are characterized by deposits of non-cohesive debris flow, mud-rich debris flows, channelized, non-cohesive debris flows, hyperconcentrated flows, and sheetfloods. The characteristics of alluvial fan 3 include highly disorganized deposits, very poorly sorted gravel, lack of erosional bases, and a wide particle-size range from clay to outsized-boulders. The facies is best interpreted as a result of debris flow following episodic localized tectonic activities of the Kavendaj Fault along with the fan head during the Quaternary Period. Relatively insignificant changes in the sedimentary facies of the studied fans from debris flows to sheetfloods during the accumulation of the three groups are attributed to a slight variation of climatic conditions, source rocks, and tectonic activities. Therefore, the debris flow-dominated fans of the Qazvin Plain recorded an arid to semi-arid paleoclimate characterized by the generation of non-cohesive debris flow and calcrete in the fans.

Keywords: Alluvial Fan, Debris Flow, Sheetflood, Paleoclimate, Quaternary Period.

Introduction
Alluvial fans are among the most important records for tracking climate changes in paleo-environments, hinterland tectonics, and sea/lake levels (Gawthorpe & Leeder, 2000; Bose et al., 2012; Chen et al., 2016). Climate, tectonic, and hinterland lithology highly affect the grain size and volume of sediments transported into the alluvial fans (Chakraborty & Paul, 2013). Studying these controls on alluvial fan facies without considering their effects is a difficult task to accomplish (Nichols & Thompson, 2005). In this regard, the classification of alluvial fans by Blair & McPherson’s (1994) based on combining the involved processes reinforces the traditional hypothesis of ‘dry fans and wet fans’ (Schumm, 1977) associated with arid and humid climates, respectively. However, the validity of climate-response hypothesis remains still in debate (i.e., Harvey et al., 2005; Blair & McPherson, 2009; Harvey, 2012). In addition, previous literature has revealed that a more humid climate leads to a larger number of flood events and also more mud fraction, as a result of the increased vegetation and chemical weathering (Blum & Tornqvist, 2000). Under this humid condition, debris-flow activity on the fans is intensified whereas climatic aridification increases the fluvial activity on fans (Chen et al., 2016). Moreover, climatic changes control the nature of fan deposits under arid or semi-arid conditions (Frostick & Reid, 1989). Fine sediments are deposited under warmer and drier conditions, whereas high flood discharge and sediment under wet and cool conditions lead to a high deposition rate of coarse sediments (Koltermann & Gorelick, 1992). The main objective of this study is to investigate the Quaternary alluvial fans in the NE margin of the Qazvin Plain. In the study area, the uplift and the climatic fluctuation during the Quaternary had profound control on geomorphic, sedimentary, and pedogenic processes. In this paper, primary depositional processes and secondary (in situ) carbonate deposition in modern alluvial fans are discussed. The results are therefore applicable for other fans deposited in similar settings. To the best of our knowledge, no previous research has been conducted on sedimentological and paleoenvironmental characteristics of these fans. Overall, the purposes of this study are 1) to describe and interpret the sedimentary facies and internal structures of the Quaternary deposits of alluvial fan systems and 2) to discuss the role of climate, tectonics, and lithology on the sedimentary facies.

Geological setting
Iran is located in the middle part of the active
Alpine-Himalayan orogenic belt. This country has been deformed due to the convergence of the Arabian plate to South Asia (Allen et al., 2003; Copley & Jackson, 2006). The Qazvin Plain, located adjacent to the Central Alborz Range in northern Iran, is a structural plain (graben) formed because of the activity of the north Qazvin and Ipak faults. This plain is filled by aggradation of various sedimentary processes such as alluvial fans, fluvial systems, playas, and aeolian deposits (Berberian et al., 1993). Rieben (1966) classified the alluvial sediments of the Qazvin Plain margins into four lithological units: Alluvial A, B, C, and D (from base to top, in the order of their appearance). The sediments of this plain are mainly composed of conglomerates, sandstones, and mudstones with local evaporate and calcrete deposits (mainly occurred as powdery, chalky, nodular, massive, and laminar). The sediments thickness of the central part of the plain is up to 350 m (Berberian et al., 1993); however, there is limited geophysical data about the plain basement depth. The only evidence on the plain basement is the outcrop of the Karaj Formation (Eocene) in the north and south of the Qazvin area (Berberian et al., 1993). This formation is comprised of a relatively thick sequence of well-stratified green tuffs, sedimentary rocks, and volcanic lava and rare evaporative rocks (Annells et al., 1975). Most alluvial fans of the region are located along the northern margin of the Qazvin Plain (Fig. 1). They occur adjacent to the compressive faults of the north Qazvin, two of which (i.e., the Qazvin North and Kavendaj faults) being recently seismically active (Berberian et al., 1993). Based on their dominant catchment lithology, these fans may be divided into two groups: 1) well-stratified carbonate rocks and fine-grained clastic sediments (mainly mudstone and siltstone) and 2) volcaniclastic rocks (i.e., green tuff) associated with other clastic sedimentary rocks (e.g., conglomerate, sandstone, and mudstone) (Annells et al., 1975). The first group is seen in the Fan 1 catchment and the latter mainly makes up catchment of the other fans. The study area has an arid to a semi-arid climate with an average annual temperature of 12 to 14°C and annual precipitation of 220 mm (Meteorological Organization of Iran, 2011).

Material and Methods
Five alluvial fans existing along 42.56 km north of the plain were studied (Fig. 1).
The characteristics of representative profiles including sedimentary structures, texture, bed geometries, and lithology were used to describe fan facies. In addition, paleocurrent directions were depicted using azimuth measurements of imbricated pebbles. Facies were described following Miall’s (2006) code system. For this purpose, a total of 355 measurements were used for the reconstruction of paleocurrent directions. Maximum clast size (No. 251) and composition were investigated to obtain information about paleocurrent directions and sediment provenance, respectively. Mineralogical composition of representative bulk and oriented samples was investigated by X-ray diffraction (XRD) in Bu-Ali Sina University, Iran (Italstructures, 40 Kv, CuKa 30mA). Also, scanning electron microscopy (SEM) was performed on the representative samples at the Bimgoster Laboratory, Iran (Mira3-TESKAN Scanning Electron Microscope, 20KV). Moreover, X-ray fluorescence analysis (XRF) of 10 non-calcareous samples (Table 1) was carried out to assess CIA (Chemical Index of Alteration; Nesbitt & Young, 1982) and CIW (Chemical Index of Weathering; Harnois, 1988).

**Facies characteristics**
Gravelly facies in this study area made up of more than 85% of the studied profiles. In some horizons, they are slightly consolidated and therefore may be considered as conglomerates. Sand and mud are subordinate facies. Generally, a distinct downward fining trend (toward the fan toe) is observed. All the studied sediments are red. Their common characteristics are basal non-erosional surfaces, mud cracks, and local/discontinuous calcrete horizons. A total of 8 gravel/conglomerate lithofacies, a sand lithofacies, and 3 types of calcrete facies were identified (Table 2).

**Facies A: Massive to crudely stratified matrix-supported gravel (Gmm)**
This facies consists of matrix-supported gravel. It displays planner beds with a thickness of a few decimeters to ∼4 m. The beds are locally stratified and their lateral continuity varies from a few meters to tens of meters along profiles (Fig. 2).

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>SiO2 (%)</th>
<th>Al2O3 (%)</th>
<th>Fe2O3 (%)</th>
<th>TiO2 (%)</th>
<th>CaO (%)</th>
<th>MgO (%)</th>
<th>Na2O (%)</th>
<th>K2O (%)</th>
<th>P2O5 (%)</th>
<th>MnO (%)</th>
<th>LOI (%)</th>
<th>BaO (%)</th>
<th>SrO (%)</th>
<th>CIA</th>
<th>CIW</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 -1</td>
<td>47.30</td>
<td>6.91</td>
<td>2.91</td>
<td>0.36</td>
<td>9.27</td>
<td>3.16</td>
<td>0.33</td>
<td>1.09</td>
<td>0.11</td>
<td>0.09</td>
<td>28.28</td>
<td>0.12</td>
<td>0.05</td>
<td>39.27</td>
<td>41.85</td>
</tr>
<tr>
<td>F1 -2 (mf)</td>
<td>55.50</td>
<td>8.42</td>
<td>5.83</td>
<td>0.59</td>
<td>6.08</td>
<td>2.89</td>
<td>0.63</td>
<td>1.99</td>
<td>0.16</td>
<td>0.15</td>
<td>20.96</td>
<td>0.04</td>
<td>0.05</td>
<td>49.16</td>
<td>55.63</td>
</tr>
<tr>
<td>F1 -3</td>
<td>45.52</td>
<td>6.58</td>
<td>3.81</td>
<td>0.23</td>
<td>5.86</td>
<td>7.16</td>
<td>0.98</td>
<td>1.37</td>
<td>0.09</td>
<td>0.18</td>
<td>27.98</td>
<td>0.19</td>
<td>0.05</td>
<td>44.48</td>
<td>49.03</td>
</tr>
<tr>
<td>F2 -1</td>
<td>45.47</td>
<td>13.59</td>
<td>6.26</td>
<td>0.63</td>
<td>10.79</td>
<td>2.28</td>
<td>1.16</td>
<td>1.90</td>
<td>0.26</td>
<td>0.08</td>
<td>17.42</td>
<td>0.10</td>
<td>0.06</td>
<td>49.53</td>
<td>53.21</td>
</tr>
<tr>
<td>F4 -1</td>
<td>47.39</td>
<td>6.92</td>
<td>3.87</td>
<td>0.36</td>
<td>9.45</td>
<td>1.64</td>
<td>0.62</td>
<td>1.09</td>
<td>0.27</td>
<td>0.07</td>
<td>28.19</td>
<td>0.06</td>
<td>0.05</td>
<td>38.29</td>
<td>40.74</td>
</tr>
<tr>
<td>F4 -2</td>
<td>58.96</td>
<td>15.15</td>
<td>3.53</td>
<td>0.68</td>
<td>6.73</td>
<td>1.32</td>
<td>1.50</td>
<td>1.25</td>
<td>0.53</td>
<td>0.08</td>
<td>10.16</td>
<td>0.04</td>
<td>0.06</td>
<td>61.51</td>
<td>64.80</td>
</tr>
<tr>
<td>F5 -1</td>
<td>32.40</td>
<td>11.81</td>
<td>11.77</td>
<td>0.66</td>
<td>7.31</td>
<td>5.57</td>
<td>2.61</td>
<td>1.19</td>
<td>1.43</td>
<td>0.06</td>
<td>25.08</td>
<td>0.04</td>
<td>0.05</td>
<td>51.53</td>
<td>54.35</td>
</tr>
<tr>
<td>F3 -1</td>
<td>39.38</td>
<td>8.92</td>
<td>5.81</td>
<td>0.35</td>
<td>8.47</td>
<td>5.88</td>
<td>0.59</td>
<td>2.08</td>
<td>0.14</td>
<td>0.07</td>
<td>28.18</td>
<td>0.06</td>
<td>0.05</td>
<td>44.48</td>
<td>49.62</td>
</tr>
<tr>
<td>F3 -2</td>
<td>52.28</td>
<td>6.83</td>
<td>3.87</td>
<td>0.31</td>
<td>7.37</td>
<td>2.24</td>
<td>0.65</td>
<td>1.08</td>
<td>0.12</td>
<td>0.11</td>
<td>24.98</td>
<td>0.10</td>
<td>0.04</td>
<td>42.89</td>
<td>46.00</td>
</tr>
<tr>
<td>F3 -3</td>
<td>50.21</td>
<td>9.97</td>
<td>5.85</td>
<td>1.38</td>
<td>8.65</td>
<td>1.64</td>
<td>0.62</td>
<td>1.12</td>
<td>0.15</td>
<td>0.09</td>
<td>20.19</td>
<td>0.06</td>
<td>0.05</td>
<td>49.03</td>
<td>51.88</td>
</tr>
</tbody>
</table>
Table 2. Facies of the alluvial fans of The Qazvin Plain.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sedimentary structures</th>
<th>Bed geometry and thickness</th>
<th>Depositional process</th>
<th>The occurrence in alluvial fans</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Massive to crudely stratified; matrix- to clast-supported gravel (Gmm)</td>
<td>Poorly sorted, matrix- to clast-supported, clast alignment, vague imbrication. Massive to crudely stratified. Lack of cross-stratification and erosional bases. Outsized clasts (Fig. 2).</td>
<td>Tabular; 90-400 cm</td>
<td>It was deposited by non-cohesive debris flow (Schulz, 1984; Miall 2006; Blair &amp; McPherson, 2009).</td>
<td>All fans</td>
</tr>
<tr>
<td>B. Matrix-supported disorganized bouldery gravel (Gmm)</td>
<td>Very poorly sorted and disorganized, matrix-supported. Abundant outsized sub-angular to sub-rounded clasts. Absence of erosive bases (Fig. 3).</td>
<td>Tabular to wedge-shaped; 60-170 cm</td>
<td>Deposits of sediment-gravity flow resulting from flash flood events or rock avalanche (Blair, 1999; Moscarello 2017) following episodic tectonic activity such as the fault reactivation.</td>
<td>Fan 3</td>
</tr>
<tr>
<td>C. Rhythmic gravelly and sandy planar couplets (Gcm and Gmm/Sm)</td>
<td>Matrix- to clast-supported couplets dominantly from rhythmically cobbly pebble gravel interbedded with pebbly sand and/or matrix supported gravel. With the same thickness and textures. Coarse clasts are generally oriented parallel to sub-parallel to the bed surface. Non-erosive and sharp contact between alternating beds. Occasionally associated with backset-beds (or antidune cross-bedding), HCS-like or HCS-mimics and normal grading structures (Fig. 4).</td>
<td>Tabular; 70-260 cm</td>
<td>Deposits of sediment-charged upper flow regime resulting from rapid drainage of a large volume of water from the catchment after heavy rainfall (Muti et al., 1996; Galloway et al., 1996; Blair 1999).</td>
<td>All fans</td>
</tr>
<tr>
<td>D. Graded clast-supported gravel (Gmg)</td>
<td>Poorly to moderately sorted, clast- to matrix-supported, and sub-angular clasts, erosional basal surface and a floor of coarse imbricated clasts. Clast imbrication. Normal grading (Figs. 4a and d).</td>
<td>Lenticular to channel-shaped; 50-200 cm</td>
<td>Channel infilling by lags and bars (Miall, 2006).</td>
<td>All fans</td>
</tr>
<tr>
<td>E. Crudely, planar, cross-bedded cobbly pebble gravel (Gp)</td>
<td>Poorly sorted, matrix- supported, crudely fining-upwards, planar cross-bedding. Erosional to non-erosional bases (Fig. 5).</td>
<td>Tabular to lenticular; 140-150 cm</td>
<td>Deposits of a) foreset cycles as a result of the downstream migration of bedforms typical of mid-channel or longitudinal bars (Nemec &amp; Postma 1982; Ghinassi &amp; Ielpi, 2016), b) hyperconcentrated flashy streams in braided channels, or C) vertically stacked debris flows (Miall, 2006).</td>
<td>All fans</td>
</tr>
<tr>
<td>F. Massive to crudely stratified clast-supported gravel (Gcm)</td>
<td>F1. Poorly to moderately sorted and clast-supported. Sharp and non-erosional bases. Ungraded or crudely stratified and inverse grading (Figs. 6a and b).</td>
<td>Tabular to wedge-shaped; 50-250 cm</td>
<td>Deposition of pseudoplastic cohesionless debris flow (or turbulent flow) (Miall, 2006).</td>
<td>All fans</td>
</tr>
<tr>
<td></td>
<td>F2. Poorly sorted and clast-supported. Well imbricated, sub-angular to sub-rounded clasts. Inverse grading. Wide range of clast size (Figs. 6c and d).</td>
<td>Lenticular; Up to 150 cm</td>
<td>Channelized hyperconcentrated flow (Miall, 2006).</td>
<td>All fans</td>
</tr>
<tr>
<td></td>
<td>F3. Concentrated pebbles. Clast-supported and well sorted. Sharp bases. Ungraded to local coarse tail. Bimodal texture (Figs. 6e and f).</td>
<td>Lenticular; 110 cm</td>
<td>Sieve deposits as a result of removal of fine sediments from the coarse fraction by sheetflood or overland flow winnowing (Hooke, 1967; Bull, 1972; Blair, 1999a; Blair &amp; McPherson, 2009)</td>
<td>All fans</td>
</tr>
<tr>
<td>G. Trough cross-bedded gravel (Gt)</td>
<td>Poorly sorted, well organized, matrix- to clast-supported, trough cross-bedding. Ungraded or normal grading. Erosional basal contact (Figs. 7a and b).</td>
<td>Lenticular to channel–shaped; 30-70 cm</td>
<td>Deposits of migrating bedforms within scours and/or channels formed at high flood-stage (Miall 2006).</td>
<td>Fan 5</td>
</tr>
<tr>
<td>H. Structureless mucky (pebbly) sandstone (Sm)</td>
<td>Moderately sorted medium to coarse gravelly sands with dispersed granules and pebbles, internally massive. Non-erosive basal contact with local scouring (Fig. 7c).</td>
<td>Tabular; 20-220 cm</td>
<td>Deposits of sediment-gravity flow within the distal areas of the alluvial fans (Miall, 2006).</td>
<td>All fans</td>
</tr>
<tr>
<td>I. Calcrete (P)</td>
<td>Authigenic carbonate, with various macro- and micro-morphology features (Figs. 8 and 9).</td>
<td>Powdery to massive; 50-200 cm</td>
<td>Secondary carbonate accumulation</td>
<td>Fan 1, 2 and 5</td>
</tr>
</tbody>
</table>
Figure 2. Sediment profile and photographs of facies A. a-b) matrix- to clast-supported gravel (Gmm) and interbedded, lenticular, red-colored, matrix-supported gravels or mudflows (mf). c) Close-up photos of Gmm and mf facies. d) Lenticular, cobble-gravel channel bodies. The inset map shows the location of the profile in the fan surface.

Interpretation

The facies exhibit typical features of debris flow deposits (Bull, 1972; Nemec & Steel, 1984; Schultz, 1984, Blair, 1999b; Blair & McPherson, 2009) characterized by episodic deposition (Mather, 2016). The prominent matrix-supported character and random orientation of clasts indicate the matrix buoyancy as the dominant transportation and depositional processes in which clasts were unable to move freely (Walker, 1975). During such flows, the outsized boulders are supported by the mechanical strength of the matrix due to a high sediment concentration of fluid (Rodine & Johnson, 1976). Moreover, the rare erosive bases, vague imbrication, and clast alignment are indicators of laminar flow with shear strength caused by low water concentration and high matrix strength rather than normal traction currents (Sohn et al., 1999).

Local stratified clasts in this facies are formed as a result of clast-alignment parallel to their long axes (Turkmen et al., 2007). In addition, the gradational base of the mud-rich flows that overlie the debris-flow deposits proposes a possible link between the two depositional processes. The former is
interpreted as a waning (dilute) cap of the underlying debris flow (Went, 2005). This cap forms in the final depositional stages of debris flows, in which a watery mud with scarce clasts develops (Blair & MacPherson, 1998). Losing boulders by getting farther from the apex of the alluvial fan causes boulder-deficient center and lower parts of the debris flow to continue downslope, where it is accumulated as a clast-rich lobe. Then, a clast-poor lobe stage occurs as a result of the more dilute tail of debris flow, capping the downslope ends of the clast-rich lobes on the low-gradient distal domain (Blair & McPherson, 2009). The red color of this facies reflects subaerial oxidation condition (Walker, 1967). Poorly developed thin pebbly layers are formed as weakly defined armors above and below mud lenses (Lindsey et al., 2005).

The cobble-rich lenses with an erosive base are formed through the winnowing, scouring, and armoring the host deposits by local runoff events (Blair & McPherson, 1998; Blair, 1999a), giving rise to local lag concentration. Their limited thickness is due to the low power of surface runoffs and also the self-limiting nature of the armoring process (e.g., Parker & Sutherland, 1990; Kleinhans & van Rijn, 2002; De Haas et al., 2014). The discontinuity of this lens-shape deposit within and/or on debris-flow beds is as a result of the spatially fractionated distribution of surface runoffs over the fan surface (De Haas et al., 2014) and highly variable discharge near the mountain front (Lindsey et al., 2014).

**Facies B: Matrix supported disorganized bouldery gravel (Gmm)**

The main characteristics of this facies are abundant outsized boulders, variability in size and composition, a very poorly sorted matrix (ranging from clay to pebbles), and a non-erosive base (Fig. 3). The maximum clast size range is from 0.3 to 1.3 m (Av= 0.45 cm). The geometry of the layers is tabular - to wedge-like. This facies occurs only in fan 3 and constitutes 40% of its area. This facies is alternated with wedge-shape clast-supported gravels. The latter facies has eroded the lower matrix-supported facies (Fig. 3a), and all parts of the fan surface (from apex to toe) are covered by a mantle of boulders (Figs. 3c and d).
They display a very poorly sorted massive fabric with local coarse tail inverse grading, vague imbrication, and clast alignment.

Interpretation
Sedimentary features of this facies include very large outsized clast, very poor sorting, sheet- to wedge-like bed geometry, the polymictic composition of clasts, non-erosional bases, local inverse grading, clast alignment, and the lack of cross-bedding. They are often typical of sediment-laden debris flows resulting from flash flood events and/or from rapid waning flows that do not allow reworking and effective sorting of surface deposits (Blair, 1999a; Moscarielo, 2017). This facies occurs only in fan 3, where the Kavendaj Fault has cut the upstream margin of the fan. Some boulders were directly derived from the catchment area, transported and re-deposited by flash floods. Moreover, tabular - to wedge-shaped geometry and alternating with wedge-shaped facies Gcm may suggest that episodic reactivation of the Kavendaj Fault probably played a significant role in the supply of the coarse-grained material to the fan area. The high amounts of the matrix that infiltrated the boulders and cobbles were probably derived from the disintegration of clasts during transportation.

Facies C: Rhythmic planar gravelly and sandy couplets (Gcm and Gmm/Sm)
This facies comprises alternating clast- to matrix-supported gravels. The former consists of cobbly pebble gravel and the latter beds are pebbly sand and/or matrix supported gravel (Fig. 4a). This horizontal to sub-horizontal couplets are common in the alluvial fans 2, 3, 4, and 5. Coarse clasts tend to be sub-angular to angular, poorly to moderately sorted, and generally oriented parallel to subparallel to the bed surface. The contact between alternating beds is often non-erosive and sharp. The field evidence shows that these couplets are associated with a set of diagnostic features such as occasional backset-beds (or antidune cross-bedding) (Fig. 4c), HCS-like or HCS-mimics (Figs. 4e and f) (Rust & Gibling, 1990; Masuda et al., 1993), and normal grading. This set is volumetrically subordinate and is mostly absent in the successions of alluvial fans (Moscarielo, 2017). Cross-lamination in the vertical profile (Fig. 4c), i.e., dipping both upstream and downstream, is a distinct characteristic of the antidune deposits. Antidune cross laminae are relatively low-dip angles and vague and therefore can be detected easily (e.g. Middleton, 1965; Barwis & Hayes, 1985). We found HCS-like sedimentary structures near the top of a 3.9-m-thick sheetflood conglomerate. This unit is characterized by wavy laminae. The bedform wavelengths were 45-120 cm and the amplitudes ranged from 15 to 35 cm. Antidune bedforms have mainly been formed in a wide range of grain sizes from cobble to very fine sand or silt and are graded vertically and laterally into flat, planar laminations.

Interpretation
The rhythmic stacking of the regular couplets arises from the upper-flow regime of supercritical water flow, which is characteristic of sheetflood facies in subaerial conditions (Mutti et al., 1996). Sheetfloods are caused by torrential rainfall directly on the surface of the alluvial fan (Galloway et al., 1996). The high volume of water caused by the heavy rainfalls from the catchment area may lead to fluid -gravity flows and sediment transfer through flash floods from the catchment slopes onto the fan. Therefore, the deposition from such sheetfloods is triggered by the migration and washout of the upper flow regime antidune bedforms beneath trains of standing waves on the fan surface (Alemader & Fielding, 1997; Blair, 1999a). The coarse-grained member of a couplet is deposited during the downslope washout phase of standing wave destruction, in which local high turbulence give rise to the suspension of finer sediments. The fine suspended sediment, following a rapid abatement of turbulence, will then deposit on the coarse couplet laminae with a sharp non-erosional contact (Blair, 2001). This alternation in modern fans is considered as bedload followed by the intermittent suspended load from an intense washout (Blair, 1999a). Alternating bed couplets can be due to debris flows and/or sheetfloods in the distal domain of the fan (Amajor, 1986). Other multi-story sheetflood products such as antidune and wavy laminae are also related to supercritical flow with the autogenic nature of standing waves (or trains of water and sediment waves) (Blair & McPherson, 2009). These waves repeatedly 1) initiate, 2) grow up, 3) migrate upslope, and 4) terminate either by gently re-joining the flood or by 5) breaking and shooting downslope. Backset-beds (Middleton, 1965) structures are developed during the first three of these stages. These units are preserved if the standing wave gently combines with the flow (Blair
Antidune could be used for recognizing the paleocurrent direction, velocities (Middleton, 1965), and high-energy deposits (Slootman et al., 2018) in the geological record. The hummocky cross-stratification (HCS)-like structure is a form of antidune stratification that is caused by maintenance of a stationary state of sheetflood standing waves (Hwang et al., 2016) along with the interface an overlying low-density layer and a denser underflow in upper flow regime (Araya & Masuda, 2001).

**Facies D: Channelized graded clast- to matrix-supported gravel (Gmg)**

This facies consists of channel-shaped depositional units (up to 2 m thick and 12 m wide). The typical characters of this facies are monomictic to polymictic clasts, distinct normal grading, moderately to well sorted, clast-supported gravel, and a floor of coarse imbricated clasts (Figs. 4d and 5a).

---

Figure 4. Sediment profile and photographs of facies C and D. a-b) Rhythmic gravelly and sandy planar couplets (Gcm and Gmm) overlying Gmg facies. c) Close-up view of couplets and cross laminations (antidune), dipping both upstream and downstream. d) Close-up view of Gmg facies. e) General view of the sheetflood couplets with HCS-like structures (wavy laminae) and Gmg facies. f) Close-up photos of wavy laminae.
The upper boundary of the conglomerate units is sharp, which is commonly marked by a sudden transition into overlying facies. In some horizons, drapes of finer sediments occur on a coarser base.

**Interpretation**

Multi-story lensoid to channel-shaped facies are interpreted as incised-channel deposits (scour lags and bars) of the alluvial fan systems, as testified by their geometry and by the erosional nature of their base. Incised channels primarily form as discharge conduits across the fan. Therefore, their sediments mainly consist of an armored channel bed that lies directly on other primary sediments such as debris flows and sheetfloods (Blair & McPherson, 2009). In shallower conditions, muddy deposits on top of channel-fill deposits may be deposited as a consequence of fall-out from waning flow after channel abandonment and avulsion episodes (Bluck, 1980).

**Facies E: Crudely, planar, cross-bedded cobbly-pebble gravel (Gp)**

This facies appears to be found only in fan 4 and oriented transverse to the southeast direction of stream flow (Fig. 5a). These facies are also subordinate among the facies. The cross-beds are planar with decimeter-thick, and dip angles of them vary from 35 to 45°. In addition, the facies shows crudely fining-upward grading cobbles into medium-grained sandy gravel, sub-angular to sub-rounded clasts, and a non-erosional basal contact scoured in places. The northeastward-dipping imbricated clasts are commonly observed in this facies.

**Interpretation**

Traction current in this facies is well evidenced through the occasional presence of imbricated clasts and the crude stratification and the crude upward grading. Upward-finishing inclined strata may be represented in the following forms: a) foreset cycles as a result of the downstream migration of bar forms typical of mid-channel or longitudinal bars (Nemec & Postma, 1982; Ghinassi & Ielpi, 2016), b) hyperconcentrated flashy streams in braided channels, and c) vertically stacked debris flows (Miall, 2006). Upward-finishing grading is proposed to form during channel abandonment or the waning flood stages (Ghinassi & Ielpi, 2016).

**Facies F: Clast-supported gravel (Gcm)**

This facies can be subdivided into three subfacies F1, F2, and F3. Evidence of facies F1 includes polymict clasts, poor sorting, massive to crudely stratified, clast-supported, subangular to subrounded clasts, moderately to well-developed imbrication, non-erosional bases (erosional in places), the predominant sheet-like geometry, non-graded, and occasionally crude reverse grading (Figs. 6a and 6b and 3a). The thickness of the beds rarely exceeds 5 m and commonly varies from 1 to 3 m. In alluvial fan 5, this facies is often interbedded with thin clast-poor lobes (< 50 cm).

Facies F2 is well exposed in two 1.2 to 1.5-m-thick sections of fan 2 (Figs. 6c and d), where lensoid conglomerates with poor sorted, clast-supported, and reverse grading are evident. The clasts are well-imbricated, subangular to subrounded, and infilled by coarse sand to the fine pebbly matrix.

Facies F3 consists of a local concentration
of cobbles and pebbles. This facies has occurred in a sidewall exposure along a mid-fan channel as lag deposits. It is typically lenticular, massive with local coarse tail, clast-supported, and moderately to well sorted, with its base contact marked by winnowed gravels (Figs. 6e and 6f). This facies exhibits a bimodal grain-size distribution. The coarse clasts are mostly sub-rounded to rounded clasts and in some cases are subangular. Bladed pebbles show imbrication.

Interpretation
Sheet-like geometry, clast-supported texture, the presence of boulder-sized clasts on conglomerates with crudely inverse grading (Steel & Nemec, 1982; Postma, 1984), coarse sandy matrix (mud <5%), and non-erosional base (Saula et al., 2002) support origin of facies F1 as product of pseudoplastic cohesionless debris flow (turbulent flow).

Figure 6. Sediment profile and photographs of facies F. a) facies F1 consists of clast-supported gravels (Gcm) is overlaid by mudflow and Gmm facies. b) facies F1 consists of clast-supported gravels (Gcm). c) facies F2 with inverse grading. d) Close-up view of facies F2. e) facies F3 consists of concentrated clast-supported gravels on the gullied surfaces with bimodal texture and sand to pebble matrix. f) Close-up view of facies F3.
Moreover, ungraded units of mass flow gravels with a-axes imbricated clasts bear definite signatures of operation of dispersive pressure and internal shear of flow (Sarkar et al., 2008). Some grain-supported beds contain abundant imbricated fragments, indicating that in most cases deposition is due to unconfined energetic floods (Sanchez-Nunez et al., 2014), with high sediment concentration (sensu hyperconcentrated flow; Saula et al., 2002), which prevents the deposition of fine-grained sediments. Moreover, due to their formation in turbulent conditions, they exhibit a massive texture (Kastic et al., 2005). On the other hand, lensoid-shaped deep scours, poor sorting, inverse grading, imbrication, and a wide range of clast size may suggest that facies F2 has been generated by channelized hyperconcentrated flow (Miall, 2006).

Facies F3 with a better sorting compared to other gravelly facies reveals its selective transport and deposition, producing concentrated gravels. It is developed by the winnowing of fine fraction from coarse fractions by sheetflows or overland flows, leaving behind coarse sediments as channelized fills (Blair, 1999b). This facies is called sieve deposits (Bull, 1972).

**Facies G: Trough cross-bedded gravel (Gt)**

Well-developed trough cross-bedded facies is also found as a minor facies in the alluvial fan 5 (Fig. 7a). This unit is composed of relatively thin cross-bedded/normal graded pebbly sandy gravel (Fig. 7b). They fill scoop-shaped scours and channels with 20-35 cm depths. The foreset dips mainly vary from 20° to 25°, but values up to 30° occur in some troughs.

**Interpretation**

Occasional trough cross-stratified sets within gravelly units may suggest the low-energy regime during the depositional of coarse-grained units. They are interpreted as having formed by dunes migrating over bars (Harms & Fahnestock, 1965). Some examples of this facies display filling of minor channels (Miall, 2006). Laterally discontinuous trough units within gravelly facies are the deposits of migrating bedforms within scours and/or channels formed at high flood-stage (Martini, 1977; Rust, 1984). Moreover, this case can be formed either by local vortices around the obstacles or by leaving an abandoned channel and channel system avulsion (Miall, 2006).

**Facies H: Massive muddy/pebbly sand (Sm)**

The layers of this facies are 0.5 to 2 m thick and contain less than 10% randomly scattered pebbles (Fig. 7c), with a non-erosive basal contact.
In some cases, these layers are rich in abundant small irregularly shaped carbonate patches. This facies typically occurs in the distal domains of the fans.

Interpretation
Overall, the sedimentary fabrics of this facies suggest that they were deposited by sediment-gravity flow within the toe of the alluvial fans (Miall, 2006).

Facies I: Calcrete facies
Calcrete (caliche or authigenic carbonate) occurs in some of the alluvial fans, typically in the alluvial fans 1, 2, and 5. The calcrete profiles of these fans show various macro- and micro-morphology features. These profiles are described individually in the following:

1.1) In the proximal part of fan 1, calcrete horizon occurs as a massive appearance (Fig. 8a). The coated grains, desiccation cracks, and root traces can be seen dominantly in this profile. Petrographically, the massive horizon mainly consists of microsparite groundmass with biogenic microfabrics such as bioturbation, root voids (Fig. 8b), clotted micrite, scattered various cracks filled with calcite cement, and expansion grains as a result of replacement and displacement (Fig. 8c). Moreover, the occurrence of overgrowth of the needle palygorskite on secondary carbonates and detrital grains are common in the calcrete (Fig. 8d).

1.2) In the distal part of fan 2, a powdery and nodular calcrete horizon is observed. This horizon is covered with several non-calcareous alluvial sediment bodies (Fig. 9a). Most remarkable features of secondary carbonate include millimeter-sized whitish powder, coated grains and bands (or thin layers) consisting of diffuse-margin nodules, which mimic the concave-up geometry of channel deposits and/or conform to the stratal planes of the sediment body (Fig. 9b), and disc-shaped (Fig. 9c) and elliptical cream color nodules (Fig. 9d). Other features of this horizon are mottling (or reddish-brown patches) (Fig. 9e) and rhizocretions that occur in different parts of this horizon. Through the petrographic study conducted in this work, the nodules showed dense microsparitic and micritic groundmass accompanied with microfabrics such as bioclasts alveolar septal structures, dendritic Mn-oxide mottlings (Fig. 9f), fenestral porosity (Fig. 9g), clotted micrite, hair-like roots or filaments (Fig. 9h), bacterial organisms (Fig. 9i), biomineralization, microborings or root trace, and palygorskite fibers.

Figure 8. a) Field photograph of the calcrete profile of fan 1 showing massive horizon (mh); b) a root trace and its concentric epidermal sections (e) and diagenetic peloids (p) (XPL); c) Displacement (d), replacement (r), and expansion of host grains (XPL); d) accumulation of host detrital grain and micrite associated with overgrows of fibrous-needle palygorskite (SEM).
Figure 9. a) Field photograph of the calcrete profile of fan 2: a powdery and nodular horizon (pnh), overlaying by non-calcareous alluvial sediments (ncas); b) diffuse-margin discontinued band (dmb) of the calcrete profile of fan 2 which mimics the concave-up base plane of the upper channel; c) Disc-shaped and elliptical cream-colored nodules; d) Column-shaped cream colored nodules; the diameter of the coin is 2 cm; e) field photo of mottling (or reddish-brown patches) occur in different parts of calcrete horizon (arrow); f) Desiccation cracks filled with calcite cement (d), bioclasts (b), Mn-oxide mottling along cracks (m), alveolar septal structures (ass), and hair-like roots or filaments (r) in the mature nodule (XPL); g) fenestral porosity (XPL); h) organic filament (SEM); i) Bacterial organisms (SEM); j) pendant various laminae of grain coating consist of exclusively of microsparitic laminae (ms), micritic laminae (m) accompanied with alveolar septal structures (ass), and microsparitic groundmass with abundant clastic grains (msg) (XPL).
The microfabrics of the discontinuous bands are predominated by alpha microfabrics.

I.3) Type-3 calcrete is found in the distal part of fan 3. The accumulation of secondary carbonate in this profile is in the form of coated grains, patch, and cement. The nucleus of the coated grains is mainly composed of the clasts of the host sediment with various sizes. They have pendent-like coatings and cement. Petrographic study reveals that the coating process has developed various laminae with different colors, thicknesses, and microfabrics such as a) the groundmass consisting exclusively of microsparitic, b) micritic laminae accompanied with root and fungal filaments, and c) thick laminae, formed of microsparitic groundmass with sand-to-silt-sized clastic grains (Fig. 9j).

Interpretation

I.1) Based on Machette (1985) calcrete classification, stages V were recognized within the limestone-hosted calcrete profile of fan 1. They are equivalent to the hardpan stage of Esteban and Klappa (1983). The prevalence of coating grains within this profile suggests that the calcretization with the formation of coated grains results from the pedogenic process, which has begun during dry periods in the vadose zone (Wright, 1990; Alonso-Zarza et al., 1992). Afterward, the progressive diagenetic alteration of host deposits, such as dissolution and cementation, contributed to blocking of porosity and forming the massive calcrete. This process has occurred during a long-term dry episode with slow or no deposition (Alonso-Zarza et al., 1998; Gallala et al., 2010). This mature profile has dominantly undergone biogenic, pedogenic, and diagenetic processes. Thus, it can be proposed that this profile has developed under stable climatic, geomorphic, and sedimentation conditions (Reeves, 1976).

I.2) In the lower part of fan 2, the powdery and nodular horizon is present in the distal zone. It is equivalent to the II stages Machette (1985) and Gile (1966), and also the powdery and nodular stages of Esteban and Klappa (1983). The nodules of this horizon are representative of a mature nodule as a result of the pedogenic/biogenic process. Moreover, calcrete diffuse-margin nodules and bands following stratification planes reveal that they have been inorganically precipitated from supersaturated groundwaters migrating along stratification plane or from carbonate-saturated river water (Kadkikar et al., 2000; Alonso Zarza & Tanner, 2006), during either carbon dioxide degassing or evaporation (Spotl & Wright, 1992). Aggradation of non-calcrete sediment bodies overlying the calcrete horizon suggests a progressive increase in the sediment supply derived from surrounding highlands through small-scale channels. Aggradation episodes govern the location of the groundwater table, especially in the distal fan areas. In these areas, every new sediment input is followed by a local rising of groundwater level (Alonso-Zarza, 1999), which gives rise to the development of calcrete bands. Therefore, it can be suggested that this horizon has been affected by the pedogenic processes for a long-time, progressive dry, and stable episode, during which the nodules have reached the final maturity. Subsequently, several new sediment supplies have occurred during unstable semi-arid to arid climatic episodes and then the re-calcretization caused by each local rising of the water table during slightly wetter climatic episodes (Alonso-Zarza, 2003; Alonso-Zarza & Wright, 2010).

I.3) The calcrete features in fan 3 are considered as an equivalent to the nodular stage of Esteban and Klappa (1983) and are also equivalent to the Stage I of Gile (1966) and Machette (1985). The diversity
of coating laminae of grains in this profile may suggest two main origins: a) biogenic laminae, consisting of roots, cyanobacteria and/or fungal filaments (Beier, 1987; Alonso-Zarza et al., 1992) and b) none-biogenic, lacking any organic features, made up of microsparitic groundmass (Hay & Wiggins, 1980). Moreover, the presence of silt and sand sized-detrital grains in the outermost laminae is due to the rolling of the coated grains within the loose host sediments resulting from mechanical force or the activity of the roots (Alonso-Zarza et al., 1998). Coated grains are considered to be pedogenic calcretes. The alternating occurrence of thin dark and light laminae followed by a thicker lamina containing detrital grains probably proposes the occurrence of the wet and dry conditions fluctuation followed by a longer dry period.

**Petrography and mineralogy of bulk-sediment and clay fraction**

Petrographic analysis of the sand fraction of fan 1 sediments show that more than 80% of the samples were derived dominantly from calcareous source rock (Fig. 10 a-b), whereas other fans consist mainly of volcaniclastic, metamorphic, and sedimentary (mainly sandstone and mudstone) rock fragments, alkali feldspar and plagioclase, and minor amounts of quartz and chert (Figs. 10 c-f).

![Figure 10. a-b) Microscopic photos of samples of fan 1, showing the abundance of calcareous rock fragments (XPL); c-f) Microscopic photos of samples of fan 2, 3, 4, 5, which also show that the abundance of volcanic rock fragments (XPL). CR: calcareous rock fragment, VR: volcanic rock fragment, P: plagioclase, and F: feldspar.](image)
XRD micrographs of bulk samples represent the predominance of calcite with a high-intensity peak at 29.41 2θ (3.03 Å) (Fig. 11a; Kraemer et al., 2005) and the presence of palygorskite, quartz, chlorite, illite, and feldspar. Moreover, diffractograms of clay fractions of calcrite samples of fans 1 and 2 and SEM photomicrographs show that palygorskite is generally high within calcrites (Figs. 11b and c).

The texture of alluvial fan deposits

The debris-flow (Gmm) and lenticular mud-rich facies are common features within all fans. The grain-size data reveal that sediments of fan 1 are relatively finer than other fans (Figs. 12 and 13).

Figure 11. XRD patterns from a) bulk sample of the calcrite profile of fan 1, b) clay fractions of samples from the calcrite profile of fan 1, oriented sample; c) clay fractions of samples from the calcrite profile of fan 2, oriented sample. XRD patterns in black – Mg-saturated air-dried, blue – glycolated, red – heated at 550°C. Abbreviations: plg: palygorskite; Ilt: illite; Sm: Smectite; Chl: chlorite; K: kaolinite; Q: quartz.
The median is approximately 4 mm and the sorting index ranges between 1 and 3, with an average value of 2.1. The matrix of fan 1 shows a slightly better sorting than other fans, with values ranging between 2 and 3 (average of 2.25). The mud content (clay and silt) is considered as a discriminant factor that controls cohesiveness of the sediment-gravity flow (Moscariello et al., 2002) and changes over the fans. The clay fraction is generated both by in situ weathering (physical weathering) and by intense biological activity (Moscariello et al., 2002). The maximum measured mud content for sediments of fan 1 is 54% (from mudflow), whereas it reaches 9.7% and 5.9 % for fans 2 and 3, respectively. The sediment with the largest grain size (boulder up to block size) typically is derived from massive lithologies of the catchment of fan 3. Blocks and boulders are relatively rare in sediments of the fan 1, where they commonly are scattered within a fine-grained cohesionless matrix.

**Discussion**

*Lithological control on fan processes and sediments*

Comparison of sediment-gravity deposits and source area materials shows that the catchment lithology can control the mud content of the resulted deposits and, in turn, control the sedimentary processes on the fan (Moscariello et al., 2002). The deposits of fan 1 reveal a rather different texture that may be as a result of the composition of parent material involved and different sedimentary processes. Depending on lithological and mineralogical composition (marly versus pure limestone), the occurrence of heterogeneous intercalations (i.e., interbedded shales), type of cementation, and rock-splitting properties (weathering and tectonic history) of carbonate rocks can produce non-cohesive debris flow (Blair, 1999a).
In the case of deposits generated from calcareous rocks (group 1 lithology), the dominant process will be debris flow, while flash- and sheet-flood processes play a significant role in the sediments of group 2. However, in general, the dominant process of both lithological groups is the non-cohesive debris flow. Furthermore, Ca$^{2+}$ needed for calcretization commonly are generated from calcareous lithologies. That is why the most mature type of calcrite is observed in fan 1 deposits (group 1 lithology).

**Paleoclimatic effects on alluvial fan processes**

The debris-flow deposits, red-coloration, interbedded mudflow, polygonal mud cracks, and calcretes of the studied areas are indicative of a generally warm and dry climate (Gile et al., 1965; Hayward, 1983; Kraus, 1999; Clyde et al., 2010), which also exists in other areas of the Qazvin Plain. Subaerial debris flows require abundant clastic debris, a steep slope, and a high discharge for their initiation. Abundant clastic detritus resulting from mechanical weathering during long dry periods are transported by flash floods, with scarce vegetation to inhibit run-off (Miall, 1977). Based on the relative frequency of facies in the study area, three groups...
(types) of alluvial fans are recognized (Fig. 13). Therefore, based on the frequency (80-95%) of facies A, alluvial fan 1 was formed predominantly by aggregation of poorly sorted, debris-flow lobes, and sheets. In other words, it can be classified as a fan dominated by non-cohesive sediment-gravity flows (type NC-4) of Blair and MacPherson (2009). Such fans are special cases arising from non-cohesive colluvium, which is formed by clay-poor colluvium during catastrophic discharge. The minor volume of runoff-related lenticular gravelly units (~10-15%) reveals that the contribution of floods to primary aggradation of the fan is insignificant and only locally redistribute sediment on the fan surface (Fig. 2d). Interbedded red colored mudflows suggest that aggradation process of the alluvial fan was episodic rather than a constant process of delivery. An indication of episodic deposition and laterally unconfined nature of flows, suggestive of debris flow deposition (Blair & McPherson, 2009; Mather, 2016), is abundantly observed in other fans (~60-70%). However, the contribution of deposits resulting from flash and sheetfloods in their deposits is about 30-40%.

The non-cohesive debris flows originate from the catchment with low mud (especially clay) content. Granulometric results revealed that mud volume of all fans (excluding mudflows) is low (<5%). This low mud content is probably due to the fact that the clay and the silt-sized fraction is a minor product in the arid climate because they form either by hydrolysis of feldspar and accessory minerals or through tight tectonic shearing (Blair, 1999c, 2003). However, such reactions are slow in arid settings because mud production requires long periods of low mud content is probably due to the fact that the clay and the silt-sized fraction is a minor product in the arid climate because they form either by hydrolysis of feldspar and accessory minerals or through tight tectonic shearing (Blair, 1999c, 2003). However, such reactions are slow in arid settings because mud production requires long periods of high-moderate humidity (Blair & McPherson, 2009). These fans can be correlated with interbedded red colored mudflow (Table 1) indicating an extremely dry climate (Yan et al., 2007). In addition, the aridification during the Quaternary can be inferred based on calcrete features (Hasegawa et al., 2009), especially the occurrence of palygorskite as a particular clay mineral of calcretes (Figs. 8d and 11) (AlShuaibi & Khalaf, 2011; Zucca et al., 2017).

Moreover, paleoclimate and paleo-weathering can be inferred from the elemental geochemistry of sedimentary rocks. Therefore, the low degree of weathering is the result of the arid climate, whereas the high degree of weathering is related to a warm and humid climate (Nesbitt and Young, 1982). Generally, we use the Chemical Index of Alteration (CIA) and the Chemical Index of Weathering (CIW) to assess chemical weathering. Overall, the CIA and CIW values of the samples support the relatively poor degree of chemical weathering. However, the highest values of CIA and CIW is related to the sample of fan 4, suggesting that this fan probably experienced relatively more intense chemical weathering (Fig. 13).

**Tectonic controls on the development of the fans and depositional processes**

Clast compositions and the analysis of paleocurrent directions based on the preferred orientations of the elongate clasts support that the sediments of all the studied fans were mainly transported in an S-SE direction. Therefore, the tectonic uplift resulting from faulting has controlled the accumulation loci of the fans. In addition, the most striking impact of tectonic on depositional processes can be seen in fan 3. The marked differences of fan 3 in facies (facies B) and clast size, from apex to toe, are possibly due to the reactivation of the fan head faults induced by the catastrophic collapse of the local source rocks. The clasts of this facies are obviously related to local lithology and delivered from physical weathering and brittle disintegration associated with fault movement. In addition, the wide range of sediments from clay to boulders probably facilitated transformation into debris-flows (Blair, 1999b; Blair & McPherson, 2009). In contrast, the relatively stable tectonic background and arid to semi-arid climate (Reeves, 1983; Wright & Tucker, 1991) may be considered as the main reasons for the development of calcrete in some horizons of the studied profiles.

**Conclusions**

The study of 5 modern alluvial fans throughout the Qazvin Plain led to the diagnosis of three different groups of fans in facies. Eight facies were identified and generally interpreted as the following depositional processes: 1) non-cohesive debris flows, 2) sub-aerial mud-rich debris flows, 3) channelized non-cohesive debris flows, 4) hyperconcentrated flows, and 5) sheetfloods. More than 85% of the deposits were formed by the first process. The other dominant processes in those fans are sourced from volcanic rocks (fans 2, 3, 4, and 5).

The arid to semi-arid climate was likely to have favored debris flows on fans of the Qazvin Plain. Such climatic conditions are expressed by the development of calcrete. Climatic aridification led
to a decrease in mud (especially clay) content and thus increased the occurrence of non-cohesive debris-flows on the alluvial fans. Therefore, the differences in the tectonic activities, climate, and bedrock types are considered as a controlling factor of the sedimentary processes.

Acknowledgments
We would like to express our special thanks to: 1- The head of the Abyek Cement Factory for assistance in field data collection 2- The President and the Research Dean of Bu-Ali Sina University for financial support.

References


