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ORIGINAL PAPER

Mass Wasting in Clastic Rocks (Elmalı Formation Upper Eocene-Lower Miocene; Muğla-SW Turkey)

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Abstract This study was carried out for determining the type, and factors of mass movements occurred in Upper Eocene-Lower Miocene mudstone and sandstone alternation (with varying ratios) of the Elmalı Formation. Those sediments crop out in a vast area in SW Turkey. The main mass movement type is determined as an earthflow understanding of tilting trees, electric pole and bumpy topography. Locally, complex mass wasting including rotational landslide with various sizes, creep, earthflow and translational movement were also determined during the field study. They are threatening people's life and property. Slope inclination, bed attitudes, joint measurement, hydrogeological observations, in situ strength measurements, geophysical application and rock sampling were performed during the field analysis. In addition, petrographic investigations, XRF and XRD analyses were performed for determining the contents of sample. Basic physico-mechanical properties, including specific gravity, porosity, Atterberg limits of samples were determined in the laboratory. Tectonic history was responsible from sheared, overturned, faulted and fractured lithology. The chaotic mudstone behaves like soil mass on hard-durable sandstone beds. Mid to high inclined slope promote the earthflow. In addition, the surface and ground water increase unstable mass weight and act as a lubricant on durable sandstone, which promote earthflow. The toe of the slope eroded and removed by streams. Thus, the earthflow continues on slope. In addition, local disturbance due to human impact (road cut, settlements, garden opening) caused small-scale but more dangerous complex mass movement.

Keywords Creep · Earthflow · Landslide · Complex mass movement · Clastic rocks

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1 Introduction

Mass movements are the type of disaster that causes the greatest number of victims, and it has been reported that about 8000 people per year are lost their life's in World (Ersoy 2014). Mass movements, which allow the transportation of sediments from block to clay size, are mentioned by names like flow, fall, slide and avalanche, depending on the type and speed of the material (Varnes 1978; Erguvanlı 1995; USGS 2017;

Yanrong et al. 2012). Landslides should be developed by association of various geological conditions, geomorphological features, and artificial-human impact (Brabb 1984; Duman et al. 2009). Landslides are commonly triggered by heavy rains (increase the weight of unstable mass and acts as lubricant on sliding surface), earthquake and volcanic activities (Brabb 1984; Duman et al. 2009). The stability of the slopes on the earth depends on the slope geometry (height and angle), gravity, lithological properties, the water contents, the discontinuities, additional load and the erosion of the toe (Erguvanlı 1995).

Many studies have been carried out on the geometry, causes and mechanisms of mass movements (Erguvanlı 1995; Gökçeoğlu and Ercanoğlu 2001; Çan et al. 2013; Hungr et al. 2014). The large-scale ones are evaluated using remote sensing techniques and geographic information systems (Erguvanlı 1995; Gökçeoğlu and Ercanoğlu 2001; Çan et al. 2013; Hungr et al. 2014). Gökçeoğlu and Ercanoğlu (2001) emphasized that the consensus on some parameters (including slope, lithology, land-use potential and vegetation) for studying landslide with GIS techniques. However, they also emphasized that there is no consensus on some parameters including slope orientation, slope shape, elevation etc. The type of moving material, depth and areal distribution of moving material, type and velocity of mass movement, scale of the study area, and aim of the study are controlling the landslide inventory map preparation with GIS (Çan et al. 2013). Studies on the characterization of a landslide in a region include detail lithological analysis, kinematic analyses and deformation measurements (Öz 2009; Alemdag et al. 2014). The failure mode and structural properties can be determined by field studies and kinematic analyses (Alemdag et al. 2014). The limit equilibrium and numerical analyses can be carried out for determination of pre-failure conditions (Alemdag et al. 2014). Human impact including excavation and blasting may act as a one triggering factors for landslide (Alemdag et al. 2014). The rock or soil strength is one of the controlling parameter of mass wasting, and mineralogy of rock including durable (quartz, limestone fragments etc.) and indurable (feldspar, clay etc.) control the strength and cause to differential weathering (Gökçeoglu et al. 2000; Corominas et al. 2015). In addition to the mineralogy, rainfall (primary trigger), and geological structures, rock weathering, steep slope angles, rugged topography and ground water were determined as a controlling factors of the Dure Besi landslide in Nepal (Regmi et al. 2013).

SW-Turkey was reported as one of the riskiest regions of Turkey in terms of landslides (Duman et al. 2009). This region hosts Lycian Nappes, including various aged sedimentary rock and ophiolite nappe slices (Figs. 1, 2). Complex tectonic forces under the different tectonic regime during and after the emplacement of nappe led to a form of highly bumpy topography in this region. The Upper Eocene-Lower Miocene clastic of the Elmalı Formation is a part of the Yeşilbarak Nappe (Şenel 1997a) and shows different examples of mass movement.

Moreover, one of the outcrop area of the Elmalı Formation was declared as a disaster area, and decided to relocation of the village based on first reports prepared in 1964. Subsequently, the General Directorate of Mineral Research and Exploration (MTA) and Disaster and Emergency Management Presidency (AFAD) prepared investigation reports about the same disaster area in Dereköy Village. These reports involved some basic data such as slope map, active and passive slide distributions (Fig. 3). However, there is no detail study about the Elmalı Formation. The general studies on landslide concentrate lithological properties without take into consideration of the depositional environment characteristic. However, sedimentary process actively controls facies variation including grain size differentiations in clastic rock. The key objectives of this study are to determine and to classify mass movements in clastic rocks, and to discuss factors controlling mass movements in the clastics of the Elmalı Formation.

2 Materials and Methods

The Elmalı Formation crops out in Seydikemer Town of the Muğla Province located in Aegean Region (SW Turkey). This region contains the plain-lowland coasts and NW–SE directed mountains, which were formed by the Lycian Nappes slices. Many tectonic blocks formed topographic height, and depression basins were developed among them (Doğu 1988). Four outcrop regions of the Elmalı Formation were selected within scope of this study based on their geomorphology and its mass wasting characteristics in the Seydikemer Town (Fig. 1). The climate of this region

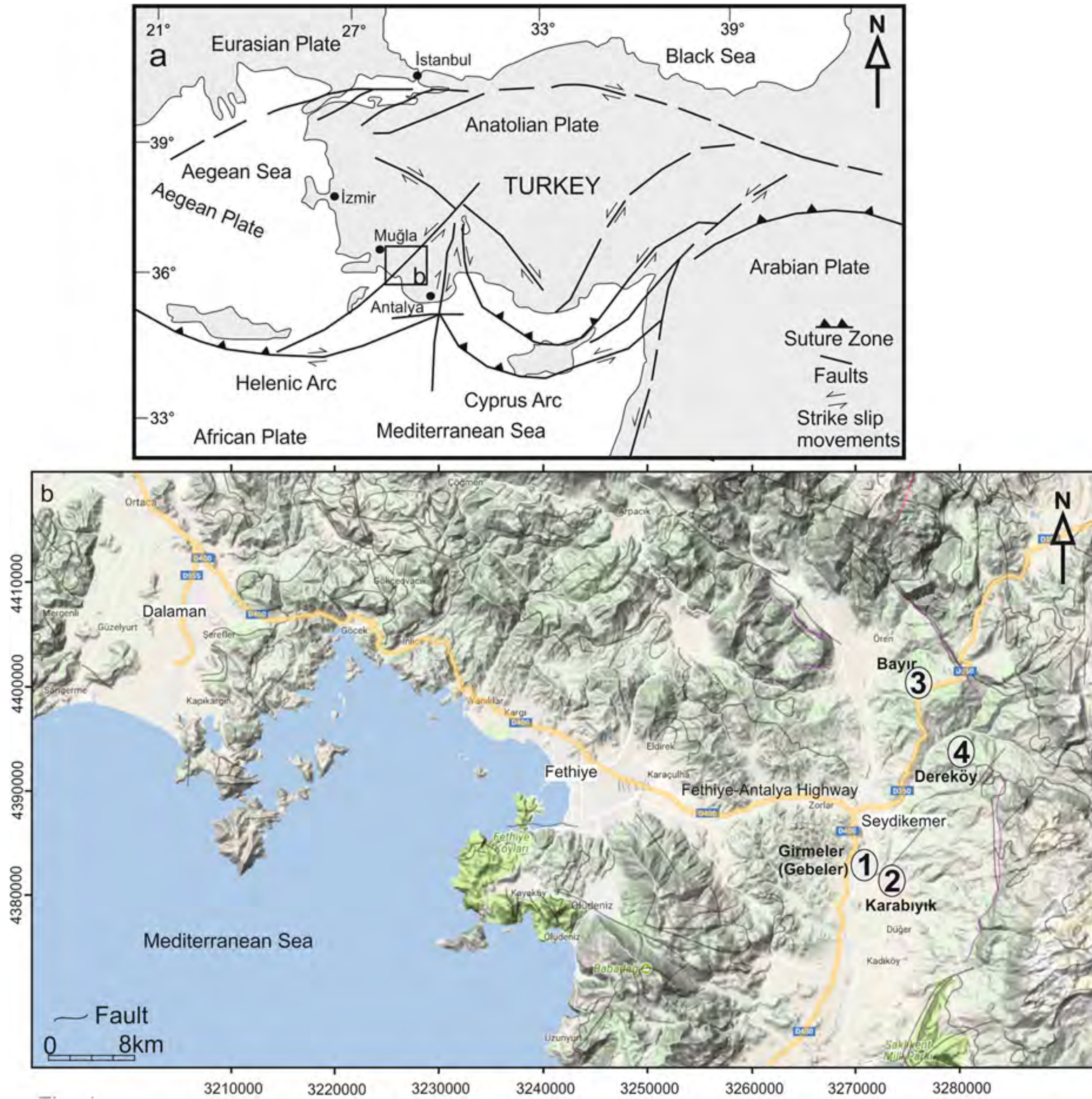
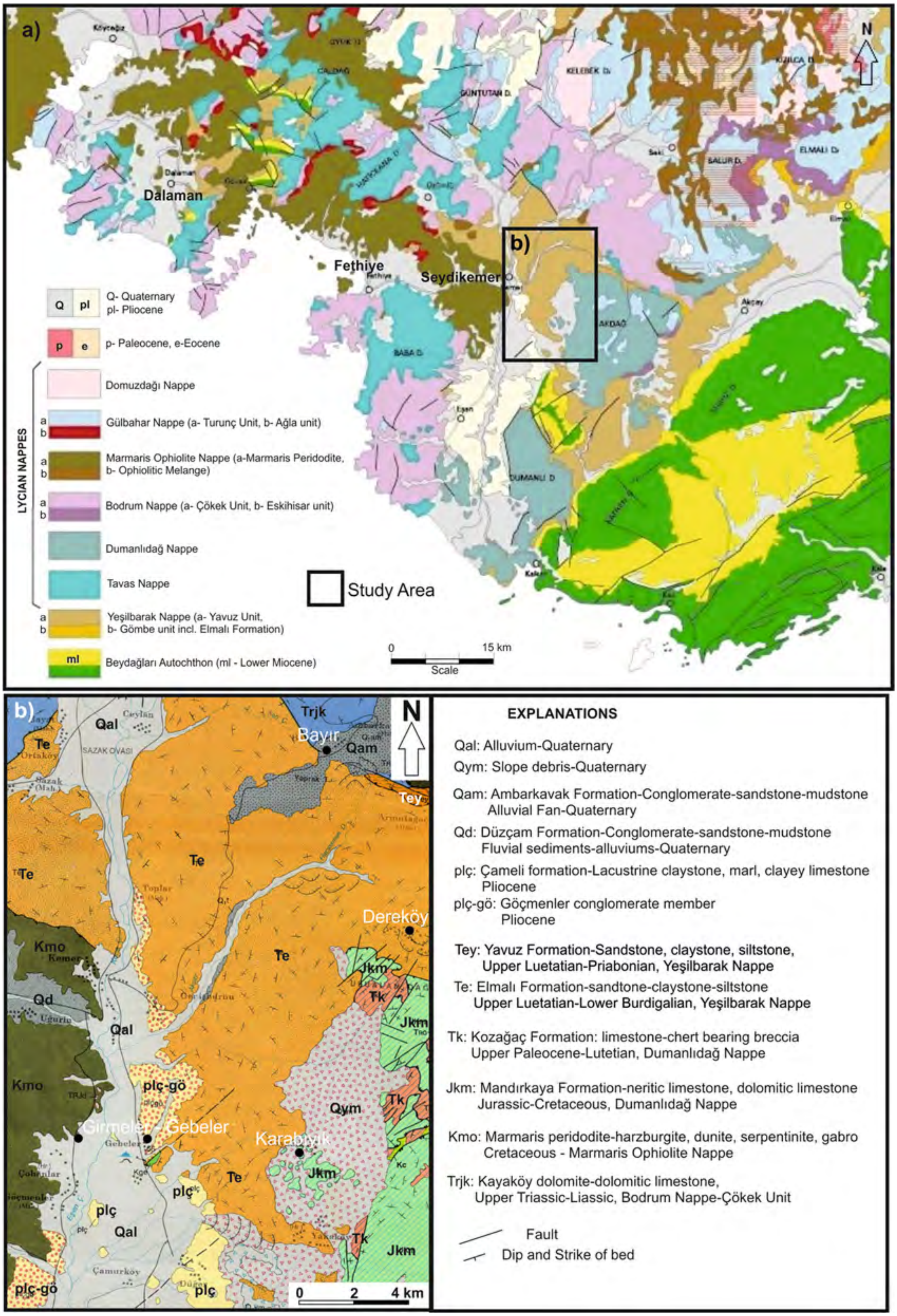


Fig. 1 **a** The location map of the study area, including main tectonic features of Turkey and the surrounding region (modified from Savaşçin and Oyman 1998). **b** The location map of the detailed study area (obtained from www.atlas.gov.tr, accessed 29.11.2017), fault data were directly obtained from the MTA (General Directorate of Mineral Research and Exploration)

is the Csa-Mediterranean climate—warm and temperate according to Köppen-Geiger classification, average annual temperature of the regions are around 17–18 °C, annual precipitations are higher than the 900 mm (CLIMATE 1, 2, 3, 4, 5).

Lateral and vertical changes of lithological units, bed attitudes, fracture characteristic, spring and surface water properties were researched during the field analysis. Moreover, type and distribution of the mass movement, deformed surface topography, tilted trees and retaining walls, tensional cracks and scarps were noted. 22 samples were compiled for detail laboratory analyses. Geophysical measurements were done in two locations by Orak (2017) for determining



a)
N
Dalaman
Fethiye
Seydikemer
b)
Q pl
Q- Quaternary
pl- Pliocene
p e
p- Paleocene, e-Eocene
LYCIAN NAPPES
Domuzdağı Nappe
Gülbahar Nappe (a- Turunç Unit, b- Ağla unit)
Marmaris Ophiolite Nappe (a-Marmaris Peridodite, b- Ophiolitic Melange)
Bodrum Nappe (a- Çökek Unit, b- Eskihisar unit)
Dumanlıdağ Nappe
Tavas Nappe
Yeşilbarak Nappe (a- Yavuz Unit, b- Gömbe unit incl. Elmalı Formation)
ml
Beydağları Autochthon (ml - Lower Miocene)
Study Area
0 15 km
Scale
b)
Qal
Te
Trjk
Bayır
Qam
Tey
Kmo
Qd
Dereköy
Jkm
Tk
plç-gö
Girmeler
Gebeler
Karabıyık
Qym
plç
0 2 4 km
N
EXPLANATIONS
Qal: Alluvium-Quaternary
Qym: Slope debris-Quaternary
Qam: Ambarkavak Formation-Conglomerate-sandstone-mudstone Alluvial Fan-Quaternary
Qd: Düzçam Formation-Conglomerate-sandstone-mudstone Fluvial sediments-alluviums-Quaternary
plç: Çameli formation-Lacustrine claystone, marl, clayey limestone Pliocene
plç-gö: Göçmenler conglomerate member Pliocene
Tey: Yavuz Formation-Sandstone, claystone, siltstone, Upper Luetatian-Priabonian, Yeşilbarak Nappe
Te: Elmalı Formation-sandtone-claystone-siltstone Upper Luetatian-Lower Burdigalian, Yeşilbarak Nappe
Tk: Kozağaç Formation: limestone-chert bearing breccia Upper Paleocene-Lutetian, Dumanlıdağ Nappe
Jkm: Mandırkaya Formation-neritic limestone, dolomitic limestone Jurassic-Cretaceous, Dumanlıdağ Nappe
Kmo: Marmaris peridodite-harzburgite, dunite, serpentinite, gabro Cretaceous - Marmaris Ophiolite Nappe
Trjk: Kayaköy dolomite-dolomitic limestone, Upper Triassic-Liassic, Bodrum Nappe-Çökek Unit
Fault
Dip and Strike of bed

◀**Fig. 2** **a** The tectonic units of the study area (modified from Şenel et al. 1989, 1994; Şenel 1997a, b, c, MTA). **b** General geologic map of the study area. (Modified from Şenel 1997b, MTA)

the vertical lithological variations, and possible slip surface of the mass movement with using Schlumberger method (Vertical Electrical Sounding) by Geotronic resistivity equipment.

During the laboratory stage, 16 sandstone thin sections were classified according to Pettijohn et al. (1987). The XRF analyses were performed on 12 samples for determining the major oxides in Mersin University Advanced Technology Education, Research and Application Centre (MEİTAM) with using the WD-XRF (Table 1). The XRD analyses were performed on 10 samples for determining fine-grained sediment mineralogy in the Muğla Sıtkı Koçman University, Research and Application Centre for Research Laboratories by using the Rigaku Smart Lab XRD. The water absorption by weight, dry unit weight, porosity and uniaxial compressive strength of 11 sandstone samples were determined in the Kahramanmaraş Sütçü İmam University, Department of Geological Engineering, Engineering Geology Laboratories based on ISRM (2007) standards (Table 2). In-situ strength determination was performed by using the Schmidt Hammer (Table 3). The relative density and the Atterberg limits of ten clay samples were determined in Kahramanmaraş Sütçü İmam University, Engineering Geology Laboratories based on ASTM (2001) standards (Table 4). The slope map of the Elmalı Formation, including the active and passive slides was compiled from reports of the Disaster and Emergency Management Presidency (AFAD) (Fig. 3).

3 Geological Background

The southwestern part of Turkey contains allochthonous units cropping out between the Menderes Massif and Beydağları Autochthonous (Fig. 2). Those allochthonous have been called under different names such as Western Taurides Nappes (Ersoy 1989), Bozkır Nappes (Özgül 1976) and Lycian Nappes (Brunn et al. 1971).

The Gömbe unit of Yeşilbarak Nappe, including Elmalı Formation crop out largely in west and southwest of the Fethiye Town, and lesser extent west of the Dalaman Town (Figs. 1, 2). The Yeşilbarak Nappe is a tectonic cover of the Beydağları Autochthonous, and is tectonically overlain by the other nappe slices of the Lycian Nappes (Ersoy 1990; Şenel et al. 1994). The Elmalı Formation has a contact with the Gebeler Formation of Beydağları Autochthonous, the Mandırkaya Formation of Dumanlıdağ Nappe, the Çameli Formation, the Düzçam Formation, slope debris (talus) and alluviums (Şenel 1997a, b, c).

The Gebeler Formation (Cenomanian-Santonian) is composed of limestone, dolomite and dolomitic limestone (Şenel et al. 1989, 1994). The Mandırkaya Formation (Jurassic-Cretaceous) contains neritic limestone (Şenel 1986). The Elmalı Formation (Upper Eocene-Lower Miocene) is formed by sandstone, siltstone and mudstone (Önalan 1979; Şenel et al. 1989). The Çameli Formation (Pliocene) consists of lacustrine mudstone, marl, and sandstone (Erakman et al. 1982; Göktas et al. 1989; Şenel et al. 1989). The Düzçam Formation (Upper Pliocene–Pleistocene) consists of old alluvial deposits, including mudstone, sandstone and conglomerates (Şenel 1997a, b, c). The Quaternary units contain slope deposits and younger alluviums (Şenel 1997a, b, c).

An emplacement of the Lycian Nappes (Early Miocene) caused foldings and fractures (Ersoy 1990; Şenel 1997a, b, c; Collins and Robertson 1999). After that, depend on Neotectonic development of Turkey E-W directed normal faults affected the region (Şenel 1997a, b, c; Alçiçek 2007; Ten Veen et al. 2009), and this also increases the discontinuities of the Elmalı Formation.

4 Elmalı Formation

After the general field studies, four regions, namely the Girmeler, Karabıyık, Bayır and Dereköy districts (Seydikemer Town) were investigated in detail due to absence and existence of mass movement.

In Girmeler (Gebeler) District (Fig. 1), the Elmalı Formation contains sandstone (FGS1 sample) -mudstone alternation, and tectonically overlies the Gebeler Formation. The mass movement was not observed in this region.

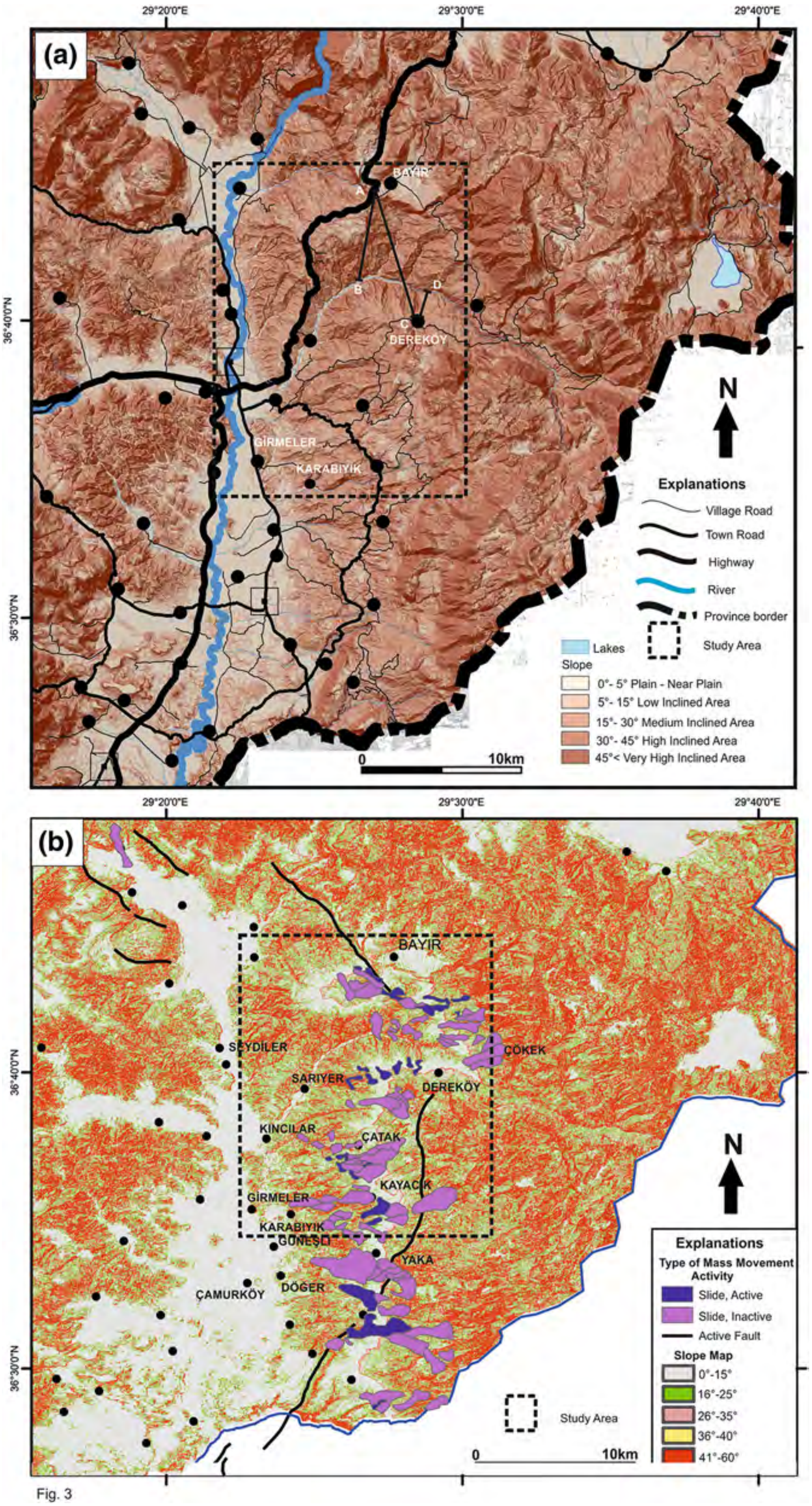


Fig. 3 **a** Slope map of the study area. (A, B, C, D show the cross section lines). **b** Active and passive slide map of the study area. (Modified from AFAD 2013)

Table 1 Chemical properties of samples taken from the Karabıyık, Bayır and Dereköy districts

WD-XRF	FKS-2	FKS-4	FKS-5	FBaS-2	FBaS-4	FBaS-5	FBaS-6	FDS-2	FDS-5	FDS-6	FDS-7	FDS-9
Na_2O	0.26	0.28	0.46	0.66	0.79	0.67	0.57	0.44	0.5	0.61	0.6	0.56
MgO	11.41	8	3.96	4.36	4.31	5.75	2.17	4.21	4.74	5.81	5.16	4.64
Al_2O_3	5.7	6.79	8.17	12.23	6.53	10.26	4.21	8.86	9.97	9.79	6.47	10.74
SiO_2	27.96	29.42	26.51	37.87	29.2	34.19	21.59	26.85	30.57	32.68	27.81	32.39
P_2O_5	0.081	0.1	0.11	0.11	0.092	0.1	0.066	0.085	0.087	0.091	0.091	0.1
SO_3	0.087	0.06	0.049	0.053	0.26	0.47	0.1	0.19	0.19	0.33	0.093	0.08
K_2O	0.89	1.34	1.52	2.4	1.18	2.05	0.82	2	2.26	1.94	1.14	2.41
CaO	24.2	25.41	30.3	18.02	32.17	21.62	41.41	27.71	23.86	22.76	31.62	22.11
TiO_2	0.43	0.47	0.59	0.75	0.56	0.68	0.31	0.55	0.64	0.61	0.5	0.64
Cr_2O_3	0.21	0.13	0.05	0.05	0.086	0.059	0.063	0.042	0.045	0.058	0.079	0.043
MnO	0.1	0.1	0.12	0.12	0.11	0.12	0.14	0.14	0.13	0.1	0.13	0.13
Fe_2O_3	7.07	6.41	5.11	7.63	4.28	6.69	2.84	6.06	6.94	6.26	4.65	6.91
NiO	0.11	0.08	0.031	0.038	0.035	0.042	0.017	0.036	0.04	0.046	0.041	0.036
CuO	0	0	0	0.009	0	0	0	0.009	0.009	0.008	0	0.009
ZnO	0.01	0.012	0.009	0.013	0	0.012	0	0.012	0.013	0.012	0.008	0.013
Rb_2O	0	0.007	0.008	0.014	0.006	0.011	0	0.012	0.014	0.011	0.006	0.014
SrO	0.055	0.068	0.064	0.043	0.069	0.051	0.089	0.084	0.075	0.067	0.076	0.055
ZrO_2	0.01	0.014	0.023	0.019	0.02	0.018	0.007	0.011	0.014	0.016	0.017	0.014
LI	21.36	21.33	22.91	15.61	20.26	17.17	25.64	22.72	19.95	18.82	21.48	19.08

LI loss of ignition, *FKS* sample from the Karabıyık quarter, *FBaS* sample from the Bayır quarter, *FDS* sample from the Dereköy quarter

Table 2 Engineering properties of sandstones of the Elmalı formation

Sample no	Uniaxial compressive strength (MPa)	Porosity (%)	Dry unit weight (kN/m^3)	Water absorption percent by weight %
FDS-1	44.83	5.07	26.41	1.58
FDS-2	38.20	3.38	24.75	0.94
FDS-3	47.43	5.83	26.85	1.73
FDS-4	40.39	11.23	25.16	3.54
FDS-7	40.24	9.62	25.11	2.53
FDS-8	44.63	4.89	25.26	1.25
FBaS-1	43.35	5.27	25.92	1.44
FBaS-2	44.68	4.36	26.29	1.02
FBaS-3	47.43	6.73	26.97	2.03
FBaS-5	40.29	10.91	25.00	3.24
FBaS-6	47.12	3.23	25.69	1.00
Average	43.51	6.41	25.76	1.85
Maximum	47.43	11.23	26.97	3.54
Minimum	38.20	3.23	24.75	0.94
SD	3.27	2.88	0.77	0.90

FBaS sample from Bayır quarter, *FDS* sample from Dereköy quarter

Table 3 Calculation of the Schmidt hardness and corresponding uniaxial compressive strength

Location	Coordinate (Eur50)	Average Schmidt hammer rebound value (N)
Bayır	35 715784E/4065906N	21
Bayır	35 715445E/4064322N	20
Bayır	35 715635E/4062335N	36
Bayır	35 715635E/4062335N	38
Bayır	35 715635E/4062335N	33
Bayır	35 715635E/4062335N	37
Dereköy	35 725366E/4059608N	26
Dereköy	35 725366E/4059608N	26
Dereköy	35 725366E/4059608N	35
Dereköy	35 725366E/4059608N	23
Dereköy	35 725366E/4059608N	32
Dereköy	35 721995E/4060729N	28
Dereköy	35 721995E/4060729N	23
	Maximum	38
	Minimum	20
	Average	29

Table 4 Classification of the samples obtained from the Elmalı formation according to its relative density and USCS

Sample no	LL	PL	PI	Relative density (g/cm^3)	USCS
FKS-1	27.5	22.4	5.1	2.75	CL-ML
FKS-4	25.4	19.3	6.1	2.87	CL-ML
FKS-5	26.2	19.8	6.4	2.93	CL-ML
FBAS-2	37.2	24.3	12.9	2.72	CL
FBAS-5	25.4	19.8	5.6	2.77	CL-ML
FDS-2	31.5	21.2	10.3	2.91	CL
FDS-5	25.5	19.6	5.9	2.77	CL-ML
FDS-6	25.5	19.2	6.3	2.85	CL-ML
FDS-7	26	19.5	6.5	2.91	CL-ML
FDS-9	30.4	21.6	8.8	2.75	CL
Average	28.06	20.67	7.39	2.82	
Maximum	37.2	24.3	12.9	2.93	
Minimum	25.4	19.2	5.1	2.72	
SD	3.89	1.68	2.50	0.08	

FKS sample from Karabıyık quarter, *FBaS* sample from Bayır quarter, *FDS* sample from Dereköy quarter

In Karabıyık District (Fig. 1), the Elmalı Formation comprises fossiliferous, fine to medium-grained sandstone at the bottom, followed by thin, medium to thick bedded, grey, greenish grey, green, light brown fine-grained sandstones, siltstones and mudstone (FKS1–2–3 samples). One mass movement exposure was observed in this region.

In Bayır District (Fig. 1), the Elmalı Formation has one of the widest exposures along the Fethiye-Antalya Highway. Several road cuts supply an information about the internal structure of formation. Massive-thickly bedded, medium to coarse-grained sandstone, and mudstone alternations were observed in this region (FBaS 1–5 sample). The earthflow and big landslides affected the formation in this region.

In Dereköy District (Fig. 1), the Elmalı Formation is tectonically overlain by the Mandırkaya Formation. The overturned layers of the Elmalı Formation contain thickly bedded medium-coarse grained sandstone and mudstone alternation (FDS1–7 samples). The tool mark (flute mark, groove mark, etc.; they are normally found at the bottom of the bed) was found at the top of the bed in this region. Mainly NE lesser extent SE and NW directed discontinuities were measured from the deformed sandstones. The earthflow and landslide also affected the formation in this region.

4.1 Petrographical Properties

The sandstones obtained from the study area contain rounded-subrounded-subangular-angular fragments, matrix or clast supported, fine to coarse-grained sandstone. They were classified as a litharenite based Pettijohn et al. (1987) classification system. They contain red algae bearing reef limestone, chert, ophiolite, volcanic rock, marble, schist, dolomite fragments, lesser extent quartz, and plagioclase. Micrite and calcite cement were found as a binding materials with variable ratios. The sandstones were evaluated both texturally and compositionally immature due to abundance of less durable rock fragments, micrite (clay-matrix) content, angularity of grains and poorly sorting of clast (Fig. 4).

4.2 Geochemical Properties

The petrographic and geochemical analyses can be used for determining the nature and composition of the source for sediment that transported into the basin. This information is then used to interpret the tectonic evolution of the source areas and basin depocentres through time (Gül et al. 2011).

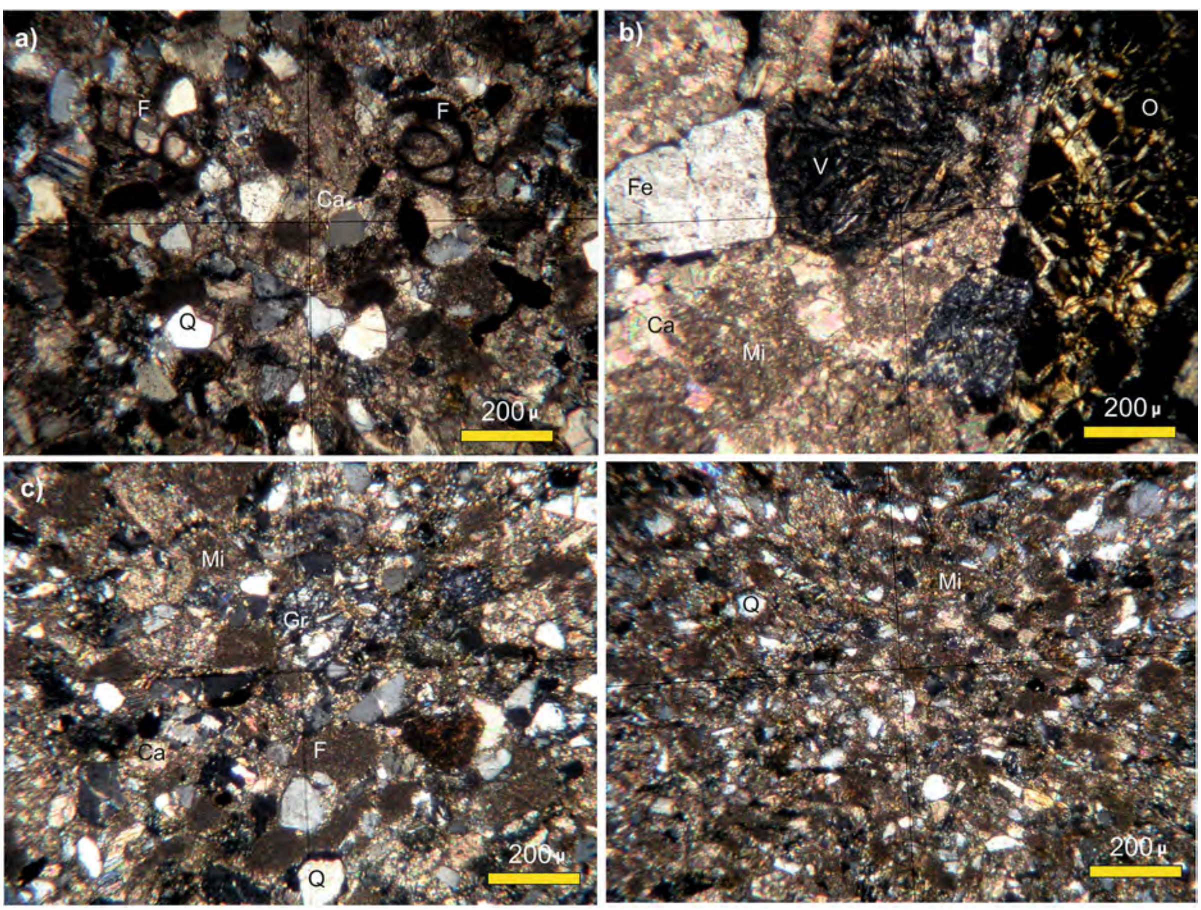


Fig. 4 Microview of the Elmalı formation clastics **a** Fine-grained sandstone including fossil fragment (F), and quartz (Q) binded with calcite cement (Ca). **b** Medium-grainedsandstone, including volcanic rock (V) ophiolite rock fragments (O), Feldspar (Fe) binded with calcite cement and micrite (Mi). **c** Fine-grained-sandstone, including granite rock fragments (Gr), fossil fragment (F), and quartz (Q) binded with calcite cement and micrite (Mi). **d** Siltstone

Orak (2017) reported positive correlations between Al_2O_3, Fe_2O_3, MgO, SiO_2 and TiO_2 that were pointed out fed from the especially mafic–ultramafic rocks and granitic rocks. If thin sections of samples were taken into consideration, the ophiolite rock fragments and lesser extent granitic rock fragments are justifying these results. The negative correlation between CaO and SiO_2 is point out the different sources. Especially limestone (fossiliferous limestone) and marble led to the higher CaO ratio. However, if the dolomite was acting as a source that causes the higher MgO content (Table 1). Orak (2017) emphasized the presence of smectite, chlorite or vermiculite, illite and kaolinite in mudstone of the Elmalı Formation from XRD analysis (Fig. 5).

4.3 Geophysical Properties

The vertical electrical sounding (VES) is a geophysical method for subsurface investigation of

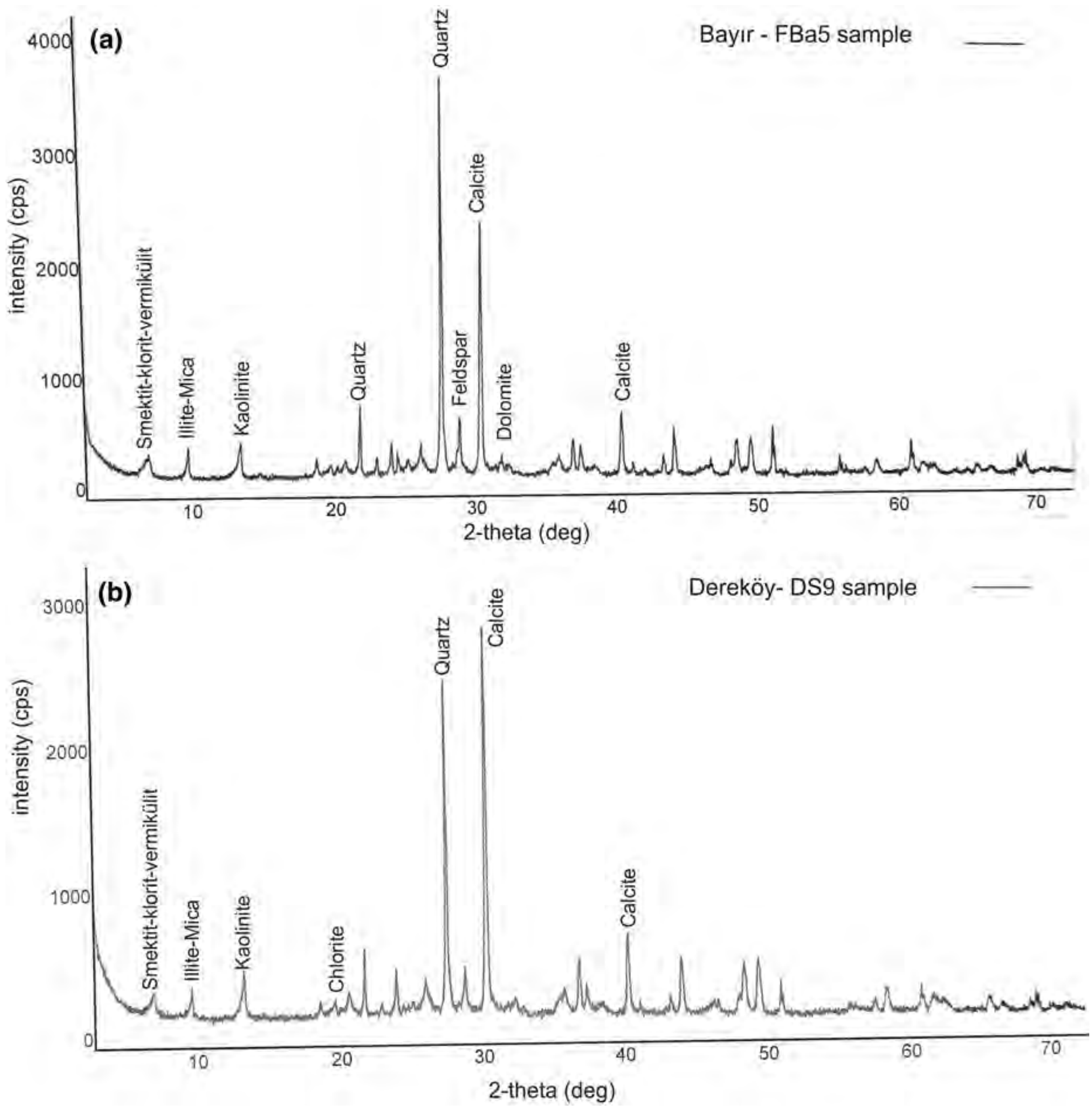


Fig. 5 **a** XRD pattern of the FBa5 sample from Bayır District. **b** XRD pattern of the DS9 sample from Dereköy District

lithological variation (Keller 1966; Sharma 1997). 3 VES (with using Geothronic Resistivity device and the Schlumberger electrode array) works were carried out by Orak (2017) in the Bayır District (VES 1) and in the Dereköy District (VES 2, VES 3). Orak (2017) applied the geophysical applications for determining the subsurface lithology variation, and to determine the slip face depth of the mass movement. The slip zones belonging to the mass wasting were thin and water saturated shear zones. It was found in transition between the mudstone and thick-massive sandstone layers (Orak 2017).

The VES 1 was applied along the highway. In VES-1, relatively low resistivity unit up to about 22 meters deep corresponds to mudstone. Below this unit, relatively low impedance with a very high resistivity (3870 Ωm) unit was interpreted as thickly bedded-massive sandstone (Orak 2017). VES 1 applied along the highway.

The VES 2 was applied along the village road, this line is perpendicular to the movement direction. In VES-2, relatively low resistivity unit up to about 55 meters thick relates to mudstone. Underneath of this unit, relatively low impedance with a very high resistivity (2269 Ωm) unit was interpreted as thickly bedded-massive sandstone (Orak 2017).

The VES 3 was applied along the village road, this line is parallel to the movement direction. In VES-3, relatively low resistivity unit of about 48 meters' depth corresponds to mudstone. Below this unit, relatively low impedance with very high resistivity (1991 Ωm) unit was interpreted as thickly bedded-massive sandstone (Orak 2017).

The VES 2 and VES 3 were taken from the same landslide southern side of the valley, thus they gave the similar lithological variations and possible slip surface below the surface (48–55 m). However, VES 2 measurement was taken from northern side of the valley and determined possible slip surface is closer to surface (22 m) than the Dereköy side. These results also point the irregular lithological variations in the Elmalı Formation.

4.4 Physico-mechanical Properties

The Uniaxial Compressive Strength (UCS) of sandstones collected from the Dereköy District and the Bayır District drop into the 'Moderately Strong (15–50 MPa)' according to Anon (1979). The porosity values of the Dereköy District and the Bayır District drop into the 'Low porous (1–5%)' and 'Medium porous (5–15%)' rock according to Anon (1979). The Dry Unit weight values of the Dereköy District and the Bayır District were classified as an abundantly 'High (2.55–2.75 g/cm3)' and lesser extent 'Moderate (2.20–2.55 g/cm3)' class rock according to Anon (1979).

The Schmidt Hammer Rebound Values of the samples vary between 20 and 38 (Table 3). Unit weight of them varies between 24.75 and 26.97 kN/m3 (Table 2). If the optimum values were taken into consideration, the lowest rebound value (20) for the lowest unit weight (24.75 kN/m3) and the highest rebound value (38) for the highest unit weight (26.97 kN/m3), average rebound value (29) for average values (25.76 kN/m3). So, according to application 505 directions, the in situ UCS of studied rock vary from 32 to 85 MPa, averagely 50 MPa. The in situ UCS values were classified as a 'Moderately Strong (15–50 MPa) and 'Strong (50–120 MPa)' rock according to Anon (1979).

The mudstones of Elmalı Formation were classified as a mostly 'Slightly Plastic (1–7%)' and lesser extent 'Moderately Plastic (7–17%)' rock according to Anon (1979). The swelling potential of all samples was evaluated as 'low swelling potential (PI: 0–15)' according to Chen (1975) classification. Based on the USCS classification mudstones were classified as CL (low plasticity clay) and ML (low plasticity silt) (Table 4).

4.5 Mass Wasting Characteristics

Two different regions, namely the Girmeler—Karabıyık Districts and Bayır—Dereköy Districts were separated and studied in detail, based on mass movement type. The slope of these regions was classified as from plain-near plain to very high slope (Fig. 3).

Recent faulted alluviums of the Eynazlı Stream unconformably overlie the Elmalı Formation in the Karabıyık District. The sandstone and mudstone stratas of the Elmalı Formation unfavorably inclined to the Eynazlı Stream valley. Moreover, the toe erosion of the Elmalı Formation's slope by this stream led to the development of the rotational slide. One of this landslide area is covering approximately 12,500 m^2 (MTA, Geoscience Map Viewer and Drawing Editor; Orak 2017). This landslide area is further away from settlements and roads. However, some close agricultural area is under the risk. The river has continued to remove the unstable mass. If the huge mass relocated due to the landslide that may cause to pond formation behind the landslide.

The region between the Girmeler-Sarıyer and the Dereköy-Bayır Districts contains sandstone and mudstone alternations with varying ratios. The Elmalı Formation is tectonically overlain by the Mandırkaya Formation limestone in this area. Generally, chaotic sediments including dominantly sheared-deformed mudstones and sandstone were observed, while regular sedimentation oriented to the different direction were rarely determined along the road cut.

The main mass movements of the Elmalı Formation were detected in the Dereköy and Bayır Districts. The Çayiçi Stream (southern branch Tezli Stream) and then the Akçay Stream valleys are located in between the Bayır and Dereköy Districts. The main stream valleys are being cut by several brooks. In addition, many springs were identified in thrust tectonic contact of the Mandırkaya Formation and the Elmalı Formation. Thick to massive bedded, overturned, fractured sandstone and chaotically appeared mudstone alternations were found in the Bayır and Dereköy Districts. The significant, complex mass movement, including translational slide, rotational slide, rock fall, earthflow and creep were developed at top of the hill. In extension of this region, generally creep-earthflow type mass movement were observed due to toe removal-erosion of the slope by streams in those regions (Figs. 6, 7, 8, 9, 10).

Figure 6 shows that the complex mass movement in the Dereköy District at top of the mass movement. The landslide scarp is located at the top of the hill. The earthflow, creep, and translational slides are extending through the district. The tilted trees-electric poles-garden fence and bumpy topographic surface were described in this region. The geophysical studies point out the significant resistivity change in 48–55 m below surface (road level) that show the rupture (shear planes) surface depth (possibly boundary between highly deformed rocks and massive sandstone boundary; Orak 2017). Moreover, the road cut creates additional and secondary shear-slide surface for mass movement. The bumpy topography and tilted trees on valley slope outside of the Dereköy District point out the large-scale earthflow movement (Figs. 3, 6, 10). The stream (namely, the Tezli Stream-easternmost; the Çayiçi Stream-middle; the Akçay Stream-westernmost) has eroded and removed the toe of the slope in Dereköy side of the valley. The determined mass movement region is approximately 26 500 m^2 (MTA, Geoscience Map Viewer and Drawing Editor; Orak 2017).

The Bayır District has a more inclined lithology than the Dereköy District. Hence, this region has a higher potential risk in terms of mass movements. Two complex mass movements were taken into consideration along the Fethiye-Seydikemer and Antalya Highway (Figs. 7, 8). The southern movement is below the highway level extend to the valley. The rotational slide and slumped blocks were determined at the crown of the landslide, in addition tensional cracks were detected on the highway (Fig. 7). The main mass movement was observed 1 km north of this southern movement (Fig. 8). The Elmalı Formation consists of gray-yellow colored, thick bedded-massive (including lamination), hard sandstone at the bottom; sandstone-mudstone alternation, and mudstone at the top. The highway cut changes the nature of the slope. Then, the slope materials destabilized. The scarp with tilted trees and slumped blocks were observed on top of slope. This mass movement destroyed earth-retaining wall in two section. In addition, the undemolished part of wall tilted 10°–15°, and oblique cracks were occurred in wall. The base heave and rotation of the base concrete structure were also developed (Fig. 8). According to the geophysical studies carried out by Orak (2017) in this region, it was determined that the surface of the rupture (shear planes) is located at 22 m below the highway level. The road construction creates secondary and small mass movement on the highway. The mass movement area covers approximately 21 000 m^2 (MTA, Geoscience Map Viewer and Drawing Editor; Orak 2017). The bottom part of the main mass movement and exposures along a few kilometers farther north shows a tilted tree (some of them formed due to road excavation waste) and bumpy topography that indicate active earthflow through the valley (Figs. 9, 10).

Figure 10 shows the main profile between the Bayır (A) and Dereköy (B) Districts. The Çayiçi Stream (C) later the Akçay Stream eroded and removed toe of the slopes including the sediments of the Elmalı Formation. Slope on both sides of the valley and anisotropy of the Elmalı Formation led to the development of the earthflow. The chaotically appeared due to deformation of the mudstone-sandstone alternations flow on the hard surface created by thick massive sandstone of the Elmalı Formation. However, the road

Fig. 6 **a** General view of the Dereköy Village. **b** The main mass movement area in the Elmalı Formation in the Dereköy District (car height for scale: 145 cm). **c** Detailed view of the NW side of mass movements. The creep-earthflow type slow mass movement is active in margin of the main mass movement. The tilted trees point out this movement. **d** Detailed view of central part of the mass movement. The main and minor scarps, deformed blocks were observed in this part

construction in both the Bayır and Dereköy Districts caused additional topography disturbances. Thus, local complex mass movement developed in those regions.

5 Controlling Factors of Mass Movement

The earthflow is a rapid or slower, intermittent flow-like movement of clayey soils, plastic-disturbed-sheared-mixed soils (Keefer and Johnson 1984; Hungr et al. 2014). This type of movements is among the common mass movements on the hill and mountainous region (Keefer and Johnson 1984). They develop on slightly inclined slope (< 12°), changes in length from few tens of meters to 6 km (Varnes and Savage 1996; Hungr et al. 2014). Earth materials contain sand and finer grained sediments higher than 80% (Hungr et al. 2001). Flow can be known as a fluid material movement on rigid surface (Hungr et al. 2001). Keefer and Johnson (1984) and Hungr et al. (2014) stated that the earthflow includes a deformed mass between

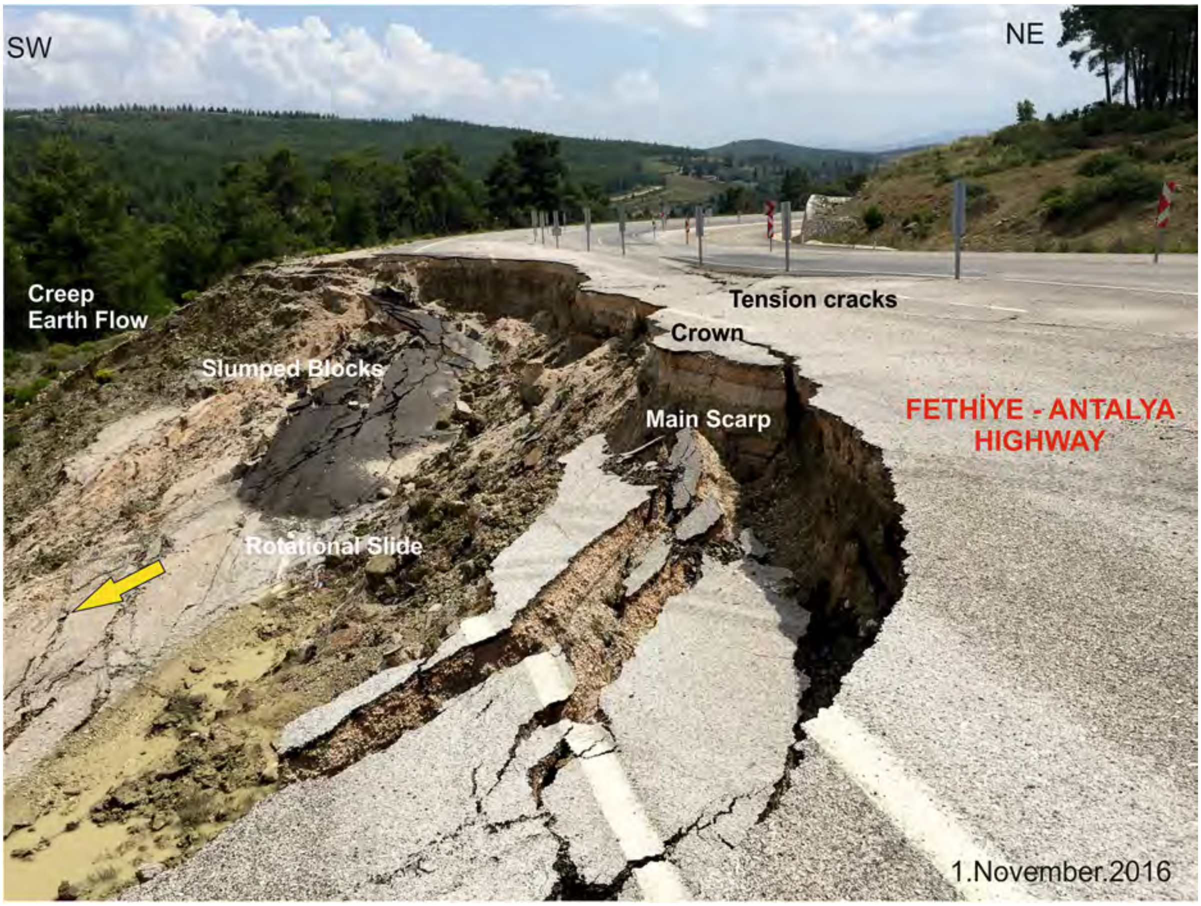


Fig. 7 The complex movement in the Bayır District along the Fethiye-Antalya Highway (traffic sign for scale: 125 cm)

source and eroding toe, the source may contain many rotational slides or compound slides, weathering and eroding steep face of weak bedrock. In addition, Keefer and Johnson (1984) reported that the earthflows consist of remolding soils and granular clasts. Several earthflow events in clastic rocks reported by Keefer and Johnson (1984). Hungr et al. (2014) defined soil creep as an extremely slow movement of the surficial soil (< 1 m below surface) as a result of the climate-driven cyclical effect such as wetting and drying, frost heave etc. Those loose-creep material is source of the shallow soil slides and debris avalanches (Hungr et al. 2014). Hungr et al. (2014) mentioned that the earthflow may in a dormant situation for many decades permitting highways and houses to be built on them.

The Dereköy region was declared as a disaster area, and was decided to relocation during 1964. After that, there is no rapid mass movement or death toll reported. Thus the dominant and slow mass movements in the study area were classified as an earthflow according to Varnes (1978) and Hungr et al. (2014). In addition to earthflow, local disturbance led to the development of complex mass movement, including creep, translational slide and rotational slide at the top of the earthflow materials. As a result of this study, lithological heterogeneity, complex tectonic history, slope of the valley, ground water, the streams and human impact were determined as a main controlling factor for mass movement of the Elmalı Formation.

During the transportation and emplacement of the Yeşilbarak nappe and tectonic forces after the emplacement of this nappe deformed the Elmalı Formations' clastics. Under the effects of compressional and extensional forces, the Elmalı Formation sheared, faulted, fractured, cracked and overturned. The relative ratio of the mudstone and sandstones of the Elmalı Formation is quite changeable. The

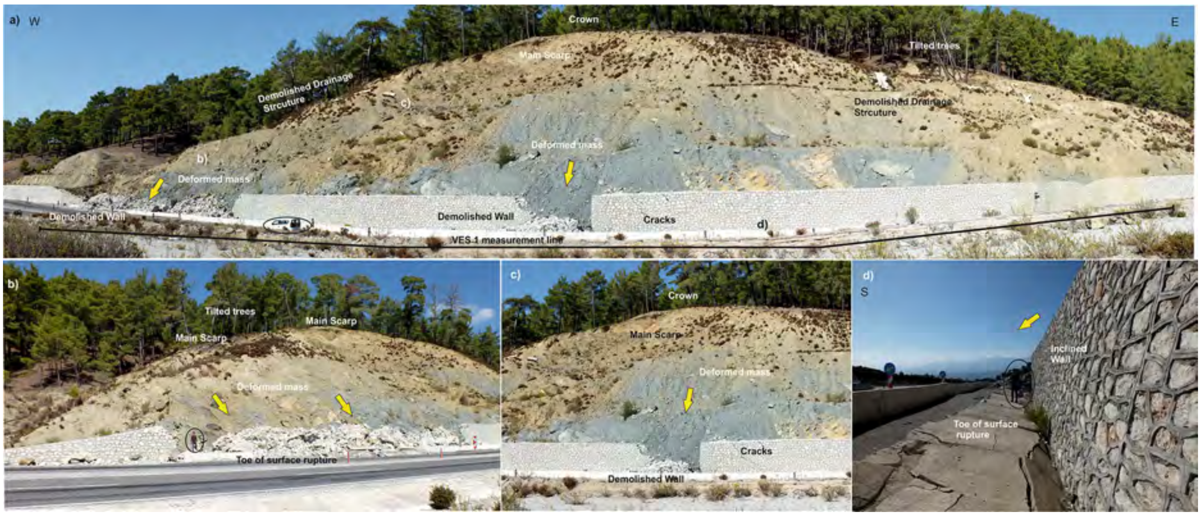


Fig. 8 **a** General view of the complex mass movement in the Bayır District, along the Fethiye-Antalya Highway (car in circle for scale). **b** Detail view of demolished part of the earth retaining wall in the western part (man in a circle for scale: 175 cm). **c** Detail view of demolished part of the earth retaining wall in the middle (man in a circle for scale: 175 cm). **d** Demolished stone walls and surface rupture in concrete drainage channel (man for scale: 175 cm)

Fig. 9 The earthflow evolved due to toe removal of slope by the Cayiçi Stream on both side of its valley

mudstone dominant parts gained chaotic appearance, sheared and behaved like an earth-mass due to intense tectonic activity. The sandstones were also fractured, while thick bedded-massive, durable-hard part preserved its lateral continuity. Geophysical studies point out the slide surface is located at 22 m in the Bayır District and 48–55 m in the Dereköy District (Orak 2017; below the road levels (Fig. 10). The resistant-thick-massive sandstone beds act as slide surface for deformed mudstone (earthflow) through the valley. The thickness and contents of the deformed earth mass point out the earthflow movement according to (Hungr et al. 2014).

There is no mass movement in lowland exposure of the Elmalı Formation. However, low-inclined (< 15°) area has been suffered from the mass wasting in the study area (Fig. 1). The tilted trees-electric pile-fence and bumpy topography point out slow, very slow or extremely slow movement dominantly earthflow and creep (Fig. 11). If there is local disturbance of the slope due to road cut etc., small complex mass movement develops, which also reported at the top of the soil creep-earthflow area by Hungr et al. (2014).

During the field analysis, it was observed that the intense deformation, and more tilted trees were detected in the region where springs and moist ground were found. The tilted trees were mostly detected side

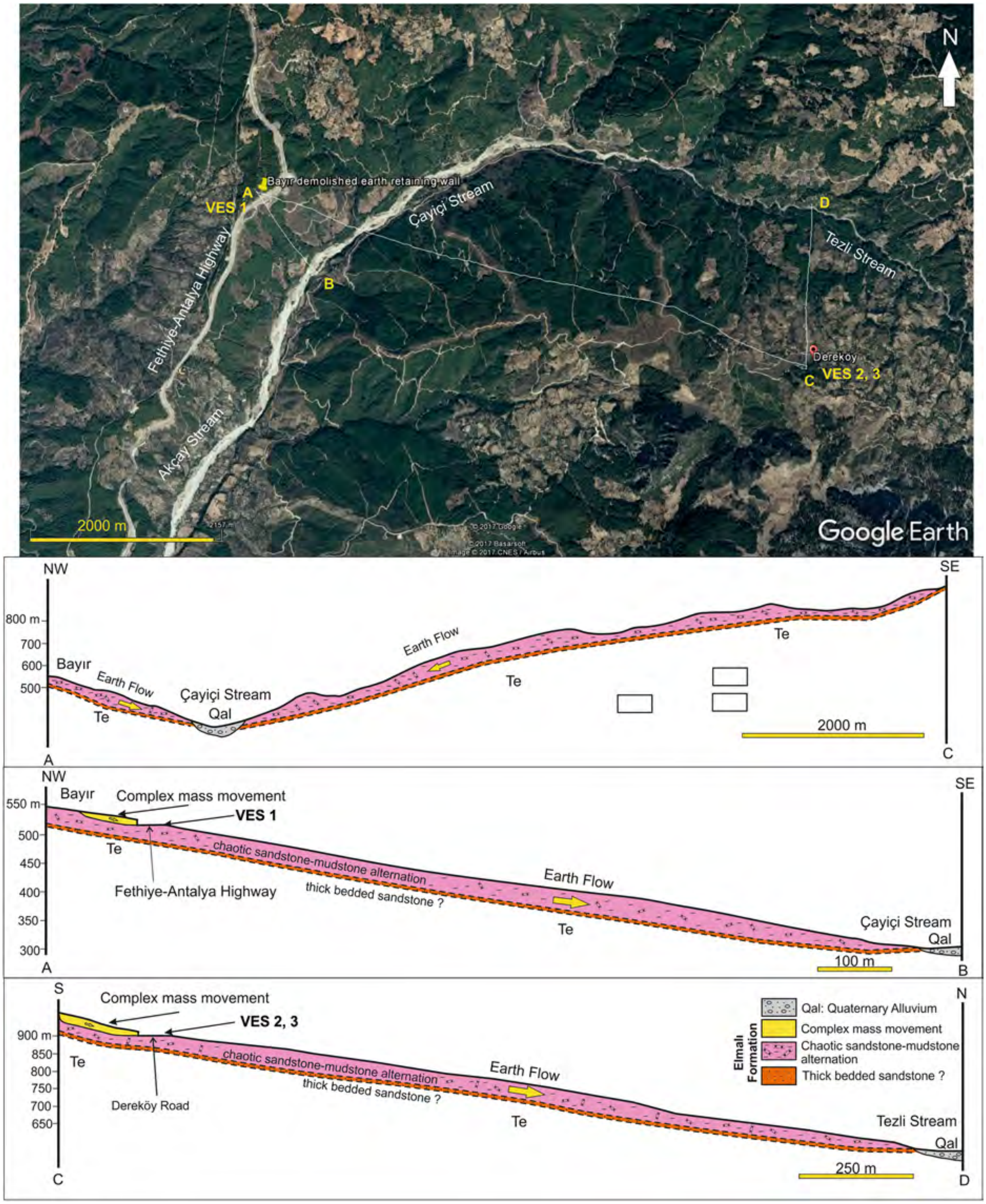


Fig. 10 Topographical sections between the Bayır and Dereköy Districts. The upper surface of the thick bedded sandstone act as a sliding surface. (Te: Elmalı Formation, Qal: Quaternary Alluvium), modified from Google Earth, accessed: 03.05.2017

Fig. 11 **a** Tilted trees due to earth flow in eastern part of Dereköy. **b** Bumpy topography due to earth flow in western part of Dereköy

of the small brook valley. They are only wet during rainy winter and spring season. When the water percolates, sometimes they cut the surface via local sandstone and mudstone contact, or they percolates until the arriving sliding surface. Thus, some temporary spring were also detected in side wall of valley from the contact of the thick sandstone-mudstone surface. The ground water increases unstable slope mass weight and acts as a lubricant on slide surface. This surface is located on top of the thick sandstone bed (Fig. 10). In addition, main mass movement develops along the Tezli Stream, later the Çayiçi Stream and the Akçay Stream valleys (southern side of the valley is Dereköy District, northern side Bayır District). The toe erosion and removal of weathered sediments promote earthflow in low-inclined sides of the valley.

The settlements in the Dereköy and the Bayır Districts are including buildings, gardens, large and small road cuts. In addition, the main road of Fethiye-Antalya is passing in the Bayır District. All of these human impacts create additional disturbances on natural topography that is already under the effect of the earthflow. The local disturbance due to artifical influence led to development local complex mass movements. Relocation decision of the Dereköy District was taken in 1964. However, some old villagers are insisting on using of their old houses and gardens. So, they are under the big risk of the local intense complex mass movement. An improper mass movement protection on the Fethiye-Antalya Highway was not properly working for stopping of the complex mass movement. Additional precautions are necessary in those problematic regions; the result or success of the applications requires continuous monitoring.

This study shows that lithological variation-facies changes of sedimentary rock control the anisotropy of rock. Moreover, the tectonic history increases the heterogeneity and anisotropy of these rocks. Chaotic appeared, mudstones behave like a soil mass. Below this fine-grained sediments, hard, coarse-grained clastic sedimentary rock perform as a sliding surface. The earthflow is expected as a dominant mass movement in the fine-grained clastic sedimentary rock. However, additional effects such as slope disturbances due to natural or artificial reasons (road cut, settlement, garden opening, etc.) led to the development of local but potentially more dangerous complex mass movement. Thus, proper site investigation requires for understanding the characteristics of mass wasting in that types of clastic sedimentary rock.

6 Conclusions

The Upper Eocene-Lower Miocene Elmalı Formation comprises various clastic rocks, including hard sandstone and soft mudstone with variable ratio. The facies characteristic of the formation is responsible for main heterogeneity. In addition, the complex tectonic movement (nappe transportation and emplacement, ongoing post-emplacement tectonic activities) increase this heterogeneity. The tectonic activities also caused sheared, fractured, faulted, overturned geologic units. The hard sandstone act as a sliding surface for thick chaotic-sheared mudstone (that behave like earth mass including sand and finer-grained sediment $> 80\%$). Moreover, erosion and removal of the toe of the slope by streams promote the earthflow type mass movement. The earthflow affects the vast area along the valleys. In addition to these natural effects, the additional slope disturbance (road construction, settlement, garden opening) at the top of this movement led to the formation of small-scale, but dangerous complex mass movement including rotational slide, translational slide, creep, and earthflow. Improper precautions were not obstructed these mass movements. The continuous monitoring, more detailed site investigation, and different precaution methods (change the road route, avoid arbitrary topography changes etc.) must take into consideration.

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