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Magnetic susceptibility of soils as affected by lithology, geomorphology and climate in Jazmoorian Watershed, central Iran

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ABSTRACT: Magnetic susceptibility (MS) as a fast, non-destructive, and reasonable technique is very useful in soil genesis and evolution studies. The MS of soils along a climolithotoposequence in Jazmoorian Watershed was studied in the present research and the vertical distribution of MS in the representative pedons affected by soil forming factors (parent material, climate and relief) was also investigated. Rock pediment, mantled pediment, piedmont plain, alluvial fan, and playa geomorphic positions with two igneous (gabbro, diorite, granite, and andesite) and sedimentary (limestone, conglomerate and playa deposits) parent materials were selected. Thirteen representative pedons which best reflected the variations of soil forming factors were studied. Results of the study showed that the maximum (877.8×10^{-8} m^3 kg^{-1}) and the minimum (5.2×10^{-8} m^3 kg^{-1}) low frequency (χ_{lf}) MS were respectively determined in the soils formed on igneous and sedimentary parent materials. The χ_{lf} values were increased with depth in soils affected by igneous parent material, but the opposite trend was found in soils with a sedimentary origin. The activity ratio of Fe_o/Fe_d in xeric and aridic moisture regimes were 0.03 and 0.09, respectively. Meanwhile, MS value in surface soil of pedon 2 (with xeric moisture regime) is lower than its parent material which is a support for the higher weathering of this soil due to higher moisture compared to pedon 5 with an aridic moisture regime. Decreasing evolution trend of soils on igneous parent material was in the order of alluvial fan < piedmont plain < mantled pediment, but in the soils on sedimentary parent material was in the order of playa < rock pediment < mantled pediment < alluvial fan. Results of the study clearly showed that the soil χ_{lf} values changed with variations in climate, parent material, and topography.

Key words: iron forms, playa, pedogenesis, soil evolution, superparamagnetism

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1. INTRODUCTION

Soil genesis is affected by climate, relief, vegetation cover, parent material, and time (Schaetzl, and Anderson, 2005; Gokbulak and Ozcan, 2008). Variation in each of the soil forming factors causes soils with different properties and horizons to be formed. Relief, parent material, and climate are among the effective factors controlling soil evolution. Magnetic susceptibility affected by single (Ayoubi et al., 2018; Ayoubi and Adman, 2019) or combination of factors (Owliaie et al., 2006; Blundell et al., 2009; Sarmast et al., 2017) has been studied.

Magnetic susceptibility (MS) as a rapid, non-destructive, and low cost method has widely been used in soil studies during the last decades (Dearing et al., 1996; Fontes et al., 2000; Lu et al., 2008; Karimi et al., 2011; Sarmast et al., 2017). Soil MS is highly influenced by soil forming factors including parent material, climate, vegetation, and relief (Feng and Johnson, 1995).

Lithology of parent material is also an effective factor controlling MS (Magiera et al., 2006; Ayoubi et al., 2014; Camargo et al., 2014; Ayoubi and Karami, 2018). Ayoubi et al. (2014) reported that physical weathering of parent material followed by accumulation of resistant primary ferrimagnetic minerals originated by weathering of igneous rocks highly affects magnetic susceptibility in arid environments. Moreover, studying magnetic susceptibility of soils developed on different parent material of western Iran, Ayoubi and Adman (2019) investigated the highest magnetic susceptibility values for ultrabasic and basalt rocks and the least values for limestone and soils developed on these rocks. Study of MS in soils of tropical regions, De Mello et al. (2020) reported the decreasing trend of diabase rocks < metamorphic rocks < sedimentary rocks.

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Climate as another factor influences soil MS (Blundell et al., 2009; Lu et al., 2012). Temperature and precipitation as two climatic factors increase the MS values of surface soils (Lu, 2000). Study the effect of parent material and climate on soil MS values of soils in Saskatchewan, De Jong et al. (2000) concluded that low frequency (χ_{lf}) and frequency dependent (χ_{fd}) MS values in soil samples from A horizons were high. Besides, the increase of MS of topsoil was higher in more humid areas. Increase of precipitation (moisture) not only increases the weathering rate and leaching, but also causes more iron release from mineral structures and increase the relative content of Fe in the pedon which in turn increases soil MS values (Owliaie et al., 2006).

Topography is closely related to drainage and soil particles transport, thus is an important factor controlling MS values (Blundell et al., 2009; Owliaie and Najafi, 2014). De Jong et al. (1998) studied soils along a catena to find out which particle size influences MS of the soil. They investigated an increase of MS in lower positions of the landscape due to alteration of parent material which was related to the variations in the fine earth fraction of the soil. Besides, in another study focused on the variations of MS related to geomorphic positions on a transect covered by Oxisols in Brazil, Camargo et al. (2014) reported the higher MS values in the older geomorphic surfaces. On the other hand, various MS values in diabase parent rocks on tropical environments were found by De Mello et al. (2020). Different geomorphic processes were reported as more effective factors controlling MS compared to lithology.

Although MS values related to soil forming factors were widely studied separately or in pair in the literature, but limited pieces of research have considered the simultaneous effects of three soil forming factors including parent material (igneous and sedimentary), climate (xeric and aridic regimes), and relief (different geomorphic positions) on soil MS and its vertical distribution related to soil genesis. Besides, since no data (including soil MS data) on soils of Jazmoorian Watershed, central Iran is available, the present research was conducted to determine 1) soil MS related to soil forming factors (climate, parent material and relief), 2) the role of MS in soil genesis and development studies in the area.

2. MATERIALS AND METHODS

2.1. Field Studies

Jazmoorian Watershed with the extent of 68378.8 km^2 covers about 7.5% of total area of the watersheds in Iran. The study area is a part of central Iran, Mokran, and southeast Iran zones which is located in Sistan Balouchestan and Kerman Provinces (Fig. 1). The maximum elevation is 4400 m above sea level (a.s.l.) at Shah Mountain, Rabor city and the minimum elevation is 360 m a.s.l. at Jazmoorian playa which show a significant variation in elevation at the watershed. The watershed is mainly consisted of granite, granodiorite, diorite, and andesite igneous rocks and limestone, evaporites (gypsum, soluble salts), conglomerate, and playa sediments (Fig. 1).

Jazmoorian playa is a depression of late Pliocene age (Namaki, 2003). Two main streams enter the Jazmoorian playa. Halilrood River heads from Kerman Province elevations (north of the watershed) and is not saline, but Bampoor River which heads from Iranshahr elevations (east of the watershed) is saline (Fig. 1). Two moisture regimes including xeric (pedons 1 and 2) and aridic (other pedons) are reported in the area (Banaie, 1998), as well as aridic moisture covers about 75% of the area in the watershed. Alluvial plain (pedon 1), mantled pediment (pedons 2 to 7), rock pediment (pedon 8), alluvial fan (pedons 9 to 11), and playa (pedons 12 and 13) are among the dominant landforms investigated in the area (Fig. 1). Considering soil moisture regime, parent material, and relief variations, 13 representative pedons were selected, described, and sampled (Schoeneberger et al., 2012). Figure 1 shows the location of the study area together with the representative pedons.

2.2. Laboratory Studies

Air dried samples were ground and passed through a 2 mm sieve. Low (0.46 kHz, χ_{lf}) and high (4.6 kHz, χ_{hf}) frequency magnetic susceptibilities (MS) were determined using MS2 Bartington magnetic susceptibility meter with MS2B sensor. The frequency related MS was calculated using Equation (1). This is an index that shows the pedogenic ferrimagnetic particles with the diameter of less than 0.03 μm (Dearing, 1999).

$$\%\chi_{fd} = 100\ [(\chi_{lf} - \chi_{hf})/\chi_{lf}]. \qquad (1)$$

Particle size distribution was investigated using pipet method (Gee and Bauder, 1986). The Jenway pH and EC meters were used to determine the pH of saturated paste and EC of saturated extract, respectively. Gypsum was determined by acetone method (Nelson, 1982). Equivalent calcium carbonate was also investigated using back titration (Nelson, 1982). Organic carbon was determined by wet oxidation using potassium di chromate (Nelson and Samners, 1982). Substitution of Na acetate by ammonium acetate at pH = 7 was used for CEC investigation (Bower and Hatcher, 1966). Crystalline, amorphous, and organic forms of iron (pedogenic iron, Fe_d) were extracted by citrate-bicarbonate-dithionate (Mehra and Jackson, 1958) and non-crystalline iron (amorphous and organic, Fe_o) was extracted by ammonium oxalate acid (Schwertmann, 1973). An AAS Varian atomic absorption was used to determine the Fe content in the extracts. The SPSS 16.0 software was used for statistical analyses of the data.

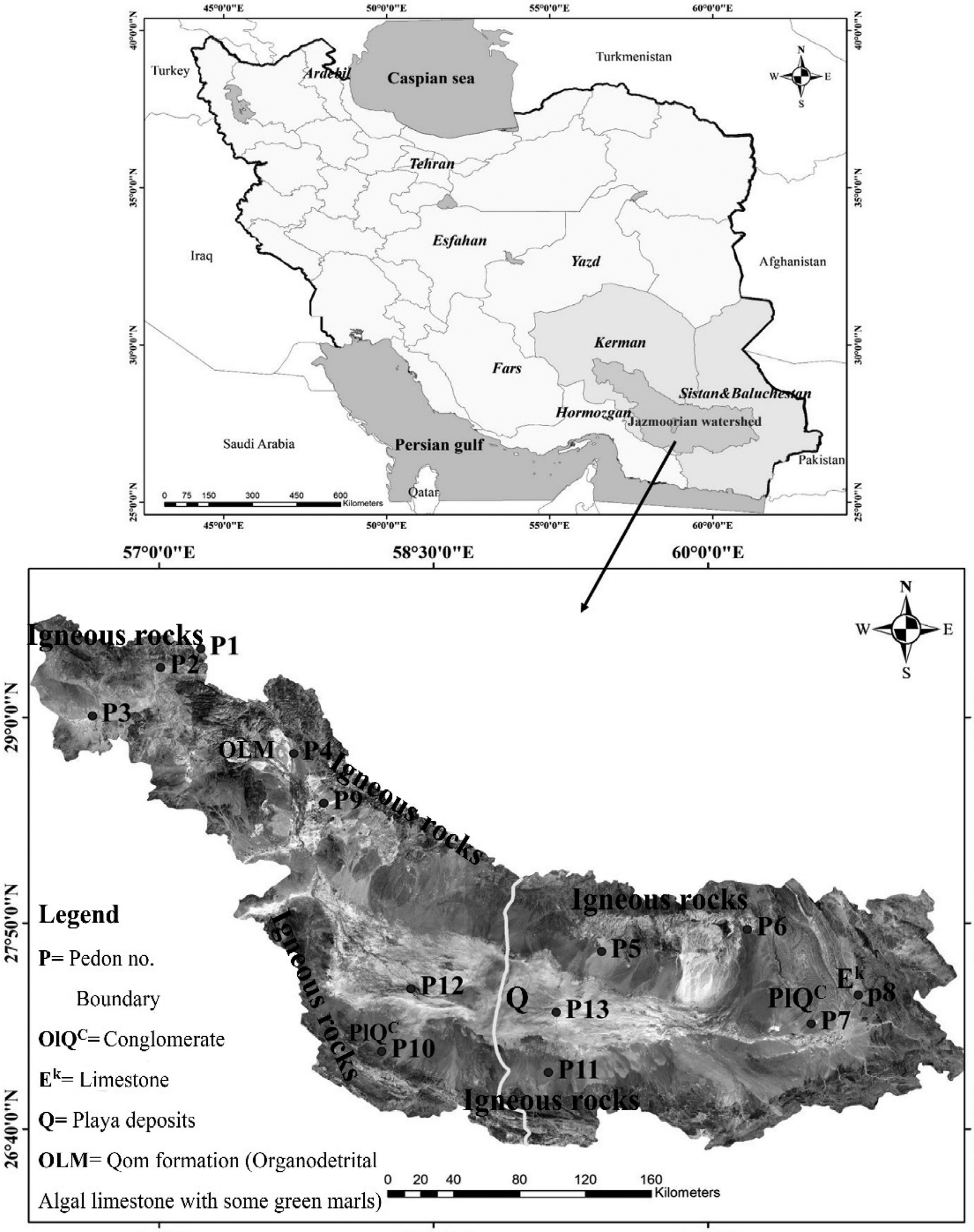

Fig. 1. Location of the study area along with the representative pedons.

Table 1. Selected physical and chemical properties of studied pedon

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	ECe[a] (dS m^{-1})	CCE[b] (%)	Gypsum (%)	OC[c] (%)	Fe$_o$[d]	Fe$_d$[e]	Fe$_d$-Fe$_o$	χ_{lf}[f]	χ_{hf}[g]	χ_{fd}[h] (%)	Fe$_o$/Fe$_d$
										g kg^{-1}			× 10^{-8} m^3 kg^{-1}			
Pedon 1, piedmont plain, 3620 m a.s.l.[i]; Mean Fe$_o$/Fe$_d$: 0.2; Mean χ_{lf}: 402.18; Diorite																
A	0–20	15.1	46.6	38.3	6.5	1.2	2.0	ng[j]	3.5	2.1	20	17.9	220.6	219.0	0.73	0.1
Bw1	20–45	19.1	50.6	30.3	6.0	0.7	1.0	ng	1.2	0.5	18	17.5	272.1	270.7	0.51	0.03
Bw2	45–80	27.1	48.6	24.3	6.4	0.5	0.7	ng	0.7	5.0	17	12.0	577.1	572.9	0.73	0.3
Bg	80–100	11.1	52.6	36.3	6.5	0.4	1.7	ng	0.9	1.6	4	2.4	63.3	63.1	0.32	0.4
C	100–140	37.1	44.6	18.3	6.6	0.5	1.2	ng	0.5	5.0	22	17.0	877.8	875.7	0.24	0.2
R	< 140	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pedon 2, mantle pediment, 2247 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.03; Mean χ_{lf}: 258.7; Andesite																
A	0–13	39.1	39.3	21.6	7.2	1.4	8.5	ng	0.5	0.4	15	14.6	222.4	221.1	0.6	0.03
Btk	13–45	35.1	37.3	27.6	7.9	0.9	26.2	ng	0.6	0.2	13	12.8	245.4	243.1	0.94	0.02
Ck	45–85	71.1	13.3	15.6	7.8	0.8	17.7	ng	0.3	0.5	15	14.5	571.2	566.7	0.79	0.03
C	85–105	77.1	9.3	13.6	7.6	0.6	14.0	ng	0.2	1.0	16	15.0	510.7	508.0	0.53	0.06
2Btk	105–145	7.1	65.3	27.6	7.7	0.6	15.0	ng	0.1	0.3	12	11.7	63.4	62.9	0.79	0.02
2Bk1	145–175	23.1	58.6	18.3	8.0	0.7	24.0	ng	0.1	0.2	9	8.8	127.7	126.6	0.86	0.02
2Bk2	175–215	11.1	68.6	20.3	7.9	0.7	44.2	ng	0.1	0.2	6	5.8	70.3	69.8	0.71	0.03
Pedon 3, mantle pediment, 1977 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.09; Mean χ_{lf}: 49.7; Limestone																
A	0–5	37.1	41.3	21.6	8.0	0.5	26.5	ng	0.4	0.4	8	7.6	90.6	89.2	1.55	0.05
Btk1	5–35	23.1	39.3	37.6	8.3	1.2	28.7	ng	0.3	0.2	6	5.8	65.3	63.6	2.6	0.03
Btk2	35–72	25.1	35.3	39.6	7.8	5.6	28.2	ng	0.3	0.2	6	5.8	59.0	57.5	2.54	0.03
C	72–78	57.1	17.3	25.6	7.8	5.5	19.5	ng	0.1	0.5	5	4.5	73.0	72.0	1.37	0.1
2Btnk	78–100	43.1	27.3	29.6	7.9	4.7	22.2	ng	0.1	0.3	4	3.7	60.0	59.1	1.5	0.07
2Btnkk1	100–135	1.12	53.3	45.6	8.3	2.8	51.2	ng	0.1	0.3	3	2.7	21.5	20.7	3.75	0.1
2Btnkk2	135–185	0	58.4	41.6	8.2	3.3	50.7	ng	0.1	0.2	2	1.8	22.8	22.3	2.19	0.1
2Ck	> 185	0	89.4	10.6	8.0	3.6	88.9	ng	ng	0.1	0.6	0.5	5.2	5.0	3.8	0.17
Pedon 4, mantle pediment, 897 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.04; Mean χ_{lf}: 354.17; Diorite																
A	0–20	75.7	12.9	11.4	7.6	2.7	9.5	ng	0.2	0.4	16	15.6	224.0	222.3	0.7	0.02
Btk	20–55	70.7	14.9	14.4	8.0	1.1	16.5	0.7	0.2	0.5	14	13.5	287.1	285.6	0.5	0.04
By	55–85	89.7	1.9	8.4	8.0	1.3	14.5	5.2	0.2	0.6	12	11.4	429.7	427.8	0.4	0.05
C	85–135	90.7	2.9	6.4	8.2	1.4	10.0	5.5	0.3	1.0	18	17.0	475.9	471.4	0.9	0.05
Pedon 5, mantled pediment, 490 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.09; Mean χ_{lf}: 239.35; Andesite																
A	0–10	55.8	33.3	10.9	7.4	43.5	37.7	0.7	0.4	1.0	12	11.0	315.5	310.8	1.49	0.08
Bkyzn1	10–35	47.8	41.3	10.9	7.1	140.5	27.2	19.4	0.4	0.4	8	7.6	163.7	161.5	1.34	0.05
Bkyzn2	35–65	61.8	28.6	9.6	7.3	84.7	24.5	24.2	0.1	0.6	7	6.4	177.5	175.5	1.13	0.09
Bkyzn3	65–110	53.8	32.6	13.6	7.3	99.6	34	15.8	0.2	0.4	6	5.6	220.7	217.3	1.54	0.07
Bkyzn4	110–160	51.8	38.6	9.6	7.6	96.1	47.5	7.5	0.8	0.8	9	8.2	232.1	227.8	1.85	0.09
Ck	160–190	69.8	20.6	9.6	7.6	9.45	45.0	0.1	0.1	2.0	14	12.0	326.6	322.0	1.41	0.14
Pedon 6, mantle pediment, 860 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.03; Mean χ_{lf}: 326.15; Granodiorite																
A	0–15	79.1	8.6	12.3	7.7	5.6	8.2	ng	0.1	0.6	16	15.4	338.2	334.0	1.24	0.04
Bk	15–40	76.5	15.3	8.2	7.4	9.2	16.0	ng	0.1	0.3	14	13.7	347.5	345.2	0.66	0.02
Btk	40–55	56.5	25.3	18.2	7.3	25.5	16.2	0.6	0.1	0.2	16	15.8	385.4	380.1	1.38	0.01
Btkyz	55–80	64.5	15.3	20.2	7.6	20.9	16.7	7.4	0.1	0.8	20	19.2	599.6	591.9	1.28	0.04
Btnkyz1	80–140	66.5	15.3	18.2	7.6	19.8	15.5	5.8	0.1	0.5	12	11.5	147.7	145.7	1.35	0.04
Btnkyz2	140–175	52.5	29.3	18.2	7.5	22.3	17.5	6.3	ng	0.5	12	11.5	138.5	136.1	1.73	0.04
Pedon7, mantle pediment, 613 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.07; Mean χ_{lf}: 124.85; Conglomerate																
A	0–15	70.0	16.0	14.0	7.5	2.0	16.0	0.1	0.1	0.6	8	7.4	223.4	220.6	1.25	0.07
Bty	15–45	38.0	38.0	24.0	7.7	6.1	5.7	40.7	ng	0.3	6	5.7	102.6	100.9	1.66	0.05
Btnyz1	45–75	36.0	34.0	30.0	7.6	43.5	10.0	38.2	0.1	0.4	5	4.6	93.0	91.7	1.4	0.08
Btnyz2	75–120	46.0	18.0	36.0	7.6	58.6	8.0	37.5	0.1	0.4	5	4.6	90.0	89.0	1.11	0.08
Btnyz3	120–155	46.0	32.0	22.0	7.9	45.2	8.5	25.5	0.1	0.5	4	3.5	113.1	112.4	0.62	0.12
Btny	155–185	34.0	36.0	30.0	8.2	24	16.7	5.3	0.1	0.3	6	5.7	127.7	125.3	1.88	0.05

Table 1. (continued)

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	ECe$^{(a)}$ (dS m^{-1})	CCE$^{(b)}$ (%)	Gypsum (%)	OC$^{(c)}$ (%)	Fe$_o$$^{(d)}$	Fe$_d$$^{(e)}$	Fe$_d$-Fe$_o$	$\chi_{lf}$$^{(f)}$	$\chi_{hf}$$^{(g)}$	$\chi_{fd}$$^{(h)}$ (%)	Fe$_o$/Fe$_d$
										g kg^{-1}			× 10^{-8} m^3 kg^{-1}			
Pedon 8, rock pediment, 793 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.08; Mean χ_{lf}: 99.98; limestone																
A	0–40	56.4	34.6	9.0	7.8	1.0	19.2	ng	0.1	0.4	7	6.6	133.3	131.8	1.13	0.06
Btk1	40–80	50.4	34.6	15.0	7.8	0.8	20.0	ng	0.2	0.2	6	5.8	119.9	118.3	1.33	0.03
Btk2	80–105	46.4	36.6	17.0	7.8	1.8	15.2	ng	0.1	0.2	5	4.8	104.2	103.2	0.96	0.04
C	105–110	56.4	28.6	15.0	7.8	2.1	16.5	ng	0.1	1.4	6	4.6	101.0	100.9	0.1	0.2
2Btk	110–125	48.4	36.6	15.0	7.6	3.6	21	0.1	0.1	0.3	5	4.7	85.7	84.9	0.93	0.06
2Bty	125–150	43.0	38.3	18.7	7.6	3.5	10.7	24.0	0.1	0.2	4	3.8	60.9	60.4	0.82	0.05
2Cy	150–170	64.5	25.3	10.2	7.7	3.8	14.0	17.6	0.1	0.6	4	3.4	94.9	94.4	0.53	0.15
Pedon 9, alluvial fan, 700 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.24; Mean χ_{lf}: 305.24; Granite																
A	0–15	91.4	3.0	5.6	8.1	0.5	4.0	ng	0.5	5.0	16	11.0	353.9	353.2	0.2	0.3
C1	15–45	95.4	1.0	3.6	8.2	0.3	0.5	ng	0.3	4.0	11	7.0	321.7	319.9	0.6	0.4
C2	45–75	96.4	1.0	2.6	8.2	0.3	6.5	ng	0.1	0.5	10	9.5	296.9	296.5	0.1	0.05
C3	75–110	97.4	1.0	1.6	8.2	0.3	4.0	ng	0.1	5.0	12	7.0	253.6	253.1	0.2	0.4
C4	110–145	97.1	1.0	1.9	7.9	0.3	3.7	ng	ng	0.5	14	13.5	300.1	298.6	0.5	0.04
Pedon 10, alluvial fan, 680 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.03; Mean χ_{lf}: 153.2; Conglomerate																
A	0–30	39.8	24.0	36.2	8.0	0.6	8.7	0.1	0.2	0.3	13	12.7	229.6	228.3	0.7	0.02
Btk	30–70	29.8	22.0	48.2	7.7	0.5	15.5	0.1	0.1	0.2	12	11.8	191.5	190.4	0.6	0.02
Bk	70–110	75.8	14.0	10.2	8.1	0.7	18.0	0.2	0.1	0.3	9	8.7	102.6	101.2	1.4	0.03
C	110–150	87.8	4.44	8.2	7.9	0.9	22.7	0.1	0.7	0.5	7	6.5	90.5	89.1	1.5	0.07
Pedon 11, alluvial fan, 632 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.1; Mean χ_{lf}: 366.23; Gabbro																
A	0–10	60.4	22.6	17.0	7.7	7.0	13.7	ng	0.1	0.6	16	15.4	327.5	325.3	0.67	0.04
C1	10–20	83.1	6.6	10.3	8.2	1.7	12	ng	0.1	2.0	18	16.0	374.7	371.3	0.91	0.11
C2	20–40	91.1	0.6	8.3	7.8	6.1	9.7	ng	ng	4.0	21	17.0	558.0	557.4	0.11	0.19
C3	40–90	92.4	0.6	7.0	7.5	27.2	11.5	ng	0.1	1.4	14	12.6	314.1	312.6	0.48	0.1
C4	90–100	90.4	2.6	7.0	7.5	25.1	9.0	ng	0.1	0.4	10	9.6	256.2	254.4	0.7	0.04
C5	100–140	91.8	0.6	7.6	7.4	18.8	14.5	ng	0.1	2.0	15	13.0	366.9	364.4	0.68	0.13
Pedon 12, playa (fan delta), 378 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.2; Mean χ_{lf}: 244.36; Playa deposits																
A	0–20	32.4	46.6	21.0	7.5	1.8	13.0	ng	0.2	1.0	17	16.0	290.5	287.2	1.14	0.06
C1	20–55	62.4	26.6	11.0	7.9	0.5	14.0	ng	0.1	5.0	14	9.0	248.1	245.6	1.01	0.36
C2	55–85	2.4	60.6	37.0	8.3	1.2	16.7	ng	0.1	0.4	15	14.6	185.1	183.5	0.86	0.03
C3	85–130	28.4	54.6	17.0	8.5	1.3	16.2	ng	0.1	0.9	13	12.1	219.2	215.8	1.55	0.07
C4	130–160	50.4	36.6	13.0	8.4	1.0	14.7	ng	0.2	6.0	13	7.0	281.9	279.0	1.03	0.46
Pedon 13, playa (clay flat), 367 m a.s.l.; Mean Fe$_o$/Fe$_d$: 0.07; Mean χ_{lf}: 74.28; Playa deposits																
Az	0–30	0.0	64.2	35.8	7.2	92.7	13.5	0.1	0.4	0.5	7	6.5	65.8	65.6	0.3	0.07
Bzn	30–60	0.0	62.2	37.8	7.3	63.8	11.0	0.5	0.3	0.4	5	4.6	64.1	63.2	1.4	0.08
Btnz	60–90	0.0	56.2	43.8	7.6	48.7	11.2	0.3	0.3	0.5	6	5.5	69.0	67.2	2.61	0.08
Bzn1	90–115	0.0	58.2	41.8	7.7	43.5	14.0	0.3	0.3	0.3	5	4.7	81.3	80.2	1.35	0.06
Bzn2	115–135	1.1	68.6	30.3	8.4	34.3	15.0	0.1	0.1	0.4	5	4.6	81.4	80.0	1.72	0.08
Bzn3	135–175	3.1	60.6	36.3	8.4	31.8	13.2	1.3	0.1	0.5	5	4.5	84.1	82.0	2.5	0.1

(a)ECe: electrical conductivity of soil saturated paste, (b)CCE: calcium carbonate equivalent, (c)OC: organic carbon, (d)Fe$_o$: oxalate extractable iron, (e)Fe$_d$: dithionite-citrate-bicarbonate extractable iron, (f)χ_{lf}: low frequency magnetic susceptibility, (g)χ_{hf}: high frequency magnetic susceptibility, (h)χ_{fd}: frequency dependence magnetic susceptibility, (i)a.s.l.: above sea level, (j)ng: negligible.

3. RESULTS

3.1. Magnetic Susceptibility of Soils from Igneous Origin

The MS values of soils on igneous parent material were in the range of 253.6 × 10^{-8} m^3 kg^{-1} (in C3 horizon of pedon 9) to 887.8 × 10^{-8} m^3 kg^{-1} (in the C horizon of pedon 1) (Table 1). The maximum MS of soils on ultrabasic and basic igneous parent materials in western Iran was reported by Ayoubi and Adman (2019) as > 1201 × 10^{-8} m^3 kg^{-1}. Besides, the mean χ_{lf} value in soils developed on igneous parent material (gabbro, diorite, granite, and andesite) in the present study was 320 × 10^{-8} m^3 kg^{-1}. Lu (2000) also reported the soil MS on basalt, andesite, and granodiorite as > 250 × 10^{-8} m^3 kg^{-1}. The mean MS values on gabbro, diorite, granite, and andesite parent material were 366 × 10^{-8} m^3 kg^{-1}, 360 × 10^{-8} m^3 kg^{-1}, 305 × 10^{-8} m^3 kg^{-1}, and 249 × 10^{-8} m^3 kg^{-1}, respectively. The decreasing trend of χ_{lf} values in soils on different igneous parent material were as andesite < granite < diorite < gabbro. The same results were also reported by Sarmast et al. (2017) and Ayoubi and Adman (2019) in central and western parts of Iran, respectively.

As Table 1 shows, the χ_{lf} values in soils with igneous parent material were high, but the χfd values were low. The MS values at the frequencies of 0.46 khz (χ_{lf}) and 4.6 khz (χ_{hf}) are similar (Table 1). The small difference of MS at the two frequencies (χ_{fd} ≤ 2%) show that pedogenic super paramagnetic particles (0.02 μm) pay an insignificant role in MS of soils under study (Dearing, 1999; Sarmast et al., 2017). The χ_{fd} values of soils on igneous parent material under study (0.1–1.85%) show that no significant change on the relative portion of super paramagnetic particles during soil formation has taken place. Dearing (1999) also reported that soils not consisting of super paramagnetic particles commonly show χ_{fd} values of < 5%. At the same time, he reported 2 ≥ or 0 for the χ_{fd} in the samples with the diameter of < 0.03 μm. Due to above findings it could be concluded that the main source of χ_{lf} in soils of Jazmoorian area is inheritance from igneous parent material. Besides, lack of correlation between χ_{fd} and Fe_d-Fe_o is another reason for the dependency of soil MS with ferrimagnetic particles inherited from igneous parent material which was also supported by Sarmast et al. (2017).

3.2. Magnetic Susceptibility of Soils with Sedimentary Origin

The range of soil MS (Table 1) developed on sedimentary rocks (limestone, conglomerate, and playa deposits) was from 5.2 × 10^{-8} m^3 kg^{-1} (Ck horizon, pedon 3) to 281.9 × 10^{-8} m^3 kg^{-1} (2C horizon, pedon 12). The mean χ_{lf} of 124 × 10^{-8} m^3 kg^{-1} was investigated for soils developed on sedimentary rocks. Range of 71.09 × 10^{-8} m^3 kg^{-1} to 264.76 × 10^{-8} m^3 kg^{-1} was reported by Ayoubi and Adman (2019) for MS of soils with a sedimentary parent material. The mean χlf values for soils formed on playa deposits, conglomerate, and limestone were 159 × 10^{-8} m^3 kg^{-1}, 139 × 10^{-8} m^3 kg^{-1}, and 75 × 10^{-8} m^3 kg^{-1}, respectively which shows a decreasing trend of limestone < conglomerate < playa deposits for χ_{lf} values. The decreasing trend of χ_{lf} for soils formed from sedimentary parent material in western Iran was in the order of limestone < Qom Formation < shale < marl as reported by Ayoubi and Adman (2019). Unlike the soils on igneous rocks, sedimentary originated soils showed low χ_{lf} and high χ_{fd} values (Table 1). The MS in both frequencies (χ_{fd} < 4%) compared to frequency related MS in soils formed on igneous parent material (2%) clearly showed more contribution of mainly pedogenic super paramagnetic particles (0.02 μm) in the samples under study which was also supported by Lu (2000). Thus, the χ_{fd} values of soils formed on sedimentary formations (0.1–3.8%) proved the variation in relative fraction of pedogenic super paramagnetic particles during soil formation. It seems that soils on sedimentary parent material were of two origins (inherited and pedogenic) in the area.

4. DISCUSSION

4.1. Magnetic Characteristics of Different Soil Types

The correlation between χ_{lf} and selected soil characteristics is presented in Table 2. A positive significant correlation among χ_{lf} and Fe_d, Fe_o, and Fe_d-Fe_o was found (Fig. 2, Table 2). The positive significant correlation could be attributed to the magnetic property of iron containing minerals. On the other hand, a negative correlation among χ_{lf} and soil characteristics including calcium carbonate, gypsum, and more soluble salts was observed which shows the decreasing effect of diamagnetic material on χ_{lf} values (Sarmast et al., 2017; Ayoubi and Adman, 2019).

As Table 2 shows, clay, and silt have negative, but sand content has positive correlation with χ_{lf} in soils of the area (Fig. 2, Table 2). Study of soil MS in southeast Iran, Sarmast et al. (2017) reported that diamagnetic material such as organic carbon, equivalent calcium carbonate, and soluble salts together with silt and clay contents have decreased the MS in soil which is a support for the findings of the present research. The positive significant correlation of χ_{lf} and sand percentage (Table 2) shows the role of primary magnetic minerals (crystalline) which have inherited from the igneous parent material (Fontes et al., 2000; Sarmast et al., 2017). Alekseev et al. (2002) also reported that the crystalline iron forms are basically coarser than clay size.

4.2. Vertical Distribution of Magnetic Susceptibility

Figure 1 shows the location of studied pedons. The variations

Table 2. Correlation among magnetic susceptibility (χ), frequency dependent susceptibility (χ_{fd}) and some soil properties

	Sand	Silt	Clay	EC	CCE	Gypsum	OC	Fe_o	Fe_d	Fe_d-Fe_o	Fe_o/Fe_d
χ_{lf}	0.505(a)	−0.476(a)	−0.424(a)	−0.168	−0. 323(a)	−0.190	0.073	0.515(a)	0.834(a)	0.763(a)	0.175
χ_{fd}	−0.511(a)	0.507(a)	0.382(a)	0.147	0.703(a)	0.037	−0.127	−0.356(a)	−0.516(a)	−0.463(a)	−0.205

(a)Stands for significance of the correlations at probability level and 0.01.

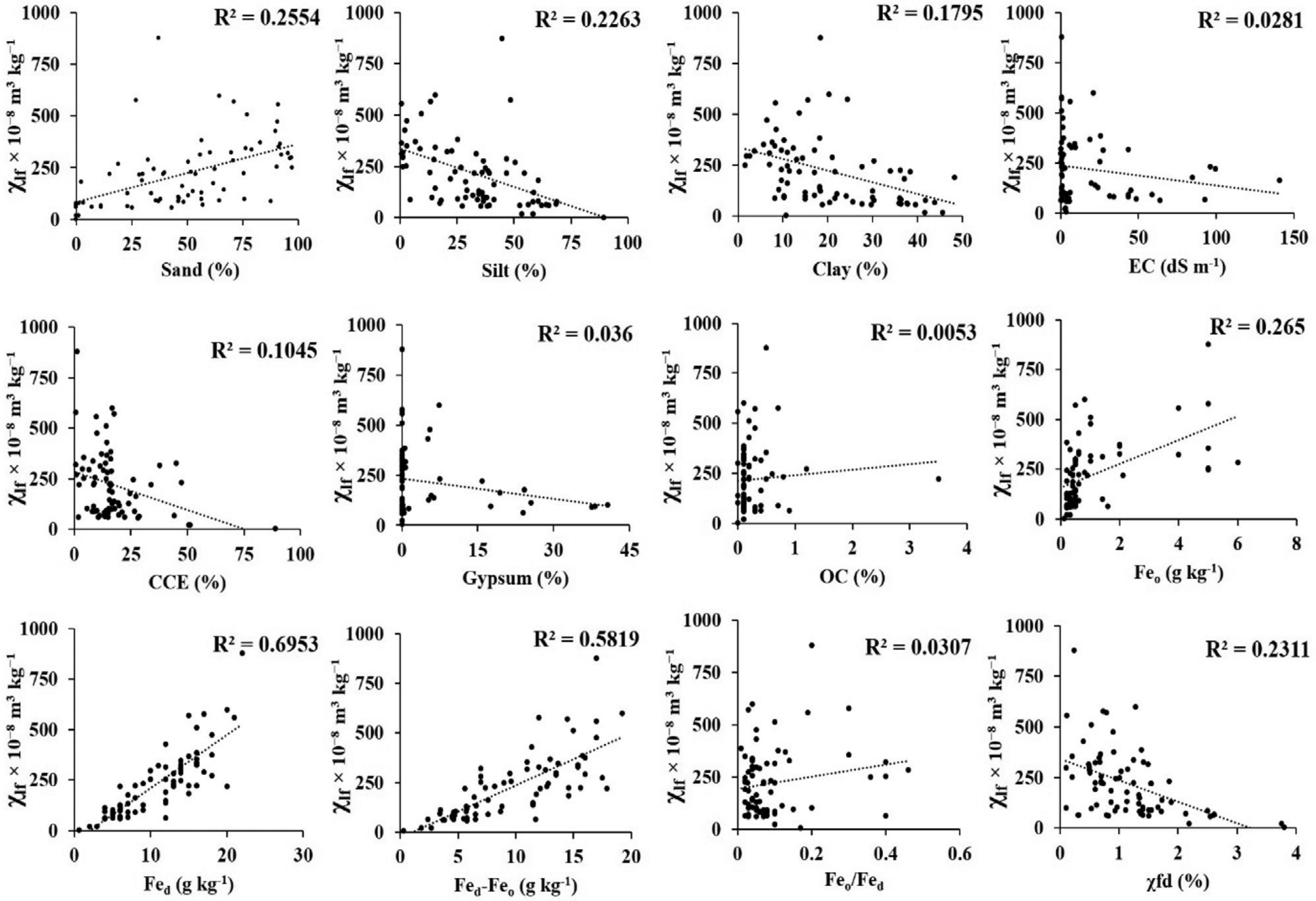

Fig. 2. Relationship between magnetic susceptibility (χ_{lf}) and some soil properties.

of χ_{lf} values with depth is presented in Figure 3. Vertical distribution of χ_{lf} values in soils affected by parent material, relief, and climate was studied.

Pedon 1 was located on piedmont plain covered by lawn vegetation and on a diorite parent material. The soil moisture regime for this pedon is xeric. This soil lacked gypsum. Besides, calcium carbonate equivalent was less than 2% and the EC contents in the A and C horizons were 1.2 and 0.5 dS/m (Table 1), respectively which are proofs of small diamagnetic material. However, organic carbon as a diamagnetic material in the surface soil was 3.5% which has decreased the χ_{lf} value at the soil surface. The χ_{lf} values (Table 1, Fig. 3) increased with depth (220.6×10^{-8} m^3 kg^{-1} in A horizon compared to 877.8×10^{-8} m^3 kg^{-1} in C horizon). Due to the low diamagnetic material content, the decreased χ_{lf} value of 63×10^{-8} m^3 kg^{-1} in Bg horizon could be attributed to the water logging conditions which was provided by small sand (11%) and high clay (36%) contents in this horizon (Table 1). It is to be noted that no water logging condition at the upper and lower horizons compared to Bg was observed. This pedon was located about 3600 m a.s.l. Due to high precipitation (rain and snow) and the slow permeability of soil resulted by increase in clay and decrease in sand contents, water logging has taken place which in turn caused Fe^{+3} to be changed to Fe^{+2}, decreasing soil MS (Owliaie and Najafi, 2018). Studying soils of western Iran, Asgari et al. (2018) reported magnetic susceptibility as a useful technique for separating soil drainage classes. They investigated the maximum MS values for soils with suitable drainage conditions and the minimum MS values for poor drained soils.

Pedon 2 was located on mantled pediment with andesite parent material and xeric moisture regime. Lithological discontinuity was found in this pedon (Table 1) which was also supported by the decrease of χ_{lf} values in 2Btk horizon (Table 1, Fig. 3). The continuing decrease of χ_{lf} in lower depths of this pedon (about 2247 m a.s.l. with relatively high precipitation) could be attributed to calcium carbonate (as a diamagnetic material) illuviated from upper horizons. The same findings were also reported for soils of southeast Iran by Sarmast et al. (2017). Lithological discontinuity and soil re-deposition cause anomaly in soil MS (Oades, 1963). The χ_{lf} value in A horizon was about 224×10^{-8} m^3 kg^{-1} which was less than the value for C (as parent material) horizon (Table 1). Due to more humidity of A horizon compared to C, more weathering and soil formation processes performed in the surface soil. That is why the primary ferrimagnetic particles in A horizon have weathered to the second (pedogenic) ferrimagnetics. This could be a reason for lower χ_{lf} value of surface soil compared to C horizon.

Pedon 3 was located on mantled pediment about 2000 m a.s.l. with limestone parent material and a weak aridic soil moisture regime. The χ_{lf} values decreased (Table 1, Fig. 3) with depth (90.6×10^{-8} $m^3 kg^{-1}$ in A horizon and 5.2×10^{-8} $m^3 kg^{-1}$ in 2Ck horizon). Lu (2000) also reported the χ_{lf} values of soils on limestone in the range of 50×10^{-8} $m^3 kg^{-1}$ to less than 10×10^{-8} $m^3 kg^{-1}$. Two reasons for the decrease of χ_{lf} in pedon 3 could be responsible. The leaching of calcium carbonate and soluble salts from topsoil and their accumulation in subsurface horizons seems to be the first and the parent material enriched by calcium carbonate close to subsurface horizons is probably the second reason. The high χ_{lf} value in the topsoil could probably be due to the leaching of diamagnetic material such as calcium carbonate from one hand, and the formation of pedogenic ferrimagnetic minerals in the surface soil, from the other hand (Lu, 2000). The increase of MS in soils developed on limestone in China was also attributed to the increase of pedogenic super paramagnetic particles which caused due to limestone weathering (Lu et al., 2012).

Pedon 4 was located on mantled pediment about 900 m a.s.l. with diorite parent material and aridic moisture regime. Magnetic susceptibility increased with depth in this pedon. Physical weathering of parent material (rock) was first released primary ferrimagnetic material and formed C horizon. Continuing removal of weatherable minerals and calcium carbonate caused the original material to be enriched by primary ferrimagnetic material (Singer and Fine, 1989). The following drought periods have caused primary ferrimagnetic particle to be preserved and calcium carbonate to be illuviated as nodule in the pedon (Btk horizon). This is the reason for higher $CaCO_3$ and lower χ_{lf} contents of Btk compared to C horizons. Continued weathering and soil formation processes caused fine sized pedogenic particles to be formed from primary ferrimagnetic particles with time (Lu, 2000). Thus, χ_{lf} value of Btk horizon is low due to the decrease of primary ferrimagnetic particles from one hand, and the increase of diamagnetic calcium carbonate along the soil formation from the other hand. This was also supported by the findings of Sarmast et al. (2017) for soils of southeast Iran.

Pedon 5 on mantled pediment was located at 490 m a.s.l. on andesite parent material and with an aridic soil moisture regime. The χ_{lf} values in this pedon showed decreasing (from 315.5×10^{-8} $m^3 kg^{-1}$ in surface soil to 163.7×10^{-8} $m^3 kg^{-1}$) and increasing (to 326.6×10^{-8} $m^3 kg^{-1}$ in Ck horizon) trends with depth (Table 1, Fig. 3). The decrease of χ_{lf} in Bkyzn1 and Bkyzn2 horizons could be due to the leaching of diamagnetic material from surface soil down to the mentioned horizons (Owliaie et al., 2006; Ayoubi and Mirsaidi, 2018). The increase of χ_{lf} in Ck horizon is probably due to the low weathering rate in aridic moisture regime of this pedon which caused the MS values of the horizons to be a function of primary ferrimagnetic particles.

Pedon 6 was located on mantled pediment about 860 m a.s.l. on granodiorite parent material with an aridic moisture regime. The χ_{lf} values increased (Table 1, Fig. 3) with depth (down to 80 cm). The increase of χ_{lf} in Btkz horizon is probably due to weathering and soil formation processes that caused destruction of primary ferrimagnetic particles in surface layers. Besides, leaching of pedogenic ferrimagnetic minerals (Fe_d-Fe_o) from surface soil toward Btkz horizon could also played a role. Considering the present aridic soil moisture regime, it seems that high weathering rate and argillic horizon formation have been due to the more available humidity of the past climate in the area which was also supported by Sarmast et al. (2017). The decreasing trend of χ_{lf} toward depth was seemingly affected by the diamagnetic material such as calcium carbonate, gypsum, and more soluble salts leached from topsoil.

Pedon 7 was selected on mantled pediment about 613 m a.s.l. with a conglomerate parent material close to evaporite deposits and with an aridic soil moisture regime. The maximum χ_{lf} value of 223.4×10^{-8} $m^3 kg^{-1}$ was determined in the A horizon (Table 1, Fig. 3) which showed a decreasing trend with depth (90×10^{-8} $m^3 kg^{-1}$ in Btnyz2 horizon). The different χ_{lf} values were probably due to the presence of more diamagnetic material such as gypsum and soluble salts in subsurface horizons compared to topsoil (Ayoubi and Mirsaidi, 2018). As Table 1 shows, gypsum and soluble salts increased with depth in this pedon.

Pedon 8 on rock pediment with a limestone parent material was located about 800 m a.s.l. in an aridic soil moisture regime. Calcium carbonate distributed all through this pedon caused a relatively uniform distribution of MS in the soil. The more decreased χ_{lf} values in subsurface horizons were attributed to the accumulation of gypsum together with calcium carbonate compared to topsoil. Due to weathering in topsoil and the increase of mainly pedogenic super paramagnetic particles (0.02 μm) occurred with the leaching of diamagnetic material, the χ_{lf} in topsoil was higher than C horizon. The same results were also reported by Sarmast et al. (2017) in the study of soils in central Iran.

Pedon 9 was located on alluvial fan at about 700 m a.s.l. with granite parent material and aridic soil moisture regime. Vertical distribution of MS showed a decreasing trend in this fluvisol (Table 1, Fig. 3). The same trend in vertical distribution of χ_{lf} was also observed is soils of central Iran with a granite parent material by Sarmast et al. (2017).

Pedon 10 was located on alluvial fan about 680 m a.s.l. with conglomerate parent material close to calcareous sediments and with an aridic soil moisture regime. The increase of χ_{lf} value at the surface soil compared to parent material was attributed to the weathering processes. Besides, increase of soil forming processes at the surface which in turn increased the pedogenic super paramagnetic particles, could not be neglected. Since the present climate in this part of Jazmoorian Watershed is arid, the considerable weathering in the topsoil could be attributed to the warm and more humid climate of the past. The high MS of paleosols in central parts of China was also related to the humid climate of the area as reported by Lu et al. (2018). The same results were also reported by Fine et al. (1989).

Pedon 11 was selected on alluvial fan at about 632 m a.s.l. on gabbro parent material and in aridic moisture regime. Vertical distribution of MS in this pedon varied due to sedimentation of different size particles (De Mello et al., 2020). Deposition of different sized particles along time periods with various climatic regimes, caused an irregular distribution of χ_{lf} in this pedon (Table 1, Fig. 3). Similar to pedon 9, this pedon was also located in alluvial fan with an aridic soil moisture regime, but difference in parent material caused different MS values in these pedons.

Pedons 12 on fan delta (378 m a.s.l.) and 13 on clay flat (367 m a.s.l.) geomorphic surfaces were selected on playa deposit parent materials with aridic soil moisture regime. Considerable variations in χ_{lf} values were found in these two pedons. The mean χ_{lf} values of 244 × 10^{-8} m^3 kg^{-1} and 74 × 10^{-8} m^3 kg^{-1} were respectively determined for pedons 12 and 13 (Table 1, Fig. 3). Different sediments with various mineralogy were seemingly the important factors controlling magnetic properties of soils in playa as also supported by Ayoubi et al. (2018) and De Mello et al. (2020). Sediments in pedon 12 originated from igneous formations of north and northwest side of the watershed. On the other hand, pedon 13 is affected by the calcareous and evaporative sediments originated from south and east of the watershed. The electrical conductivity in pedon 12 was about 1 dS m^{-1}, however the EC of surface soil in pedon 13 was about 90 dS m^{-1} (Table 1). The χ_{lf} value increased with depth in pedon 13. The smaller values of χ_{lf} at the topsoil were attributed to the capillary movement and evaporation of saline water at the soil surface compared to lower depths which in turn caused the dilution by diamagnetic material and decrease of χ_{lf} at the soil surface. The same conclusions were also reported by Sarmast et al. (2017) and De Jong et al. (2000).

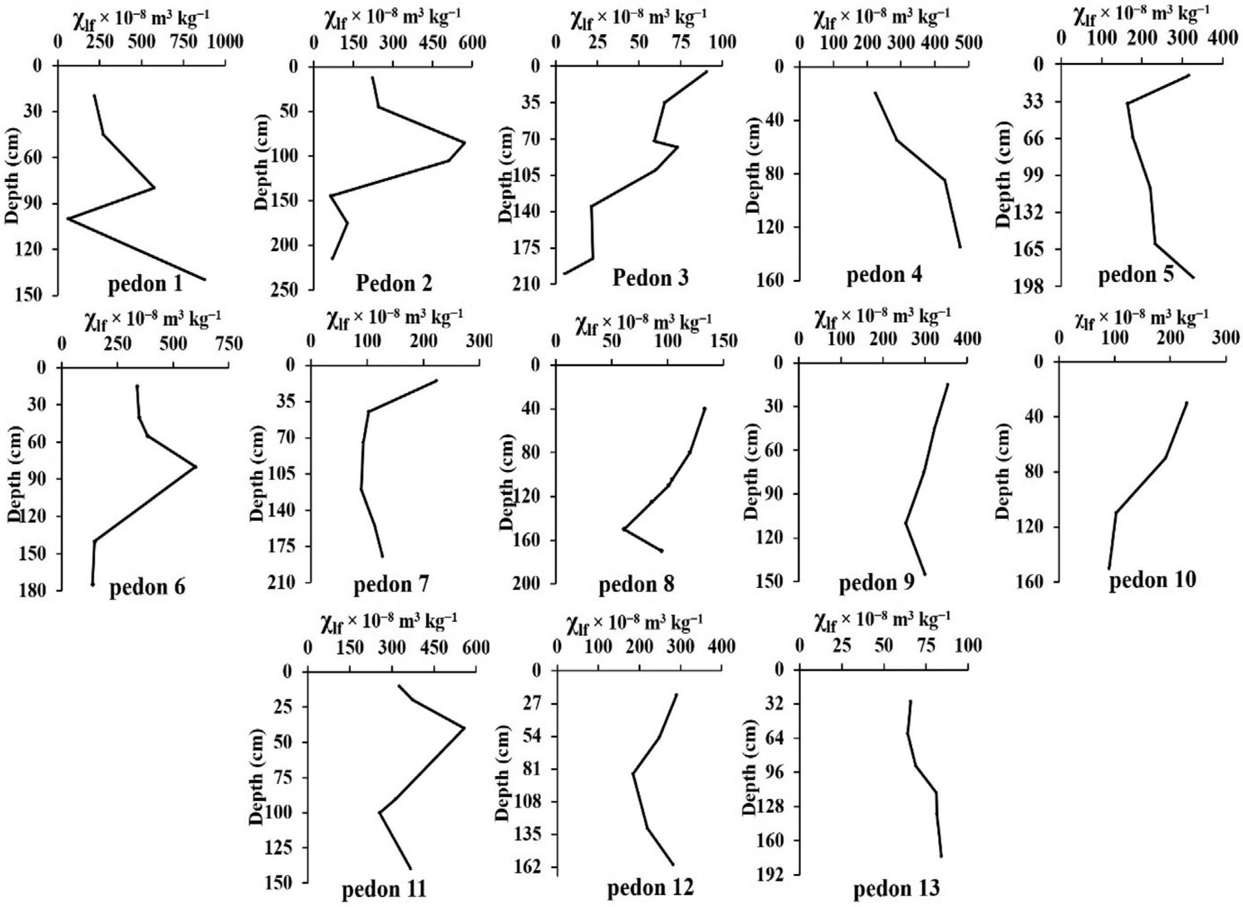

Fig. 3. Vertical distribution of magnetic susceptibility (χ_{lf}) in soils.

4.3. Soil Development Related to Geomorphic Position

4.3.1. Soil development related to activity ratio of Fe_o/Fe_d

The variation in the Fe_o/Fe_d activity ratios on different landforms were in the range of 0.03–0.3 and < 0.1 on igneous and sedimentary parent material, respectively. The Fe_o/Fe_d activity ratio reflects weathering rate and soil development and is used as an index for soil relative age (Sarmast et al., 2017).

The increasing trend of mantled pediment, piedmont plain, and alluvial fan in soils affected by igneous parent material for Fe_o/Fe_d activity ratio was investigated. However, this trend for soils affected by sedimentary parent material was in the order of alluvial fan, mantled/rock pediments, and playa. According to the interpretations on the Fe_o/Fe_d activity ratio, alluvial fans affected by the igneous formations showed the least soil development. On the other hand, the maximum development for soils affected by sedimentary parent material was found in alluvial fan (Table 1).

The Fe_o/Fe_d activity ratios of 0.03 and 0.09 for pedons 2 and 5 (these pedons are located on mantled pediment with andesite parent material) are proofs of more soil development in pedon 2 compared to pedon 5. This was also supported by field and laboratory investigations. Change of soil moisture regime from xeric (pedon 2) to aridic (pedon 5) which affected more weathering and soil development of pedon 2 compared to pedon 5 seems to be the main reason for the different soil development rates in the mentioned pedons.

4.3.2. Soil development related to magnetic susceptibility

A positive significant correlation between soil χ_{lf} values and Fe_o/Fe_d development index in both igneous and sedimentary parent materials was observed (Table 2). This correlation shows that χ_{lf} values decreased with the increase of soil development rate. The higher MS in soils developed on igneous parent material was attributed to the presence of primary magnetic minerals inherited from parent material. Increasing weathering processes in more developed soils originated from igneous parent material caused destruction of inherited primary magnetic minerals through time. That is why the increase of diamagnetic material during soil formation processes has probably decreased soil χ_{lf} values. On the other hand, MS in developed soils originated from sedimentary parent material increased with the soil development stage due to formation of pedogenic ferrimagnetic particles (Fine et al., 1989; Lu, 2000). However, the opposite trend was found in developed soils formed on sedimentary parent material due to destruction of primary magnetic minerals (Lu et al., 2008; Sarmast et al., 2017). Besides, different MS values in soils formed on basic igneous rocks (diorite, granodiorite, andesite, and gabbro) located in different parts of the watershed were observed that seemed to be affected by geomorphic processes involved. The same variations were also reported by De Mello et al. (2020) for diabase rocks in Sao Paulo State, Brazil.

5. CONCLUSIONS

The results showed that the χ_{lf} values for soils affected by igneous parent material were much higher than soils with sedimentary origin. The decreasing trends of andesite < granite < diorite < gabbro and limestone < conglomerate < playa sediments were respectively observed for soil MS values on igneous and sedimentary parent materials. Soil development increased with the decrease of χ_{lf} in soils formed on igneous parent material. However, the χ_{lf} values increased with soil development in sedimentary parent material. The reason is that the MS in soils formed on igneous parent material was highly affected by primary ferrimagnetic particles inherited from parent material. However, secondary ferrimagnetic particles (mainly pedogenic) influenced soil MS on sedimentary parent material. Moreover, soil development rate was quite different in the landforms with different parent material. Soils on alluvial fans with sedimentary parent material showed the most soil development compared to undeveloped soils on alluvial fans with igneous parent material.

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