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Provenance of heavy minerals from recent sediments of Balakyan River, Kurdistan Region, Iraq

Faraj H. Tobia[1] & Rand H. Kafy[1]

1 Department of geology, Salahaddin University, Kurdistan Region, Iraq
E-mail: farajabba58@gmail.com

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Abstract

Heavy mineral assemblages of the sediments in Balakyan River have been studied to determine their concentrations and provenance. Twelve sediment samples were analyzed for heavy mineral assemblage determination. The unstable heavy minerals (pyroxene and amphibole) represent more than 50%. The mineral chemistry and petrographic studies refer to the predominant clinopyroxene mineral is diopside. Actinolite, tremolite, and magnesiohornblende are common calc-amphibole in the sediments. The ultrastable heavy minerals are present in trace amounts.

According to the mineral chemistry the clinopyroxene is derived from basic igneous rocks crystallized at 1150-1220^{0}C and low pressure. Amphibole and epidote crystallized under low temperature and/or formed under low grade metamorphism. The detrital chromian spinel is derived from basic and ultrabasic igneous rocks of Alpine type peridotite formed in fore-arc. The probable source of these assemblages is Ophiolite Complex to the north of the studied area (north Iraq) and igneous parts of Walash Series and Red Bed Series also the sedimentary rocks of Shiranish and Tanjero formations.

Introduction

Clastic rocks, especially sands and sandstones, provide information about the provenance of the sediments [1, 2]. The sands contain geochemical and mineralogical information relating to the history of the source area. River sediments originate from the near surface, exposed igneous, volcanic and sedimentary rocks. Some of these are easily eroded, whereas others, especially the grained crystalline and metamorphic rocks, are affected by streams only when altered in surface layers [3].

The drainage system of Balakyan River originates from the south east of Mergasur Town about 12km south of Iraqi-Turkish border, flows southeastward to intersect Sidekan River, about 23km to the southeast of Mergasur *(Figure:1)*. The studied area lies in the mountainous region of north Iraq between latitudes 36^{0}42′00″N- 36^{0}50′15″N and longitudes 44^{0}19′30″E- 44^{0}30′20″E *(Figure: 1)*.

The objective of this work is to study the chemistry of heavy minerals from the recent sediments of Balakyan River and their possible provenance.

Geological setting

The studied area lies within the High Folded Zone which is part of the Unstable Shelf tectonic zone of Iraq *(Figure: 2)*. This zone was most strongly subsiding part of the Arabian Plate since the opening of the southern Neo-Tethys in Late Jurassic. Maximum subsidence occurred during the Late Cretaceous ophiolite obduction onto the NE margin of the Arabian Plate and during Mio-Pliocene continental collision [5, 6].

The High Folded Zone was intermittently uplifted in Cretaceous and Palaeogene time and strongly deformed in Late Tertiary. The zone was the marginal part of the Palaeogene molasse that covers most of the Iraqi Kurdistan Region. It comprises harmonic folds with Mesozoic limestone formations in their cores and Palaeogene and Neogene limestone and clastic formations on their flanks [6].

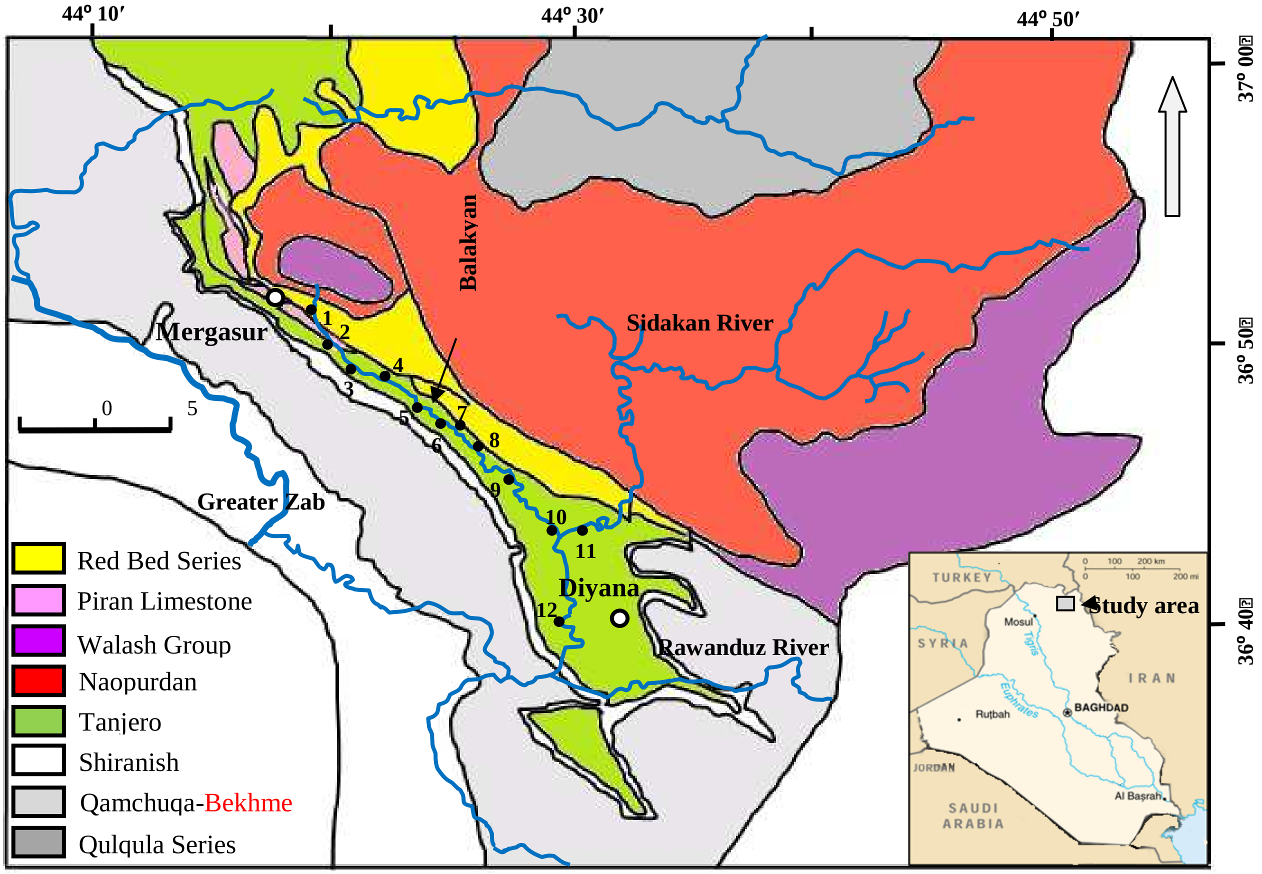


Figure- 1: Geological map and location of the fluvial sediment samples from Balakyan River, Kurdistan Region, Iraq (modified from Stevanovic and Markovic, 2003 [4]).

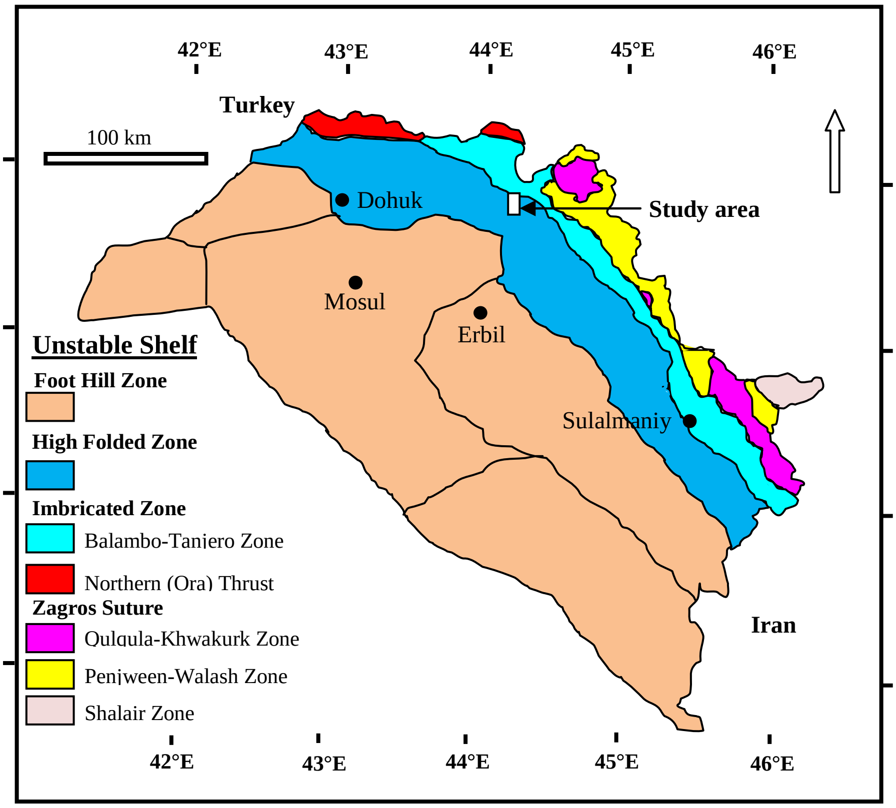


Figure- 2: Location and tectonic map of the northern part of Iraq (after Jassim and Buday, 2006[6]).

The Balakyan River incises different formations. The age of the exposed rocks in the surrounding area ranges from Late Campanian (Shiranish and Tanjero formations) to Pliocene (Red Bed Series). The sedimentary rocks of Shiranish and Tanjero formations are exposed along the Balakyan River, the former consist of blue marl and thin bedded marly limestones and the latter is composed of silty marl, siltstones, sandstones, conglomerates, and sandy or silty organic detrital limestones and globigerinal marl in the lower part [5, 6]. Tanjero is Upper Cretaceous unit, which crops out within the Imbricated and High Folded zones in NE Iraq. It stretches as narrow NW-SE belt near and parallel to the Iranian border. It mainly consists of alteration clastic rocks of sandstone, marl and calcareous shale with very thick conglomerate and biogenic limestones. The formation is divided to three parts: lower, middle, and upper [7]. Many sedimentary structures are found in the formation, by these, it was proved the lower and upper parts were deposited in shallow water and middle part in deep basinal one [8].

The Walash (volcanic) Group and Naopurdan (shaly) Group are exposed to the northeast of the river. The Walash Group contains a volcanic core enclosed in immature sedimentary rocks which consists of mudstones, siltstones and sandstones. The mudstones are slightly calcareous and are more common than the siltstones and contain sandstones up to few meters in thickness. The volcanic are classified as basic dykes and lava flows which consists of spilitic diabase, pyroxene-bearing spilitic basalts and spilites, and intermediate volcanic which consists of pyroxene andesites and altered andesites. The Naopurdan Group is dividing in to two subgroups, the Naopurdan type (intercalated sedimentary and volcanic units) and the Sidekan Type (sedimentary rocks only) [5]. The sedimentary units of Naopurdan subgroup consist of grey shale with thin beds of green greywacke, lenticular conglomerates and coralline limestone, overlain by massive nummulitic limestone capped by red shale. Meanwhile the volcanic unit is composed of andesitic volcanic which comprise lavas, agglomerates and tuffaceous slates with occasional basic pillow lavas. The Sidekan subgroup consists of multicolored grit and sandstone, silty shale and marls, and black bituminous limestone [9].

The Red Bed Series was introduced by Bolton (1958) [10] for a sequence of clastic with occasional limestone beds ranging in age from Late Maastrichtian to Pliocene. He divided the series into the lower Suwais Red Beds, the middle Lailuk limestone (Govanda limestone) and the upper Merga Red Beds. The former group comprises both flysch and molasse- type clastic alternating with neritic nummulitic limestone. The second group comprises a red pebbly sandstone and siltstone overlain by silty and sandy detrital limestone and 80-90m of limestone of fore-reef to reef facies [6]. The lithology of the latter group is massive thick bedded limestone, white, pinkish and light brownish, recrystallized with occasional nodules of red chert [11, 5]. Recently, on the basis of stratigraphy and lithology, Al-Barazinjy (2005) [12] divided the Red Bed Series in Chwarta-Mawat area into six units in contrast to the previous studies: red fine clastic, chert and limestone conglomerate, thick bedded gray sandstone, alternation of red layer of claystone with sandstone, limestone with igneous and metamorphic pebbles and boulders, and the upper most part consist of marl and claystone with some sandstone. He proved that the Red Series and Kolosh Formation sharing the same depositional basin and have the same tectonic setting.

Materials and methods

The heavy mineral occurrence in the fluvial recent sediments of Balakyan River was studied along 32km traverse from Mergasur to Diyana. Twelve recent river sediments were collected and their heavy mineral content were separated from the very fine sand fraction (63-125 μm) using bromoform liquid by the standard gravity separation method.

Thin and polished thin sections were prepared for the separated heavy minerals which were studied petrographically under transmitted and reflected light microscopes, and by electron microprobe analyzer (EPMA). The heavy minerals were counted using Ribbon counting technique.

Quantitative (WDS) and semiquantitative (EDS) analysis of major and trace elements for the individual heavy minerals was performed using fully automated EPMA- JEOL 8200 type, equipped with four wavelength spectrometers, operating under the following conditions: accelerating voltage (15 kV), beam current (20 nA), beam diameter (1 μm), peak count-time (20 sec), background count-time (10 sec); available at Dalhousie University in Canada.

Petrography of heavy minerals

The results of petrographic examination of the heavy minerals in fluvial recent sediments (transparent and opaque heavy minerals) are shown in *Table: 1*. Seven different transparent minerals were identified in sand fraction (63µm- 125µm) according to their optical properties [13, 14]. The non-opaque heavy minerals spectrum is characterized by pyroxene, amphibole, epidote, serpentine, apatite, zircon, tourmaline and weathered grains (i.e., unidentifiable heavy minerals because of weathered nature).

The heavy mineral assemblage is characterized by abundant pyroxene and amphibole that forms >50% of the transparent heavy minerals and to a lesser relative percentage of epidote, serpentine, apatite and rarely tourmaline and zircon *(Table: 2)*.

A. Unstable heavy minerals

Pyroxene is the most important group of ferromagnesian rock-forming minerals. They occur in almost every type of igneous and metamorphic rocks, and crystallize under a range of different conditions [13]. It appears in the source rocks of basic and ultra-basic igneous rocks [15, 16]. Pyroxene grains constitute the dominant heavy mineral in the studied sediments ranging between 39.35 - 47.87% with an average of 44.67% *(Table: 2)*. The pyroxenes are mostly clinopyroxenes including augite, diposide diallage and aegerine *(Figures 3a-f)*.

Table- 1: Total heavy minerals, opaque and non-opaque mineral contents in the fluvial recent sediments.

Sample	*Location*	*% Total heavy*	*% Opaque minerals*	*% Non- opaque*
1	*Bawa*	*1.02*	*16.42*	*83.58*
2	*Khardan*	*1.10*	*15.17*	*84.83*
3	*Lailuk*	*20.10*	*22.70*	*77.30*
4	*Nawmergan*	*0.13*	*22.43*	*77.57*
5	*Khalan*	*0.92*	*22.11*	*77.89*
6	*Khirra*	*1.88*	*21.65*	*78.35*
7	*Balakyan*	*4.59*	*20.97*	*79.03*
8	*Kwnagwnd*	*0.42*	*15.72*	*84.28*
9	*Shorawa*	*0.88*	*20.97*	*79.03*
10	*Mazna*	*0.87*	*17.13*	*82.87*
11	*Sader*	*2.30*	*19.63*	*80.37*
12	*Ashkawta*	*3.01*	*20.71*	*79.29*
average		*3.10*	*19.63*	*80.37*

Table 2:Relative abundance of the main and minor minerals in the non opaque heavy minerals in the fluvial recent sedimen

Sample	*Pyroxene*	*Amphibole*	*Epidote*	*Serpentine*	*Apatite*	*Tourmaline*	*Zircon*	*Others*
1	*42.78*	*18.34*	*12.23*	*4.31*	*1.03*	*0*	*0*	*4.89*
2	*47.87*	*17.72*	*11.35*	*3.82*	*0*	*0*	*0*	*4.07*
3	*46.95*	*13.64*	*8.9*	*2.03*	*0.72*	*0.72*	*0*	*4.34*
4	*45.25*	*11.75*	*11.34*	*3.93*	*0*	*1.09*	*0*	*4.21*
5	*44.25*	*12.39*	*12.87*	*3.74*	*0*	*0*	*0*	*4.19*
6	*46.39*	*12.38*	*13.74*	*0*	*0.72*	*0*	*0.72*	*4.4*
7	*39.35*	*10.79*	*14.83*	*5.94*	*1.09*	*0*	*2.84*	*4.19*
8	*46.85*	*15.84*	*12.37*	*0*	*0.72*	*0*	*0.72*	*5.74*
9	*44.80*	*12.76*	*12.86*	*2.97*	*1.58*	*0*	*1.93*	*3.12*
10	*46.87*	*12.94*	*13.45*	*0*	*0.72*	*0*	*0.72*	*5.17*
11	*44.35*	*13.24*	*13.73*	*4.23*	*1.09*	*0*	*0*	*3.73*
12	*40.37*	*12.72*	*11.95*	*6.74*	*2.36*	*0*	*0*	*5.15*
Average	*44.67*	*13.70*	*12.46*	*3.14*	*0.83*	*0.15*	*0.57*	*4.43*

Amphibole constitutes an extremely complex group of minerals that form in a variety of igneous and metamorphic rocks. They crystallize over a broad spectrum of pressure- temperature (P-T) conditions, with a wide variation of chemical and physical properties [16, 13, 14, 18]. Members of the amphibole group are well represented in young detrital sediments and, being more stable than pyroxenes, are more frequently encountered in older strata [14].

Amphiboles occur in all samples with ranges and average of 10.79%-18.34% and 13.70 % respectively. The highest percentages are recorded in sample 1, 2, 8 with relatively moderate concentrations in the other samples *(Table: 2)*. The most common minerals of amphibole are tremolite- actinolite; the former is characterized by colorless to light grey without pleochroism *(Figure: 3g)*, While the latter have pale green to pale yellowish green color with clear pleochroism *(Figure: 3h)*.

Other type of amphibole is hornblende that characterized by its light green to brownish green and brown color *(Figure: 4a)* with two set of cleavage unperpendicular and inclined extinctions with clear pleochroism from green to pale green. Hornblende is an indication to the metamorphic rock such as schist and gneiss [19, 20] and the brown varieties occurring in basic igneous rocks often contain considerable amounts of titanium [21] and also derived from acidic igneous rocks [22, 23]. There are different sizes of the amphiboles grains, some of them are relatively large in size with elongated shape and the others are small. Generally, the amphibole grains are characterized by low weathered surface.

B. Metastable heavy minerals

Epidote occurred in over all samples, and its content in the heavy mineral fractions ranges from 8.9% to14.83% with average 12.46% *(Table: 2)*. It appears as epidote and clinozoisite, the former appears as yellowish green to pale brown *(Figure: 4b)*, while the latter appears as colorless to pale color *(Figure: 4c)*. Generally, epidote grains appear as irregular, short prisms and sometimes equate shape; in addition, some of epidote grains are weathered. The clinozoisite characterizes by weak double refractions and lacking to the pleochroism [24]. The type of the epidote minerals vary with the differences in the degree of metamorphism of the source rocks [25, 23, 26]. Both of them were domain in the low to medium grade metamorphic rocks [14].

Serpentine generally occurs as elongated grains with a low relief and a smooth round outline. It has light yellow color with opaque inclusions, wavy extinction and with no pleochroism *(Figure: 4d)*. Serpentine is recorded relatively higher content in the sample 12 and low content in the sample 3, and not observed in the sample 6, 8, 10.

Apatite commonly occurs sporadically, it occurs in volcanic rocks and in basic to acid plutonic rocks [25], and as a common accessory mineral of all type of igneous rocks [14]. The apatite is present in some of the studied samples of relatively little content ranging between 0.72- 2.36% with average 0.83%, higher content is recorded in the sample 12 *(Table: 2)*. It appeared as colorless, moderately relief and show pleochroism *(Figure: 4e)*.

C. Ultrastable heavy minerals

The ultrastable minerals are very rare and recorded in few studied samples.

Zircon is observed only in the samples 6, 7, 8, 9, 10 with relatively low content ranging between 0.72- 2.84% with average 0.57% *(Table: 2)*. It has a light green color with euhedral shape and bipyramid with high relief, and parallel extinctions *(Figure: 4f,g)*.

Zircon is good indication for the source rocks, thus its rounded shape is indication for the high grade metamorphic rocks and the euhedral shape is indications to the acidic igneous rocks [27].

Tourmaline is observed in the samples 3 and 4 with small relatively percentage 0.72- 1.09% with average 0.15%, it has moderately relief and distinct pleochroism. It appears as tabular or irregular shape *(Figure: 4h)*.

D. Opaque heavy minerals

Opaque minerals are present in over all samples, its content in the heavy mineral fractions of the fluvial recent sediments ranges from 15.17% to 22.70% with average 19.63% *(Table: 1)*.

The most common opaque heavy minerals in the studied samples are Fe-oxides: magnetite, hematite, and goethite *(Figure: 5a)*. Magnetite is characterized by the low reflectivity and isotropy. The wide range of the shape (angular to rounded) is a good indication for the different sources of the magnetite.

Chromian spinel is present in most of the samples. Under transmitted light, the grains of chromian spinel are generally fresh and there their shape ranges from angular euhedral to rounded *(Figure: 5b)*, and is deep reddish brown color *(Figure: 5c)* in thin section indicating high-Cr character with a pronounced conchoidal fractures for the broken ones. Thicker grains are almost opaque, and are truly isotropic. Ilmenite is detected in most of the studied samples and is characterized by trellis texture. Pyrite is detected in few samples of euhedral shape with yellow color *(Figure: 5d)*.

The most important alterations in the opaque heavy minerals in the studied samples are: ***Alteration of magnetite to hematite:*** Magnetite is generally completely replaced by hematite under the oxidizing conditions. The mechanism of martitization (hematization of magnetite) could involve an intermediate phase of maghemite (γ-Fe_2O_3), or a compound intermediate in composition between Fe_3O_4 and Fe_2O_3 or the direct formation of hematite (α-Fe_2O_3) from magnetite (Fe_3O_4) [28, 29]. This replacement is common in most of the studied samples *(Figure: 5e)*.

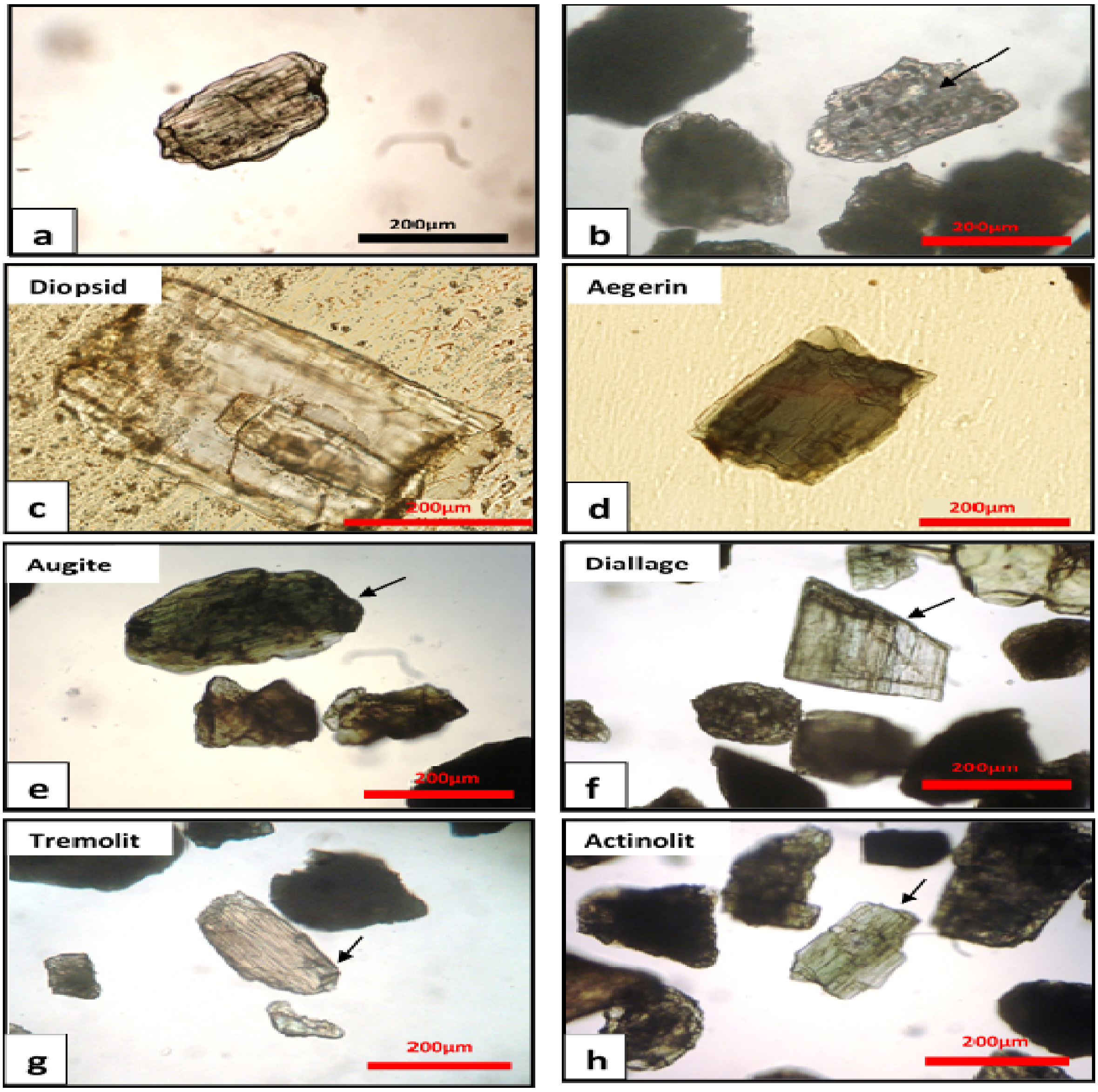


Figure- 3: Photomicrographs of heavy minerals from the fluvial recent sediments (under plane- polarized light, PPL); (a) Pyroxene grain shows a diagenetic feature like saw tooth (sample no.1), (b) Pyroxene grain shows weathering feature and pitting (sample no.2), (c, d, e, and f) Varieties of clinopyroxenes (sample no. 9, 3, 7 and 4 respectively), (g, and h) Varieties of calc- amphiboles (tremolite and actinolite, sample no. 8 and 2, respectively).

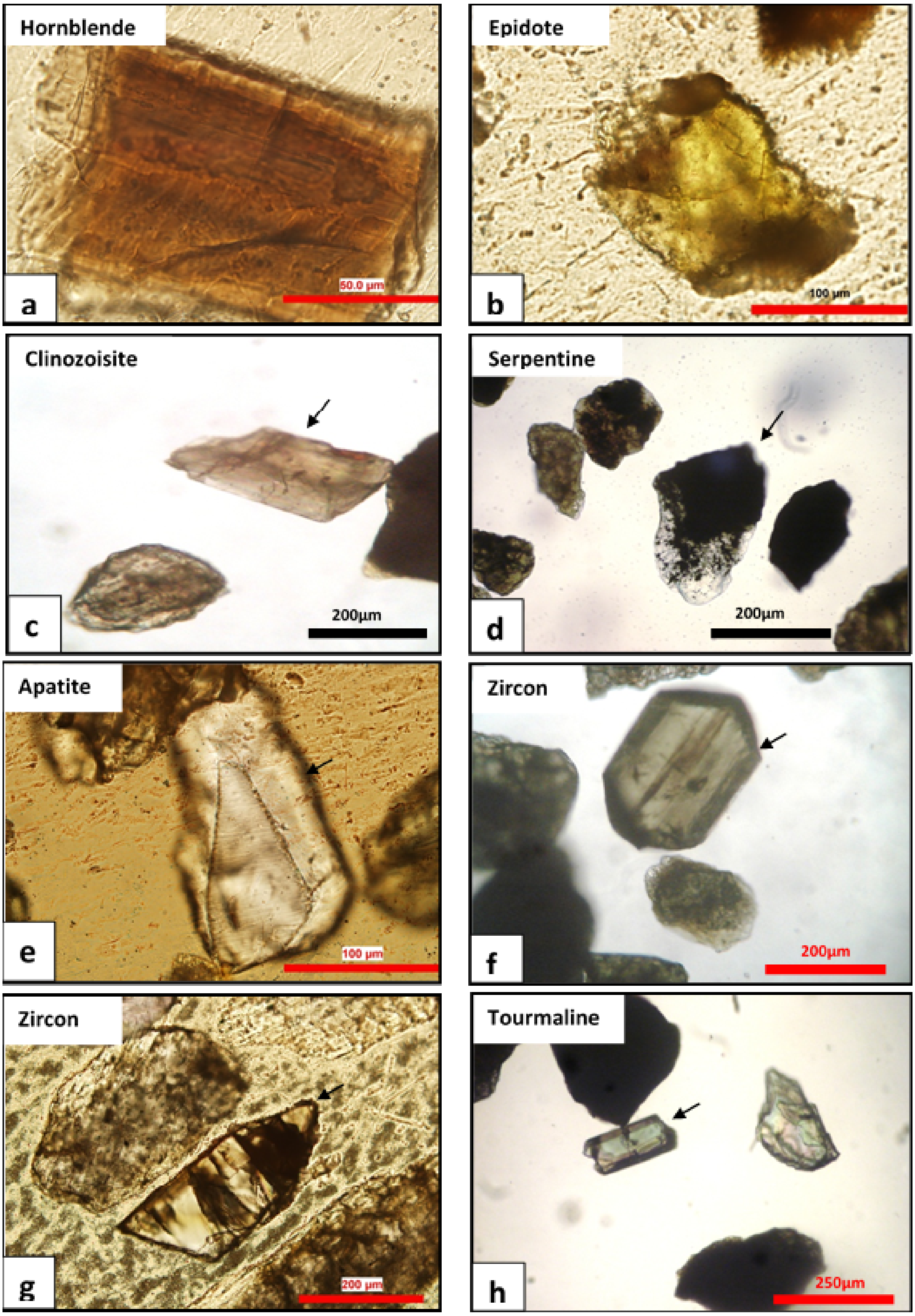


Figure- 4: Photomicrographs of heavy minerals from the fluvial recent sediments (under plane- polarized light, PPL); (a) Hornblende (sample no.12), (b) Epidote (sample no.12), (c) Clinozoisite (sample no.9), (d) Serpentine (sample no.7), (e) Apatite (sample no.12), (f) Bipyramid Zircon (sample no.7), (g) High relief of Zircon (sample no.9), (h) Tourmaline (sample no.4).

Alteration of pyrite to goethite: Pyrite mineral is altered to goethite under oxidation condition that the process termed as goethitization *(Figure: 5f)*. The framboids of pyrite is detected in some studied samples *(Figure: 5b)*. Framboidal pyrite is common in sediments and low temperature ore deposits [30].

Alteration of ilmenite to leucoxene: Ilmenite is unstable under oxidizing conditions and is commonly altered to leucoxene *(Figure: 5g)*, thus promoting anatase and iron-oxide/hydroxide (goethite or hematite) formation. This alteration is observed in different samples with a trellis texture *(Figure: 5h)*.

Chemistry of heavy minerals

EPMA was used to analyze pyroxene, amphibole, epidote, and chromian spinel.

A. Pyroxene

Forty spots of detrital pyroxene were analyzed and the formulas were calculated on 6 oxygen basis *(Table 3)*. The data were plotted on Morimoto (1988) [31] diagram for their classification which showed that they fall in the field of diopside *(Figure: 6)*. The EDS-EPMA scan shows the peaks of the main constituents of diopside (O, Si, Mg, Ca, Fe, and Al; *Figure: 7)*. The clinopyroxenes have a compositional range Wo_{43-51} En_{42-53} Fs_{0-11}, Al_2O_3= 2.64%, TiO_2= 0.44%, and Cr_2O_3= 0.32%. Detrital clinopyroxenes are a more reliable indicator of source rock chemistry [2].

The presence or absence of clinopyroxenes is thought to be primarily a function of P and T, and bulk-rock chemistry; i.e., only the rocks with bulk CaO from 11- 14.4% contain clinopyroxenes [32, 33]. Soesoo (1997) [34] calculated P-T crystallization condition of pyroxene based on the statistical multivariate calculation. Depending on this calculation, all the clinopyroxene samples plot in the low pressure field (2-5kb) with some close to the lower pressure line of Johnson et al. (1985) [35], and formed between the temperature 1150- 1220^{0}C *(Figure: 8)*.

B. Amphibole

Amphiboles are crystallized over a broad spectrum of P-T conditions, with a wide variation of chemical and physical properties [17, 13, 14, 18].

The formula of studied amphiboles which are represented in Table 4 was calculated on the basis of 23 oxygens and proved to be actinolites and magnesiohornblendes based on the classification of Leake et al. (1997) [18] *(Figure: 9)*. The [$Mg/(Mg+Fe^{2+})$] ratio vary between 0.68-0.86 in actinolites and 0.74 in magnesiohornblende. Most actinolites have the ratios of 0.75-0.85, in metabasalt= 0.55 reflecting the high content of iron in the host rocks [33]. The [$Mg/(Mg+Fe^{2+})$] ratio in the studied actinolites ranges between 0.68 to 0.86, i.e. it have low Fe contents in the host rocks.

The studied amphiboles are Al-poor (8.83 wt. % Al_2O_3 in magnesiohornblende and <4 wt.% Al_2O_3 in actinolite), Ca-amphiboles. There is relation between the tetrahedral Al contents of the amphibole pairs (actinolite and hornblende) and the estimated temperature of crystallization [36]. Also, the tetrahedral Al and alkali contents decrease with decreasing grade of metamorphism [37]. Ernst and Liu (1998) [38] suggest low-temperature to crystallization for amphiboles when $Al^{(iv)}$ is less than one and Ti is less than 0.30, this is typical of retrograde metamorphic rocks or altered mafic igneous rocks [39]. Accordingly, the low tetrahedral Al and alkali content of the studied amphiboles can be considered to have been crystallized under low temperature and/or formed under low grade metamorphism *(Table 4)*.

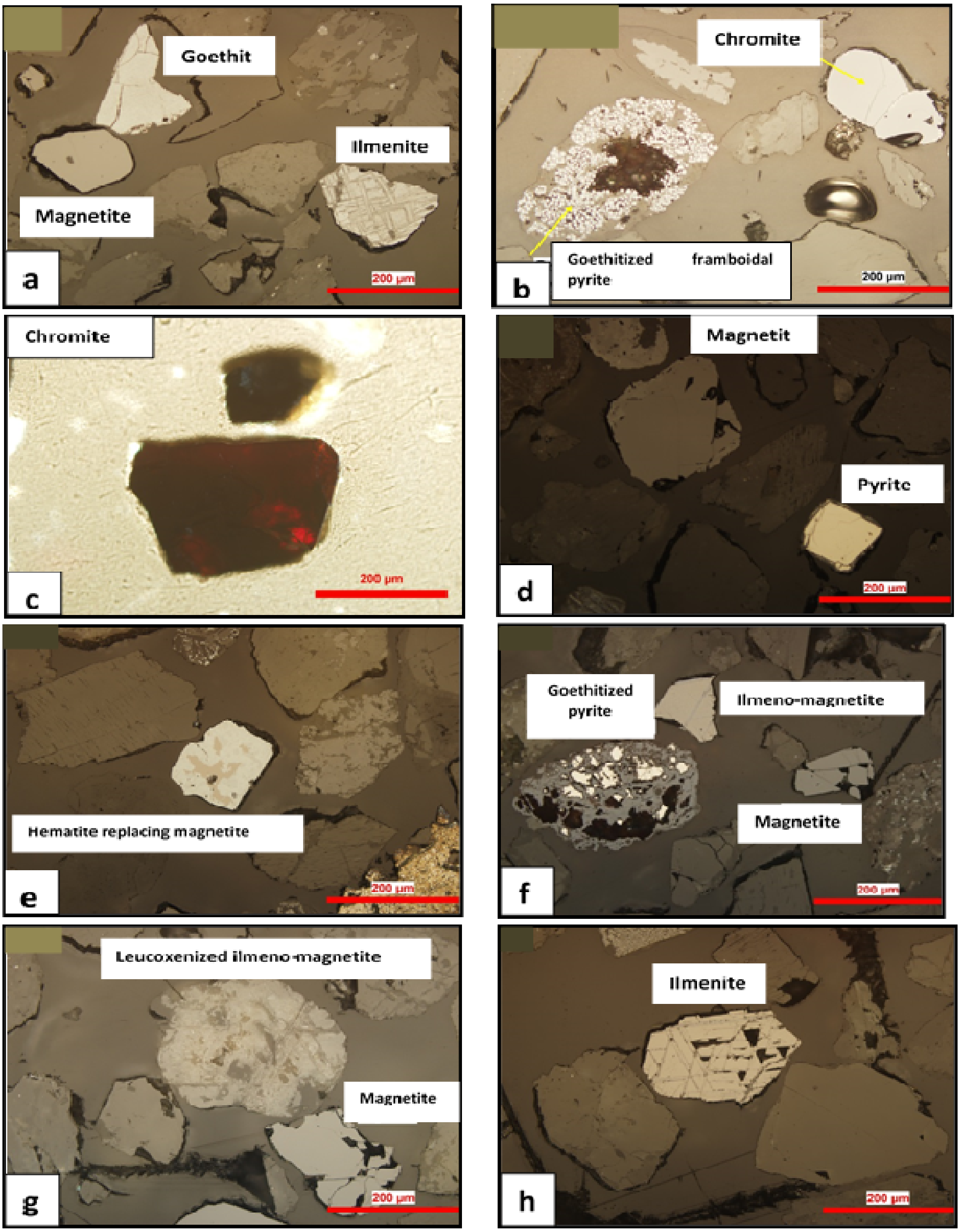


Figure- 5: Photomicrographs of heavy minerals from the fluvial recent sediments (under reflected light except c is under PPL); (a) Goethite, magnetite, and ilmenite (sample no. 12), (b) Rounded chromite and goethitized framboidal pyrite (sample no.9), (c) Reddish brown chromite (sample no.3), (d) Euhedral shape of pyrite (sample no.3), (e) Hematite replacing magnetite (sample no. 12), (f) Goethitized pyrite and ilmeno-magnetite (sample no. 9), (g) Leucoxenized ilmeno-magnetite (sample no. 9), (h) Trellis texture of ilmenite (sample no. 9).

Table- 3: Electron microprobe analysis of clinopyroxene from the fluvial recent sediments, formulae calculated to 6 Oxygen.

	Grain number															
Elements	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
SiO_2	53.12	50.98	53.31	51.03	52.02	51.69	51.20	51.88	51.40	51.27	52.37	52.38	53.17	51.84	52.44	48.78
TiO2	0.23	1.20	0.18	0.36	0.201	0.33	0.32	0.15	0.39	0.36	0.27	0.36	0.06	0.10	0.44	1.59
Al_2O_3	2.31	2.96	1.49	3.52	2.37	1.87	2.18	1.77	1.58	2.50	3.43	2.70	3.14	3.49	2.42	5.317
Cr_2O_3	0.10	0.37	0.07	0.15	0.59	0.17	0.19	0.26	0.22	0.17	1.38	0.42	0.51	1.04	0.35	0.15
FeO	3.68	5.75	6.10	5.93	4.89	4.59	4.59	4.29	8.13	5.40	1.90	5.37	3.25	2.96	4.88	7.68
MnO	0.10	0.14	0.17	0.14	0.14	0.15	0.13	0.14	0.22	0.16	1.11	0.17	0.09	0.09	0.15	0.14
MgO	17.40	16.18	15.92	16.89	17.68	16.96	16.68	16.75	14.87	16.00	17.14	16.27	18.718	17.00	16.65	13.92
CaO	22.56	21.66	22.29	19.25	21.52	22.53	22.84	23.40	22.02	22.60	23.02	22.02	21.0	23.19	22.29	21.88
Na_2O	0.25	0.32	0.19	0.87	0.13	0.27	0.27	0.12	0.31	0.25	0.49	0.30	0.13	0.13	0.35	0.45
K_2O	0.02	0.01	0.01	0.10	0.02	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.03	0.02	0.03	0.02
Total	99.76	99.59	99.75	98.23	99.57	98.57	98.42	98.77	99.15	98.73	101.05	100.00	100.17	99.85	100.00	99.87
Si	1.93	1.88	1.97	1.89	1.90	1.91	1.90	1.92	1.92	1.90	1.88	1.92	1.92	1.89	1.92	1.81
Al(iv)	0.10	0.13	0.07	0.15	0.10	0.08	0.10	0.08	0.07	0.11	0.11	0.12	0.13	0.15	0.10	0.23
Sum	2.03	2.03	2.03	2.04	2.01	1.99	1.99	1.99	1.99	2.01	1.99	2.04	2.05	2.04	2.02	2.04
Ti	0.00	0.03	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.003	0.01	0.04
Cr	0.00	0.01	0.00	0.00	0.02	0.01	0.07	0.09	0.07	0.01	0.04	0.01	0.02	0.0	0.01	0.00
Fe	0.08	0.12	0.18	0.07	0.08	0.05	0.03	0.05	0.17	0.09	0.00	0.13	0.08	0.04	0.09	0.14
Mn	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.08	0.01	0.03	0.01	0.00	0.00	0.01	0.00
Mg	0.94	0.89	0.88	0.93	0.96	0.94	0.92	0.92	0.83	0.89	0.94	0.89	1.08	0.92	0.91	0.77
Ca	0.88	0.86	0.88	0.76	0.84	0.89	0.91	0.93	0.88	0.90	0.90	0.86	0.82	0.91	0.87	0.87
Na	0.02	0.02	0.01	0.06	0.01	0.019	0.019	0.01	0.02	0.02	0.03	0.02	0.01	0.01	0.03	0.03
K	0.00	0.00	0.00	0.01	0.00	0.001	0.001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wo	46.33	45.94	45.47	43.47	44.75	47.60	48.71	48.82	46.9	48.08	49.12	45.98	42.96	48.45	46.62	48.78
En	49.69	47.78	45.21	52.93	51.16	49.86	49.50	48.62	44.08	47.35	50.88	47.27	53.07	49.43	48.47	43.15
Fs	3.98	6.30	9.32	3.70	4.09	2.53	1.79	2.37	9.00	4.59	0.0	6.75	3.97	2.13	4.91	8.07

	Grain number															
elements	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
SiO_2	48.83	52.36	52.35	49.73	52.14	51.90	51.13	51.28	47.38	44.82	52.30	51.14	52.72	51.85	53.63	52.69
TiO_2	1.64	0.12	0.18	0.02	0.04	0.07	0.05	0.22	2.33	3.51	0.14	0.65	0.05	0.33	0.17	0.26
Al_2O_3	5.33	3.07	2.28	2.09	2.45	1.96	3.10	2.37	4.72	6.80	2.17	2.84	0.05	3.14	0.69	1.72
Cr_2O_3	0.05	0.70	0.13	0.01	0.86	0.100	0.50	0.72	0.05	0.01	0.45	0.05	0.83	0.19	0.02	0.25
FeO	7.60	3.1	5.63	7.80	3.18	4.90	3.75	4.44	7.26	6.90	4.34	5.73	2.57	6.09	5.60	4.89
MnO	0.14	0.12	0.18	0.18	0.07	0.12	0.09	0.14	0.13	0.15	0.11	0.13	0.05	0.16	0.14	0.13
MgO	13.94	16.68	15.89	13.95	17.19	17.47	17.10	16.16	13.46	12.72	17.44	16.42	16.93	15.44	16.34	16.53
CaO	22.26	23.64	23.20	21.08	23.05	22.17	20.52	22.73	22.49	22.81	22.07	21.88	23.23	21.55	22.85	22.94
Na_2O	0.46	0.12	0.15	0.19	0.19	0.14	0.15	0.33	0.48	0.52	0.19	0.24	0.10	0.21	0.23	0.20
K_2O	0.01	0.00	0.01	0.03	0.00	0.00	0.03	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.008	0.021
Total	100.30	100.00	100.05	95.13	99.21	98.88	96.45	98.45	98.34	98.28	99.26	99.15	96.57	99.01	99.72	99.67
Si	1.80	1.91	1.91	1.94	1.91	1.91	1.93	1.90	1.79	1.69	1.92	1.89	1.99	1.93	1.97	1.93
Al(iv)	0.23	0.13	0.10	0.10	0.11	0.09	014	0.10	0.21	0.30	0.09	0.12	0.00	0.14	0.03	0.08
Sum	2.03	2.04	2.02	2.03	2.02	1.99	2.06	2.01	2.00	2.00	2.01	2.01	1.99	2.06	2.00	2.01
Ti	0.04	0.00	0.01	0.00	0.00	0.00	0.02	0.07	0.07	0.10	0.00	0.02	0.00	0.01	0.01	0.01
Cr	0.00	0.02	0.004	0.00	0.02	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.02	0.01	0.03	0.01
Fe	0.13	0.06	0.12	0.21	0.04	0.05	0.11	0.06	0.11	0.07	0.07	0.10	0.08	0.19	0.00	0.10
Mn	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Mg	0.77	0.91	0.87	0.81	0.94	0.96	0.96	0.89	0.76	0.72	0.95	0.90	0.95	0.86	0.90	0.90
Ca	0.88	0.92	0.91	0.88	0.91	0.88	0.83	0.90	0.91	0.92	0.87	0.87	0.94	0.86	0.90	0.90
Na	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.01
K	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.000	0.00	0.000	0.00
Wo	49.58	48.83	48.09	46.35	48.09	46.34	43.60	48.69	51.15	53.96	45.90	46.38	47.60	45.20	46.45	47.34
En	43.22	47.95	45.84	42.69	49.91	50.79	50.58	48.17	42.61	41.85	50.48	46.45	48.28	45.06	46.21	47.45
Fs	7.20	3.23	6.07	10.96	2.00	2.86	5.82	3.14	6.24	4.20	3.62	5.16	4.12	9.74	7.34	5.21

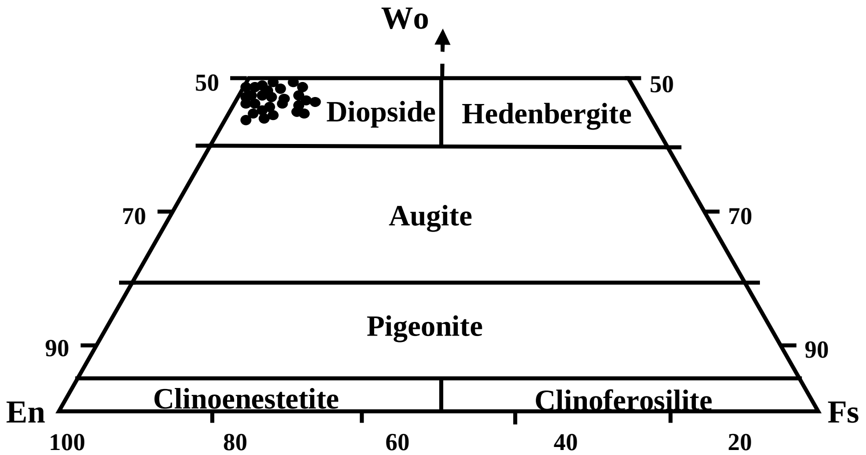


Figure- 6: Clinopyroxene classification diagram for the fluvial recent sediments according to Morimoto (1988).

C. Epidote

Epidote minerals crystallize dominantly in regionally metamorphosed rocks and also form in a wide variety of igneous parageneses, and they are also common in the sedimentary record.

Formula calculations based on 12.5 oxygens for representative minerals of epidote group showed that they fall between the field of epidote and clinozoisite closer to epidote *(Table: 5; Figure: 10)*. The EDS-EPMA spectrum of epidote shows the main peaks of Si, Al, Ca, Fe, and Mg *(Figure: 7b)*. The $100Fe^{3+}/(Fe^{3+}+Al)$ ratios of these epidotes are between 21-33 mole% and are restricted to pistacite (Ps) in comparison with epidotes from mafic schists from other areas whose Ps content has a wide range between 12-70 mole% [27, 33]. The Fe content in epidote decreases with increasing metamorphic grade. The studied epidote can be considered rich in Fe which ranges between 9.19-14.20 wt. %.

Experimental studies of Moody et al. (1983) [41] on mafic systems indicated that the composition of epidote is a function of P and T as well as of the bulk rock composition. Normally, Fe-rich epidote crystallizes with Mg-actinolite at low temperatures of the green schist facies. Epidote and clinozoisite are common with hornblende at intermediate temperatures. The average Fe/Al ratios in the coexisting epidote and clinozoisite from the low grade zone are 0.33 and 0.13, respectively; while those from the high-grade zone are 0.28 and 0.20, respectively); i.e., decrease with increasing temperature [37]. The Fe/Al ratios for the studied samples are between 0.26- 0.49, this may suggested the low-grade metamorphic source complexes [39].

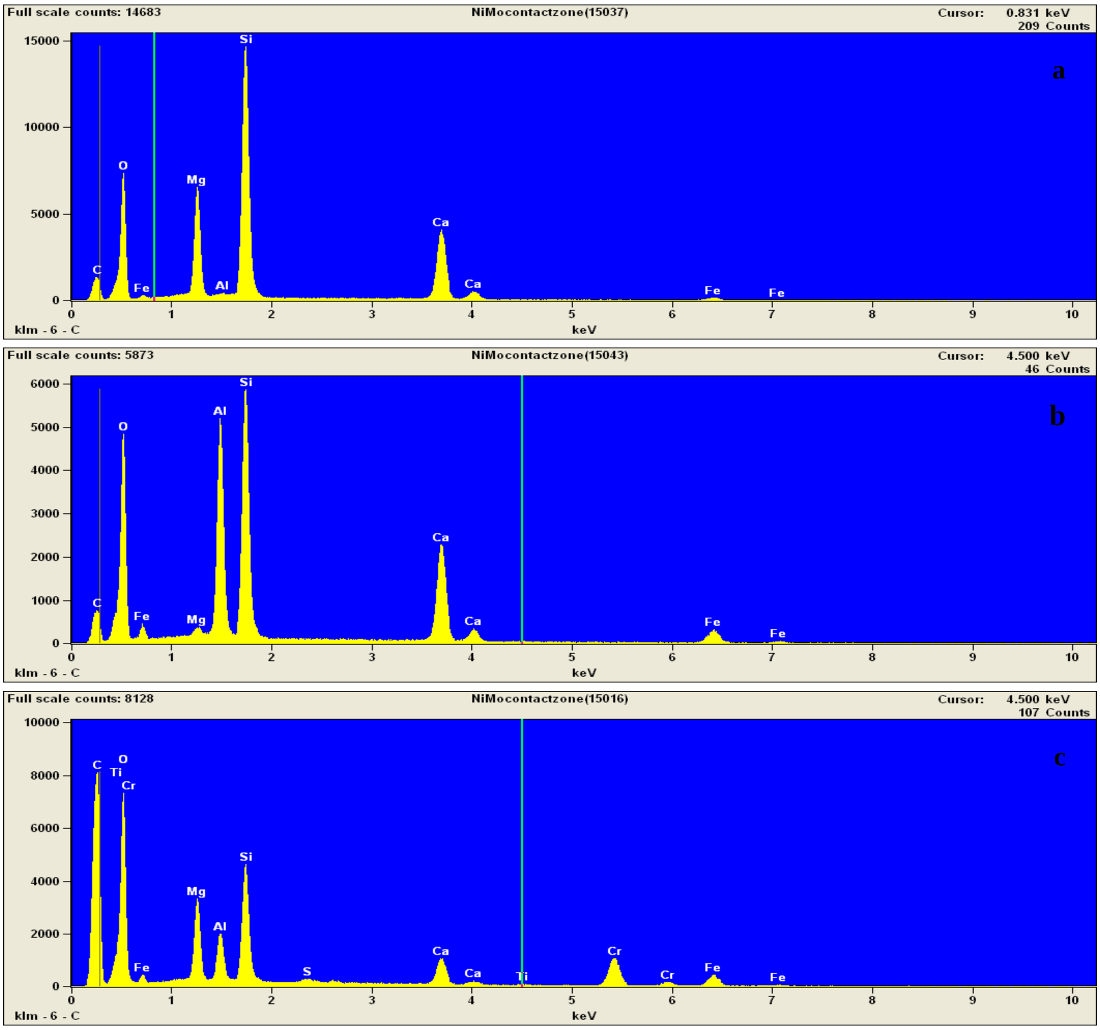


Figure- 7: Energy Dispersive X-Ray Analyzer (EDXRA) spectra for; (a) Diopside (pyroxene group) for grain no. 4 (Table 3), (b) Epidote (epidote group) for grain no. 49 (Table 5), (c) Chromian spinel for grain no. 59 (Table 6).

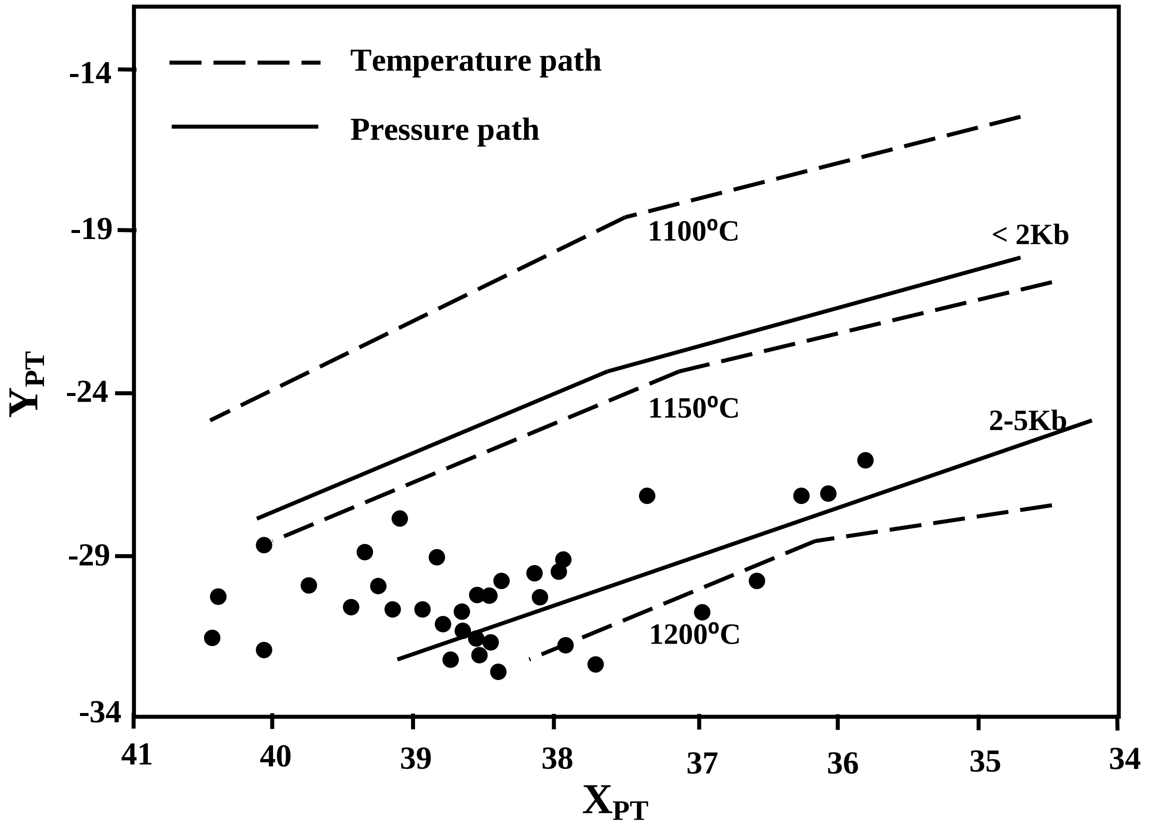


Figure- 8: Calculated pressure- temperature crystallization conditions for pyroxenes of fluvial sediment samples, based on the statistical multivariate calculation of Soesoo (1997) [34].

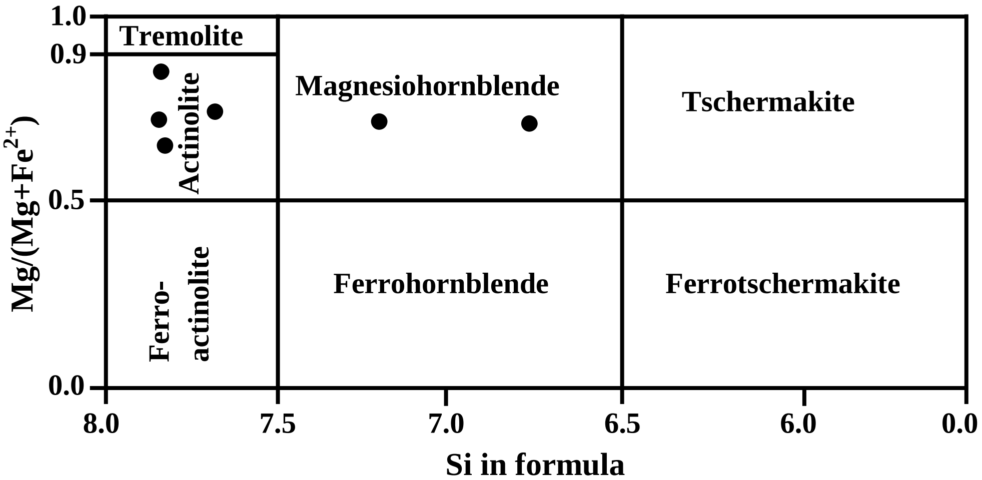


Figure- 9: Amphibole classification diagram for the fluvial recent sediments, according to Leake et al. (1997) [18].

Table- 4: Electron microprobe analysis of amphibole from the fluvial recent sediments, formulae calculated to 23 Oxygen.

	Grain number					
Oxides	***41***	***42***	***43***	***44***	***45***	***46***
SiO_2	*53.15*	*46.35*	*53.90*	*53.45*	*52.50*	*54.02*
TiO_2	*0.11*	*1.82*	*0.03*	*0.04*	*0.00*	*0.09*
Al_2O_3	*2.64*	*8.83*	*1.09*	*1.57*	*3.11*	*2.92*
Cr_2O_3	*0.48*	*0.27*	*0.289*	*0.03*	*0.00*	*0.04*
FeO	*10.83*	*10.07*	*6.1*	*12.24*	*12.75*	*11.36*
MnO	*0.21*	*0.16*	*0.09*	*0.35*	*0.17*	*0.31*
MgO	*17.48*	*15.96*	*20.69*	*16.35*	*15.44*	*16.79*
CaO	*11.37*	*12.06*	*12.70*	*12.20*	*11.01*	*11.41*
Na_2O	*0.27*	*1.39*	*0.18*	*0.19*	*0.23*	*0.27*
K_2O	*0.05*	*0.12*	*0.01*	*0.03*	*0.02*	*0.01*
ZnO	*0.13*	*016*	*0.02*	*0.05*	*0.00*	*0.03*
Total	*96.59*	*97.03*	*94.95*	*96.37*	*95.20*	*97.20*
Si	*7.57*	*6.75*	*7.75*	*7.78*	*7.72*	*7.73*
Al (iv)	*0.33*	*1.25*	*0.18*	*0.22*	*0.28*	*0.27*
T	*8.000*	*8.000*	*7.93*	*8.000*	*8.000*	*8.000*
Al (vi)	*0.11*	*0.26*	*0.00*	*0.05*	*0.26*	*0.23*
Ti	*0.01*	*0.20*	*0.00*	*0.00*	*0.00*	*0.01*
Cr	*0.06*	*0.03*	*0.03*	*0.00*	*0.00*	*0.00*
Fe(iii)	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Fe(ii)	*1.31*	*1.23*	*0.74*	*1.49*	*1.57*	*1.36*
Mn	*0.03*	*0.02*	*0.01*	*0.04*	*0.02*	*0.04*
Mg	*3.76*	*3.46*	*4.44*	*3.56*	*3.39*	*3.58*
C	*5.27*	*5.20*	*5.23*	*5.15*	*5.24*	*5.22*
C-5	*0.27*	*0.20*	*0.23*	*0.15*	*0.24*	*0.22*
Ca	*1.76*	*1.88*	*1.96*	*1.90*	*1.74*	*1.75*
Na	*-0.03*	*-0.08*	*-0.18*	*-0.06*	*0.03*	*0.03*
B	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*	*2.000*
Type	*magnesio*	*magnesio*	*actinolite*	*actinolite*	*actinolite*	*actinolite*
$Mg/(Mg+Fe^{+2})$	*0.74*	*0.74*	*0.86*	*0.70*	*0.68*	*0.73*
$Fe^{+3}/(Fe^{+3}+^{[iv]}Al$	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*

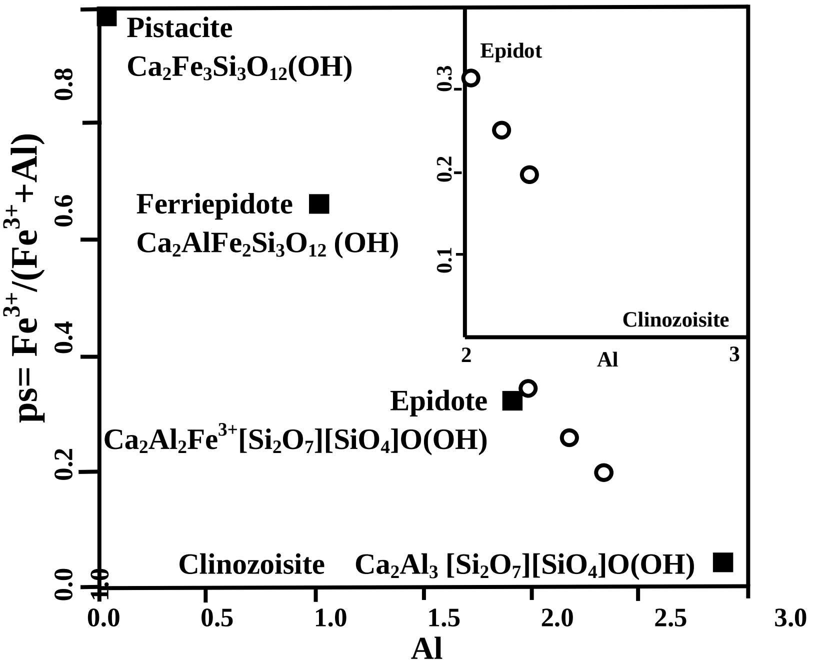


Figure- 10: Nomenclature of the epidote group for the fluvial recent sediments according to Armbrusterl et al. (2006) [40].

Table- 5: Electron microprobe analysis of epidote from the fluvial recent sediments, formulae calculated to12.5 oxygen.

	Grain number No. (3)		
Elements	**47**	**48**	**49**
SiO_2	38.01	37.60	37.67
TiO_2	0.00	0.14	0.07
Al_2O_3	24.72	20.52	23.28
Cr_2O_3	0.03	0.04	0.03
FeO	9.19	14.20	11.33
MnO	0.11	0.05	0.11
MgO	0.01	0.02	0.80
CaO	23.73	23.23	22.396
Na_2O	0.00	0.002	0.00
K_2O	0.01	0.01	0.00
Total	97.71	97.69	97.59
Si	3.03	3.04	3.02
Ti	0.00	0.01	0.00
Al	2.32	1.96	2.20
Fe(iii)	0.61	0.96	0.76
Mn	0.01	0.00	0.01
Mg	0.00	0.00	0.10
Ca	2.03	2.01	1.92
Na	0.00	0.00	0.00
K	0.00	0.00	0.00
$Fe^{+3}/(Fe^{+3}+Al)$	0.21	0.33	0.27

D. Chromian spinel

Chromian spinel [(Mg, Fe^{2+})(Cr, Al, Fe^{3+})$_2O_4$] is a ubiquitous accessory mineral in ultramafic to mafic rocks. It owes its value as a petrogenetic indicator to its particular chemical character, being extremely sensitive to bulk rock composition and petrogenesis of the host rock [42]. The principal constituents (Cr, Mg and Al) behave differently during fractional crystallization or partial melting [43, 44, 45, 46, 47].

The chemical composition of the detrital chromian spinels can potentially be used as a sensitive indicator of the host-rock tectonic setting or of physicochemical conditions under which the host rock formed [46, 47, 48, and 49].

The EPMA of 11 chromian spinels and an EDS spectrum showing the main constituting peaks (Cr, Si, Mg, Al, Ca, and Fe) are presented in *Table: 6* and *Figure: 7*c, respectively. The calculations of ferrous (Fe^{2+}) and ferric (Fe^{3+}) are from raw analysis assuming spinel stochiometry. The Cr/(Cr+Al) ratio (Cr#), the Mg/(Mg+Fe^{2+}) ratio (Mg#), and Fe^{3+} # and TiO_2 contents are the common parameters used to get petrogenetic information from the composition of the chromian spinels.

The analyzed chromian spinals fall in the fields of magnesiospinels, chromite, and spinal *(Figure: 11)* and have relatively high Cr and low TiO_2 contents *(Table: 6)*.

Provenance of the sediments

The most common association of heavy minerals in the studied sediments is the unstable minerals (pyroxene and amphibole) which represent more than 50% of the heavy minerals. This means that these sediments were not transported for very long distances and are close to the source area.

The heavy mineral assemblages can distinguish between some tectonic settings. Plotting of percentage of heavy minerals on a right angle MF/MT/GM diagram, in particular, MT (at the right angle corner of the diagram) is less certain in distinguishing between sediments of different tectonic settings than the other two components [52]. The plotted data shows that the studied sediments reflect the active continental margin where MF>GM in the samples *(Figure: 12)*.

Depending on Soesoo (1997) [34] calculations the studied clinopyroxene is derived from igneous rocks of low pressure (2-5kb) and temperature between 1150-1220^{0}C *(Figure: 8).*
The minerals of amphibole group are well represented in young detrital sediments [42], it form in variety of igneous and metamorphic rocks. All analyzed amphiboles are Ca-amphiboles, the majority is Mg-rich (Mg# 68–86) and Al- poor with compositions ranging from magnesiohornblende (8.83wt% Al_2O_3) to actinolite (<4wt% Al_2O_3). Based on the low tetrahedra Al and alkali contents of the studied actinolite and hornblende *(Table: 4)*, the amphibole is crystallized under low temperature or/ and formed under low grade of metamorphism.

Fe-rich epidote crystallizes with Mg-actinolite at low temperatures, and epidote and clinozoisite are common with hornblende at intermediate temperatures. The Fe/Al ratios are between 0.26- 0.49, this may suggest the low metamorphic source complexes [37, 39].

Chromian spinel is an accessory mineral in ultramafic to mafic rocks. The Cr# and Mg# are the most characteristic parameters employed in classification and nomenclature of chromian spinel. These are integrated by major and minor oxides (Cr_2O_3, MgO, Fe_2O_3 and TiO_2) which are very important as provenance indicators. The relatively high content of Cr_2O_3, when plotted against Al_2O_3 shows that all of the studied chromian spinels are of podiform type except two samples are of stratiform type *(Figure: 13).*

The Cr# is the most characteristic indicator of chromian spinel discrimination of tectonic setting. Lee (1999) [47] suggests the range of the Cr# of chrome spinel as summarized in *Figure: 14*. They reviewed from both volcanic rocks and peridotites; the latter would be the more probable source for the detrital chromian spinel in sediments and sedimentary rocks. Detrital chromian spinel can be derived from various types of ultramafic complexes, such as Alpine type, Alaskan type, and stratiform peridotites complexes [47]. For distinguishing these complexes, a ternary diagram between the major constituents Cr^{3+}, Al^{3+}, and Fe^{3+} is commonly used [55].

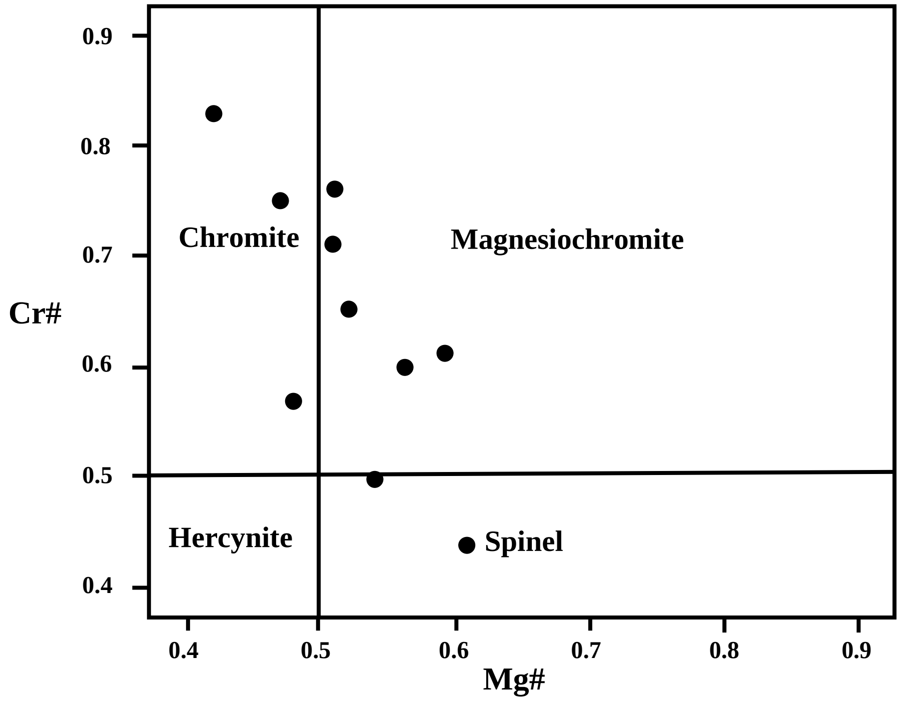


Figure- 11: The Cr# versus Mg# plot showing the classification and nomenclature of the chrome spinel from the fluvial recent sediments, according to Augé (1987) [50] and Ahmed and Arai (2002) [51].

The studied samples fall within the Alpine type peridotites spinel *(Figure: 15)* in fore-arc dynamic processes *(Figure: 14)* where Cr# ranges between 0.44- 0.83 *(Table 6)* and most frequently around 0.7 [56, 47]. This is supported by low content of Fe^{3+} (0.340- 1.871) as shown in *Table: 6* [57, 58, 49].

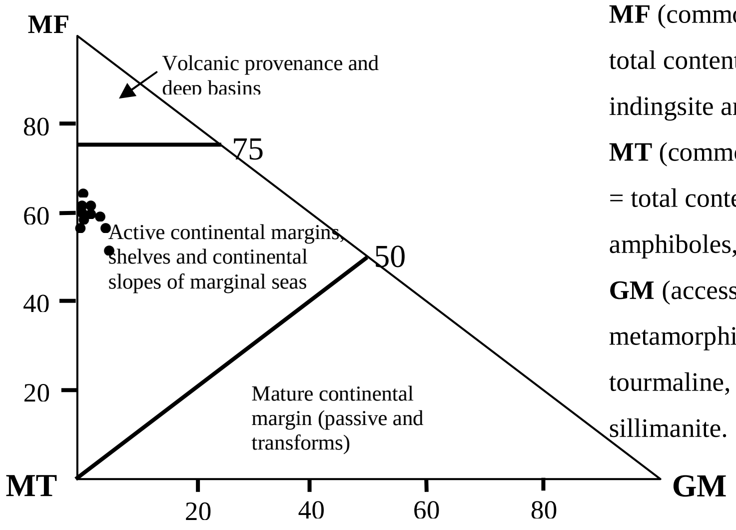
Based on the TiO_2 content *(Table: 6)*, it is suggested that the studied chromian spinel is derived from two sources; the low content (less than 0.2) is from peridotitic source rock, whereas more than 0.2 may indicate volcanic source [59, 49]. Mohammad (2008) [60] suggested that there are four main ultramafic rock bodies distribute along Iraqi Zagros Thrust Zone, which are the typical lithological markers of the suture zone between Arabian and Iranian plates. The peridotites indicate that they are mantle tectonite, rather than cumulate or replacive rock. He studied the spinel, and found some of them are analogous to those from abyssal peridotites and the chromian spinel resembles those from arc-related peridotite.

The rare occurrence of ultrastable minerals such as zircon and tourmaline suggest the lack of or rare presence of the acidic igneous rocks in the source area for the studied sediments".

According to the mineralogical and chemical studies, the most probable source of the sediments is south eastern Turkey and north eastern Iraq that representing Ophiolite Complex, Walash Series, and Qandil Series (represent the basic and ultra basic rocks). The studied chromian spinels belong to the Alpine- type peridotite spinel as they contain low Fe^{3+} and TiO_2.

Table- 6: Electron microprobe analysis of chromian spinel from the fluvial recent sediments, formulae calculated to 24 oxygen.

	Grain number Sample number (3)										
Elements	***50***	***51***	***52***	***53***	***54***	***55***	***56***	***57***	***58***	***59***	***60***
SiO_2	0.08	0.07	0.10	0.10	0.12	0.11	0.14	0.13	0.12	0.11	0.06
TiO_2	0.17	0.26	0.27	0.18	0.47	0.24	0.11	0.09	0.21	0.25	0.30
Al_2O_3	11.6	24.89	13.5	11.6	20.00	11.8	8.06	20.84	20.0	17.17	30.50
Cr_2O_3	56.4	37.46	49.9	56.2	38.81	42.3	60.4	48.63	45.3	48.26	35.72
FeO	20.1	24.48	24.1	20.1	28.02	24.2	21.7	17.18	21.1	21.65	19.34
MnO	0.46	0.38	0.45	0.46	0.45	0.44	0.49	0.38	0.39	0.41	0.29
MgO	10.2	11.55	10.2	10.1	9.91	9.48	8.14	12.71	11.7	10.66	15.66
CaO	0.04	0.05	0.04	0.04	0.06	0.04	0.05	0.03	0.04	0.03	0.03
ZnO	0.38	0.45	0.41	0.42	0.52	0.45	0.52	0.41	0.35	0.42	0.323
Total	99.6	99.60	99.1	99.3	98.37	99.1	99.6	100.39	99.4	98.97	100.21
Si	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.01
Ti	0.03	0.05	0.05	0.04	0.09	0.05	0.02	0.02	0.04	0.05	0.05
Al	0.61	7.21	4.17	3.62	6.03	3.69	2.57	6.07	5.93	5.20	8.50
Cr	11.7	7.28	10.3	11.7	7.85	10.9	12.9	9.47	9.00	9.81	6.68
Fe^{+3}	0.58	1.37	1.37	0.54	1.87	1.22	0.38	0.34	0.93	0.84	0.69
Fe^{+2}	3.84	3.69	3.90	3.89	4.13	4.14	4.55	3.21	3.50	3.81	3.14
Mn	0.10	0.08	0.11	0.10	0.10	0.10	0.11	0.08	0.08	0.09	0.06
Mg	4.02	4.23	3.99	3.97	3.78	3.74	3.29	4.68	4.41	4.07	4.81
Ca	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Zn	0.07	0.08	0.08	0.08	0.10	0.09	0.10	0.08	0.07	0.08	0.06
Total	24	24	24	24	24	24	24	24	24	24	24
$Cr^{\#}$	0.76	0.50	0.71	0.76	0.57	0.75	0.83	0.61	0.60	0. 65	0.44
$Mg^{\#}$	0.51	0.54	0.51	0.51	0.48	0.47	0.42	0.59	0.56	0. 52	0.61



MF (common constituents of mafic magmatic rocks) = total content of all pyroxene, brown-green hornblende, indingsite and olivine.

MT (common constituents of basic metamorphic rocks) = total content of pale colored and blue green amphiboles, epidote (group) and garnet.

GM (accessory minerals of granites and sialic metamorphic rocks) = total content of zircon, tourmaline, staurolite, kyanite, andalusite, monazite and sillimanite.

Figure- 12: Interrelationship of the MF, MT, GM suites in the studied sediments, Kurdistan Region (after Markevich et al., 2007 [53]).

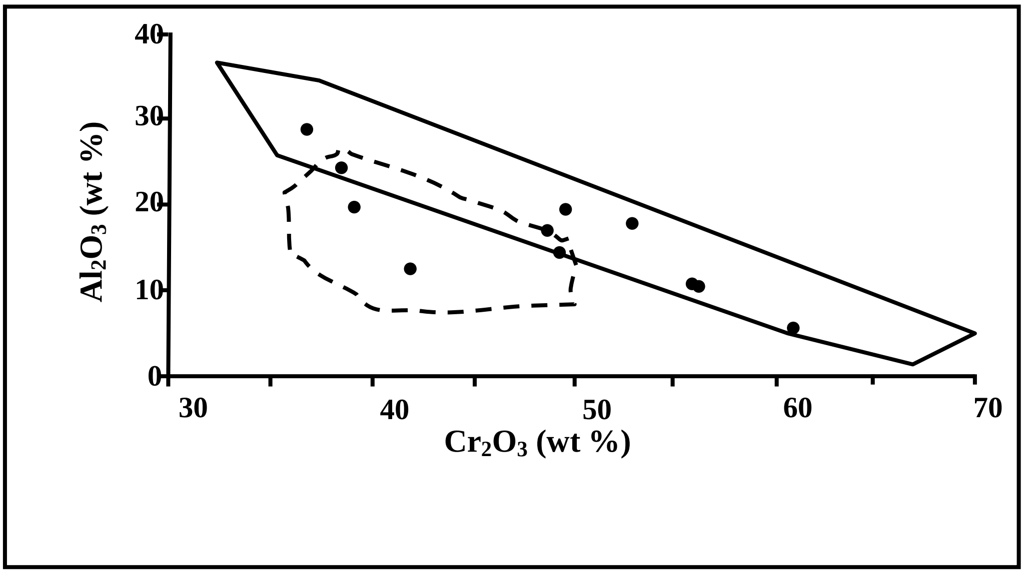


Figure- 13: Relationship between Al_2O_3 and Cr_2O_3 to determine the origin of chrome spinel, the fields are from Bonavia et al. (1993) [54].

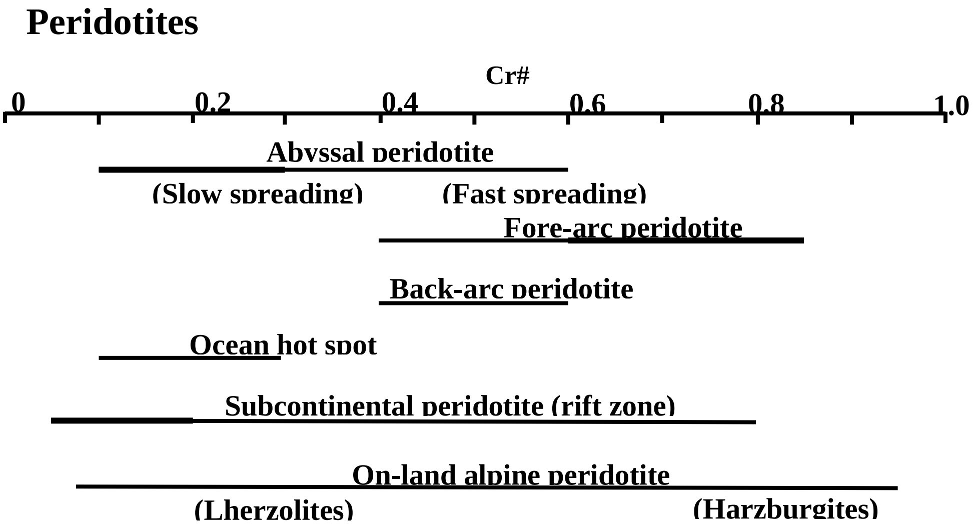


Figure- 14: Ranges of Cr# of spinels in peridotites from different tectonic settings. The heavy- line parts represent the majority of data plots [47].

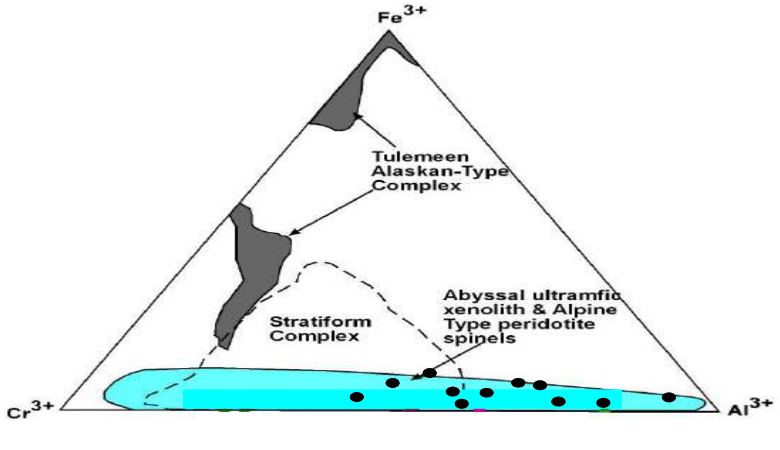


Figure- 15: Ternary plot of the major trivalent cations in chromian spinels for discriminating types of ultrabasic source [45, 57].

Conclusions

The heavy mineral assemblages in fluvial recent sediments from Balakyan River are mainly represented by pyroxene, amphibole, epidote, serpentine, apatite, tourmaline, zircon, and opaque minerals (chromian spinel, magnetite, hematite, goethite, and ilmenite).

The high contents of unstable and metastable minerals confirm their direct derivation from the adjacent primary source.

According to the chemistry of clinopyroxene it seems possible that their source could be basic igneous rocks crystallized under temperature 1150-1220^{0}C and low pressure. While from the chemistry of calc-amphibole the low temperature crystallization and/ or the low grade of metamorphism; also the present epidote group suggests the low metamorphic source complexes.

The chromian spinel is derived from basic and ultrabasic rocks of the Alpine type peridotite of the fore-arc origin. The heavy mineral assemblages reflect the active continental margin were MF⍰GM in the sediments.

The presence of few zircon grains of euhedral shape reflects the limited effect of the acidic igneous source rocks.

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