Islamic Azad University
Mashhad Branch

Elahpour and Heuss-Aßbichler / Iranian Journal of Earth Sciences 9 (2017) / 154-167

Petrology and Presentation: A Seven-Stage Model for Geodynamic Evolution of the Northeast Region of Birjand, East of Northern Lut, Eastern Iran

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Received 3 March 2016; accepted 5 December 2016

Abstract

The northeast region of Birjand is located in Lut structural and geological province. In this area we can distinguish two separate volcanic rock groups: intermediate to acidic volcanic rocks, including dacite, andesite, rhyolite and trachyandesite; and basic rocks, including basaltic andesite, mugearite and basalt. In this region, intermediate to acidic rocks, which belong to the Eocene-Miocene period according to dating results, are the main formation, and we can see the second, younger (evidently Pliocene) volcanic rock group as outcrops with a northwest-southeast trend in the background of the intermediate to acidic volcanic rocks. Geochemical studies show the differences between these two distinctive groups clearly, and reveal that intermediate to acidic rocks belong to active continental margin calc-alkaline rocks. Studies also show the related mantle magma has been influenced by subducted lithospheric slab and metasomatized by crustal materials. The second volcanic rock group belongs to within-plate alkaline rocks. The linear successions and the arrangement of the basic volcanic rocks' outcrop in a northwest–southeast trend is in relation to the right lateral fault zones that have branched out of the Nehbandan fault system. As a result of the extensional regime development, and the high depth of these faults, alkaline magma could have formed and ascended to the surface. Considering with accepted ideas concerning eastern Iran geodynamic evolution and our new data, we have tried to complete the previous findings and present a seven-stage model for geological evolution of eastern Iran.

Keywords: *Andesite, basalt, Geodynamic, Birjand, Lut.*

1. Introduction

The investigated area in southern Khorasan Province in the east of Iran is a part of the Lut block's eastern area. The Lut rigid area in eastern Iran, 900 km long and 350 km wide, is situated between the central Iran microcontinent to the west and the Sistan flysch zone to the east. Its limits are the NS trending right-lateral strike-slip faults, the Gowk-Nayband fault system to the west and the Nehbandan fault to the east. The south boundary of Lut block is the Makran subduction zone (definitely the Bashagard fault system), and in the north it is limited by the EW trending left-lateral Doruneh fault. The stability of this area depends on compaction and lithification of its metamorphic basement, which formed in the Middle Triassic (Carnian stage) after the early Cimmerian orogenic phase (Alavi Naeini 1993). The presence of Mesozoic sediments more than 5000 m thick is a remarkable characteristic of this area. Ever since the Upper Cretaceous extensional main phase was predominant in Iran (except the Zagros and Kopetdag areas), volcanic activities have extended into this area.

Although the maximum volcanic activity occurred in the Eocene, we have identified several onsets of volcanic activities in other periods, such as: Lower Oligocene, Middle Miocene (19-22 MA), Pliocene (6-8 MA) and the Quaternary phase. The Lut block's Tertiary volcanic rocks are between 2000-3000 m in thickness, and their main chemical compositions are dacite, andesite, tuff and ignimbrite (Darvishzadeh 1976; Lotfi 1982). According to our study field observations, we can divide Lut volcanic rocks into intermediate to acidic older type (Eocene-Miocene) with components of rhyolite, dacite, extraordinary amounts of ignimbrite and andesite, with large amounts of an Al_2O_3 and calc-alkaline nature, and younger alkaline basaltic rocks. Since in this study we benefit from new dating results, after consideration and study of how these rocks have formed and developed, we have compared all earlier researchers' related ideas with our data and have succeeded in renewing the geodynamic knowledge of Lut block.

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2- Geological setting

The northeast region of Birjand is located in the Lut geo-structural field in the eastern part of Iran. As shown in Figures 1 and 2, it covers an area of 2,600 square km, lying at 59°, 30′ to 60° east longitude and 33° to 33°, 30′ north latitude. Two important features were observed in the geological study of this area. One aspect is the significant fracturing like that characterizing the major geological parts of Iran and, of course, the Alpine-Himalayan orogenic belt.

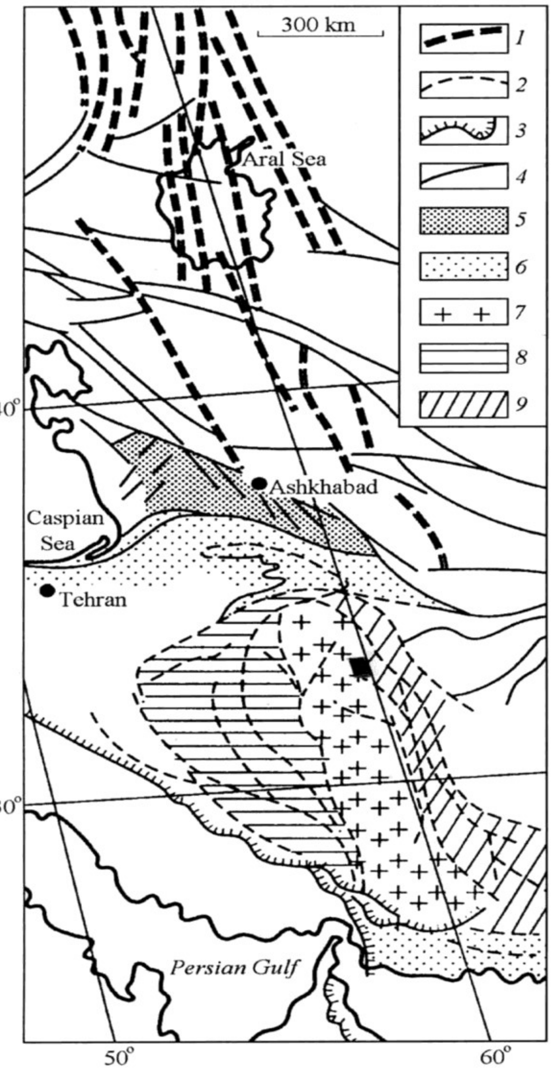

Fig 1. Elements of the tectonic structure of Ural – Oman lineament. 1- Meridian and submeridian raptures of south Ural and Turan plate. 2- Raptures of internal zones of Alpine belt took the modern place as a result of lateral movement and rotation of blocks. 3- Boundaries of allochthon ophiolite plates of Zagros, Oman. 4- Other raptures of Turan plate and Kopet Dagh including shear- faults. 5- Fold zone of Kopet Dagh. 6- north and south (Makran) chains of Alpine belt. 7- the Lut block. 8- central Iran microcontinent. 9- Sistan flysch zone (Leonov 1995). Black quadrangle shows our study area.

The second significant characteristic is the considerable amount of Paleogene volcanic rocks spread in this area. Paleogene acidic and intermediate volcanic rocks are the main rock component found in this area, and basic volcanic rocks, mostly young rocks, are distributed as outcrops with Paleogene rocks in northwest-southeast orientation.

3- Analytical techniques

In this work, a petrographic study was carried out on all samples and we analysed 41 representative fresh samples from two different groups of rocks for whole-rock major and trace analysis. We selected 20 suitable and fresh samples for rare earth element (REE) analysis (Table 1). The whole rock powders were split from 1 to 5 kg of crushed rocks, and were prepared by removing the altered surfaces. We performed XRF analysis for measuring major and selected trace element abundances at the GeoForchungsZentrum, Potsdam, Germany. Loss on ignition (LOI) was determined by heating a separate aliquot of rock powder at 1000 ºC for more than 2 h. For iron splitting and calculation of the real amount of FeO, we used titration with 0.02 N $K_2Cr_2O_7$. We also measured Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Sc with an ICP-AES vista MPX axial in Potsdam's geological research centre. In this method, the sample is transported into the instrument as a stream of liquid. The liquid is converted into an aerosol through a process known as nebulization. The sample aerosol is then transported to the plasma where it is desolvated, vaporized, atomized and excited/ionized by the plasma. The excited atoms and ions emit their characteristic radiations, which are collected by a device that sorts the radiation by wavelength. The radiation is detected and turned into electronic signals that are converted into concentration information. The excitation/atomization source is an argon-supported inductively coupled plasma. For this study, we used $^{40}Ar/^{39}Ar$ geochronology at the Paris Lodron University of Salzburg, Austria.

4 - Petrography

For classification of the volcanic samples, we used different diagrams based on the main oxides, rare elements and normative classification. All of these confirm the results that were obtained from petrographic studies and TAS diagram (Le Maitre 1989). As shown in Figure 3, according to the TAS diagram and petrographic studies, and from the lithological point of view, extrusive igneous rocks found in the northeast region of Birjand can be classified into two groups: (1) basic, containing basaltic andesite, mugearite and basalt, and (2), intermediate to acidic rocks, including andesite, trachyandesite, dacite and rhyolite. Basic rocks in this region have similar chemical properties, and can be distinguished from other volcanic rocks.

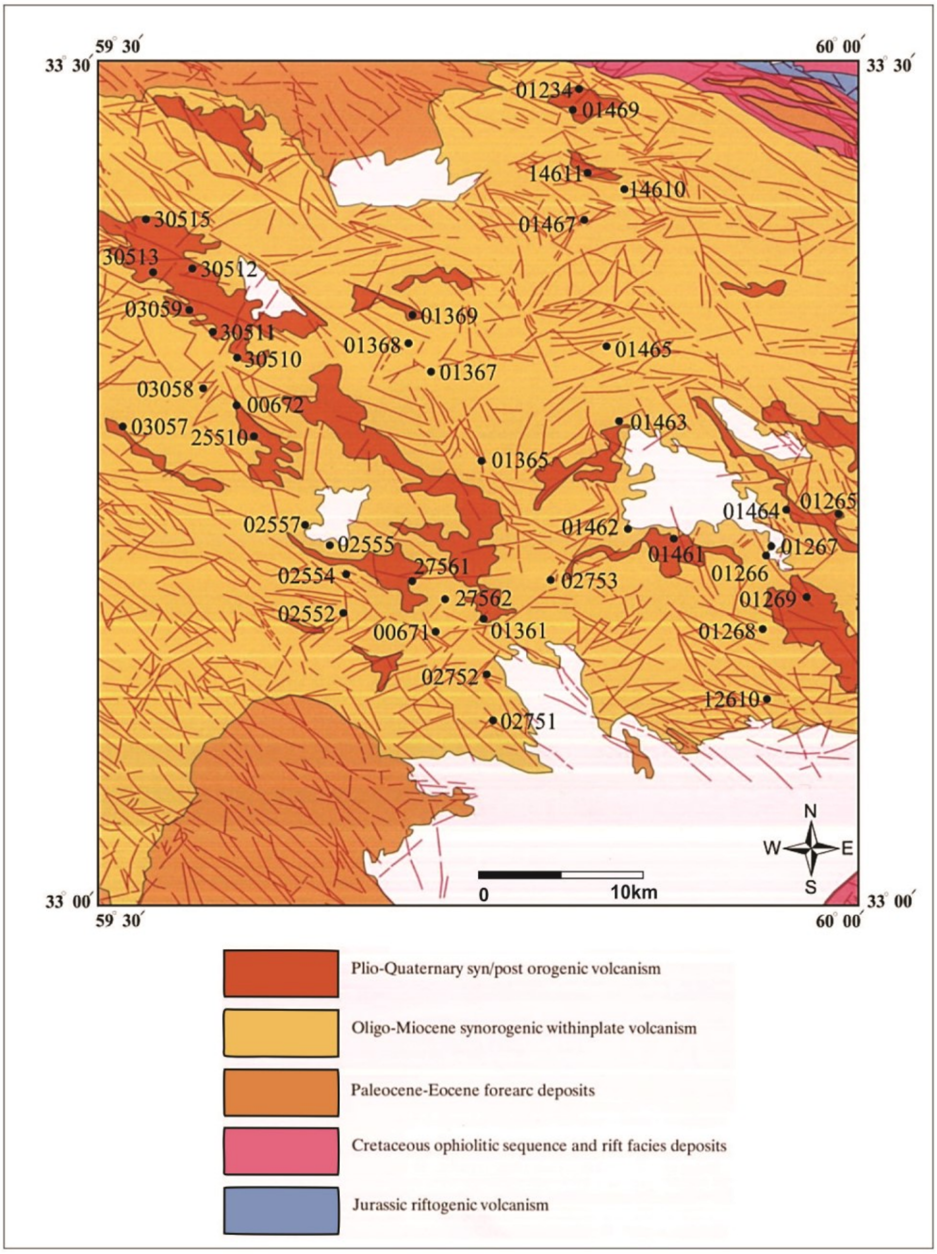

Fig 2. Sample locations on Interpretative tectono - stratigraphic map of area (after providing 1/100,000 geological map of Sarchah, geological survey of Iran).

They are mostly dark with porphyritic texture and microlitic to glassy mesostasis. As shown in Figure 4a, the amount of phenocrysts in these rocks is low and they consist of olivine, clinopyroxene (diopside and augite diopsidic) and plagioclase, with an average composition of labradorite. The lack of peripheral reactive edges on the olivine crystals in basaltic rocks studied here is a sign suggesting the alkaline nature of these rocks.

As shown in Figures 4b, 4c and 4d, the major texture found in intermediate to acidic rocks includes a broad spectrum from mesocratic to leucocratic rocks, which are porphyritic; we can also see scattered phenocrysts in the vitric to microcrystalline mesostasis. The texture of dacitic rocks is mostly porphyritic, with glassy-microlitic mesostasis, while the dominant texture in rhyolitic rocks is porphyritic with approximately glassy mesostasis.

Table 1. Major (wt %), trace and rare earth elements (ppm) compositions of volcanic rocks of East of Northern Lut

Sample	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Ba	Cr	Ga	Nb
44/2008 1234	51.22	1.31	17.31	3.53	4.31	0.15	6.73	8.46	4.4	2.03	0.55	338	126	18	30
44/2008 1264	51.77	1.33	16.24	5.44	2.66	0.12	7.92	9.28	3.7	1.14	0.41	99.71	341	283	17
44/2008 14611	53.15	1.75	16.45	8.23	0.87	0.14	5.78	8.44	3.71	1.08	0.39	347	116	22	18
44/2008 1268	53.37	1.2	16.48	7.28	0.91	0.14	4.22	10.2	4.37	1.22	0.6	234	184	18	20
44/2008 1269	54.22	1.61	16.31	3.62	4.7	0.13	5.7	8.71	3.53	1.1	0.37	241	179	17	18
44/2008 1469	54.61	1.54	16.02	4.72	3.66	0.13	5.25	8.4	3.41	1.9	0.36	304	139	17	19
44/2008 1265	54.66	1.22	17.15	5.12	2.5	0.13	5.15	8.63	3.93	1.02	0.47	382	156	17	12
44/2008 672	54.95	1.42	17	2.72	4.82	0.15	5.64	7.76	3.82	1.34	0.37	188	170	15	15
44/2008 30513	54.98	1.26	17.32	2.46	4.52	0.13	5.6	8.54	3.58	1.26	0.37	229	148	21	17
44/2008 3059	57.4	0.96	16.29	2.19	4.33	0.12	5.94	8.04	3.4	1.06	0.27	245	224	16	13
44/2008 30510	58.66	0.93	16.6	3.78	1.85	0.11	4.01	7.28	4.89	1.5	0.38	313	86	17	24
44/2008 3058	59.73	0.69	17.66	3.19	2.04	0.09	3.41	7.49	3.83	1.4	0.48	331	85	16	16
44/2008 27562	60.67	0.98	16.63	2.53	2.96	0.11	4.01	6.3	3.77	1.7	0.35	332	97	16	16
44/2008 14610	60.78	0.99	16.76	2.9	2.77	0.11	3.41	6.23	4.16	1.53	0.35	363	57	17	16
44/2008 27561	60.95	0.84	17.49	2.2	2.73	0.09	3.56	6.31	3.94	1.59	0.31	307	94	16	16
44/2008 30511	62.08	0.91	17.05	2.49	2.51	0.1	2.9	5.97	4.06	1.59	0.34	243	41	16	14
44/2008 30512	62.59	0.78	16.1	1.95	2.7	0.08	3.58	6.4	3.65	1.99	0.17	310	135	15	11
44/2008 2554	62.67	0.81	16.46	1.93	3.26	0.11	3.3	5.91	4	1.23	0.32	310	49	16	16
44/2008 30515	62.73	0.82	16.26	2.6	1.98	0.14	2.83	6.99	3.88	1.46	0.3	318	141	15	17
44/2008 1463	62.95	0.58	16.64	2.4	2.35	0.1	2.43	6.27	4.15	1.79	0.34	262	76	14	13
44/2008 1462	63.11	0.72	16.38	1.62	3.24	0.11	3.3	5.75	4.17	1.3	0.3	248	85	14	14
44/2008 1267	63.36	0.72	16.33	1.43	3.37	0.1	3.23	5.73	4.06	1.35	0.31	272	90	18	15
44/2008 1461	64.21	0.62	16.27	2.19	2.43	0.1	2.87	5.83	3.98	1.17	0.32	259	81	18	15
44/2008 3057	64.49	0.58	17.02	3.67	1.03	0.11	1.36	5.87	3.97	1.57	0.33	379	67	17	15
44/2008 2557	64.65	0.58	16.7	2.83	1.72	0.11	2.17	5.44	3.85	1.63	0.32	558	48	15	14
44/2008 2555	64.99	0.66	16.84	2.64	1.72	0.07	1.89	5.18	3.7	1.98	0.35	307	42	15	13
44/2008 25510	65.5	0.55	16.56	2.64	1.56	0.07	1.96	5.36	3.82	1.73	0.24	376	55	17	13
44/2008 2552	66.25	0.45	16.56	2.53	1	0.06	2.07	5.22	3.89	1.69	0.27	312	59	18	16
44/2008 1467	67.35	0.48	16.32	2.38	1.1	0.07	1.8	5.12	3.58	1.58	0.21	316	60	17	11
44/2008 1369	67.46	0.48	16.17	1.59	1.98	0.08	1.84	4.69	3.56	1.89	0.26	500	53	16	15
44/2008 1266	67.52	0.48	16.05	2.73	0.8	0.05	1.47	4.96	3.87	1.85	0.22	483	36	14	11
44/2008 1361	67.96	0.49	16.1	3.7	0.08	0.06	0.66	4.39	3.97	2.32	0.27	384	58	15	10
44/2008 671	68.71	0.45	15.59	2.55	0.77	0.05	1.51	4.68	3.9	1.64	0.14	296	48	17	17
44/2008 1367	69.12	0.38	15.76	2.18	0.59	0.04	1.69	4.83	3.58	1.68	0.14	297	52	17	10
44/2008 2753	69.17	0.4	16.06	2.97	0.12	0.07	0.27	4.63	3.87	2.25	0.17	296	48	14	9
44/2008 12610	69.39	0.41	15.21	1.51	1.42	0.07	1.38	4.64	3.9	1.91	0.16	478	50	17	10
44/2008 1368	69.51	0.42	15.3	2.04	1.01	0.07	1.49	4.09	3.88	2.01	0.17	333	69	15	12
44/2008 2752	70.4	0.32	15.88	2.4	0.01	0.04	0.94	4.03	3.84	2.01	0.12	433	40	14	10
44/2008 2751	70.49	0.32	15.88	2.38	0.01	0.02	0.91	3.94	3.98	1.95	0.12	429	39	19	9
44/2008 1365	72.09	0.32	14.78	2.49	0.01	0.04	0.54	3.38	3.6	2.63	0.11	452	35	16	9
44/2008 1465	72.71	0.29	15.23	2.07	0.01	0.02	0.52	3.33	3.69	2.03	0.09	321	28	14	8

Table 1 (continued)

Sample	Ni	Rb	Sr	V	Y	Zn	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd
44/2008 1234	90	34	671	152	27	75	212	21	32	60	6.3	24	4.8	1.5	4.7
44/2008 1264	11	173	23	699	166	24	188	21	31	60	6.5	25	4.8	1.6	4.7
44/2008 14611	78	27	839	213	21	94	200	23	21	44	5.3	23	5	1.6	5.1
44/2008 1268	103	<3	500	160	28	89	203	22	25	49	5.3	21	4.3	1.4	4.6
44/2008 1269	105	32	488	167	26	84	188	23	24	47	4.9	20	4.3	1.4	4.5
44/2008 1469	86	26	528	141	26	76	201	22	23	45	4.9	19	3.9	1.2	4.2
44/2008 1265	74	34	494	201	26	84	183	24	29	55	5.8	23	4.6	1.4	4.7
44/2008 672	94	26	531	144	24	84	208	19	28	52	5.3	20	4	1.2	4
44/2008 30513	91	13	537	148	26	70	213	20	21	41	4.3	17	3.5	0.98	3.7
44/2008 3059	142	37	392	124	26	63	194	24	27	54	5.7	22	4.5	1.3	4.7
44/2008 30510	57	53	424	102	28	64	278	23	31	56	5.9	22	4.3	1.2	4.4
44/2008 3058	52	35	520	107	20	88	225	25	27	52	5.5	21	4.3	1.2	4.6
44/2008 27562	69	53	486	107	29	64	247	22	28	53	5.5	21	4.2	1.3	4.3
44/2008 14610	54	59	492	88	22	61	206	24	32	57	5.9	22	4.3	1.2	4.5
44/2008 27561	63	36	400	94	30	62	244	20	29	51	5.2	20	3.8	1.1	3.9
44/2008 30511	26	50	410	97	25	61	223	14	26	47	4.6	17	3.3	0.97	3.2
44/2008 30512	79	69	288	95	25	49	187	19	29	53	5.3	20	3.9	1.1	3.9
44/2008 2554	28	50	355	85	29	70	238	17	23	42	4.2	16	3.1	0.84	3.1
44/2008 30515	62	44	329	98	26	68	223	12	24	41	3.8	14	2.7	0.68	2.5
44/2008 1463	49	32	337	95	32	69	244	11	22	38	3.3	12	2.3	0.7	2.2
44/2008 1462	55	42	299	90	31	66	243	Tb	Dy	Ho	Er	Tm	Yb	Lu	Sc
44/2008 1267	58	44	429	84	27	62	241	0.66	4	0.77	2.3	0.35	2.2	0.32	18
44/2008 1461	55	37	302	85	31	64	254	0.68	4.1	0.8	2.4	0.36	2.3	0.33	21
44/2008 3057	36	59	359	69	26	64	237	0.77	4.5	0.85	2.5	0.38	2.3	0.33	20
44/2008 2557	29	36	352	75	27	63	241	0.64	4.3	0.85	2.6	0.37	2.5	0.35	19
44/2008 2555	25	43	322	84	28	66	234	0.66	4.2	0.86	2.6	0.4	2.5	0.36	19
44/2008 25510	33	65	328	75	25	60	205	0.63	4	0.8	2.5	0.38	2.5	0.36	18
44/2008 2552	28	49	380	64	18	54	215	0.7	4.3	0.9	2.7	0.41	2.7	0.4	13
44/2008 1467	29	73	342	57	17	41	195	0.57	3.6	0.72	2.2	0.33	2.2	0.31	12
44/2008 1369	27	48	471	65	26	51	252	0.56	3.6	0.73	2.3	0.36	2.3	0.34	14
44/2008 1266	18	89	439	46	22	49	190	0.65	4.4	0.92	2.8	0.43	2.9	0.42	12
44/2008 1361	30	57	348	60	17	52	197	0.61	4.2	0.86	2.6	0.4	2.7	0.4	9.8
44/2008 671	31	104	313	65	25	55	175	0.67	4.5	0.92	2.9	0.46	3	0.44	12
44/2008 1367	25	80	271	59	22	44	184	0.61	4.1	0.85	2.6	0.39	2.7	0.4	10
44/2008 2753	28	60	299	42	12	43	182	0.64	4.2	0.88	2.7	0.44	2.8	0.42	10
44/2008 12610	26	66	293	34	18	32	195	0.57	3.6	0.71	2.2	0.34	2.3	0.34	9.5
44/2008 1368	77	76	239	53	25	47	212	0.45	2.7	0.54	1.6	0.23	1.6	0.23	7.7
44/2008 2752	23	64	471	28	11	39	164	0.54	3.5	0.72	2.2	0.33	2.2	0.33	7.7
44/2008 2751	21	69	326	37	13	45	158	0.46	2.9	0.59	1.9	0.3	2	0.3	8.2
44/2008 1365	25	92	242	25	16	41	159	0.38	2.2	0.43	1.3	0.2	1.3	0.2	5.7
44/2008 1465	15	74	239	22	15	32	170	0.34	1.9	0.39	1.2	0.17	1.3	0.2	4.1

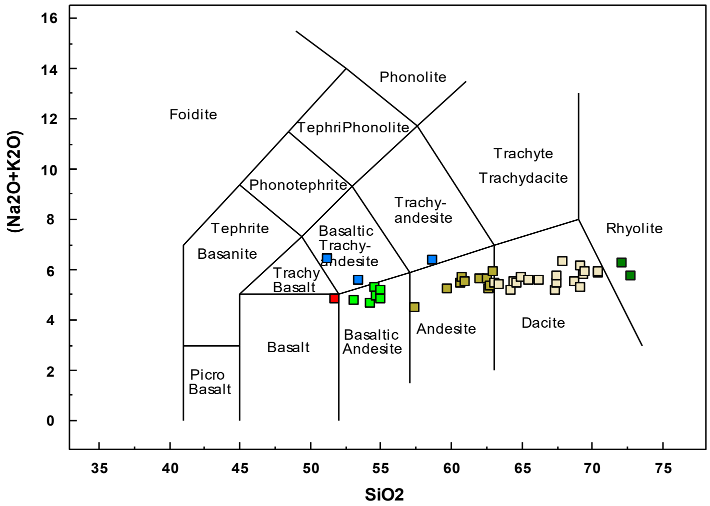

Fig 3. classification of rock samples with TAS diagram (Le Maitre 1989).

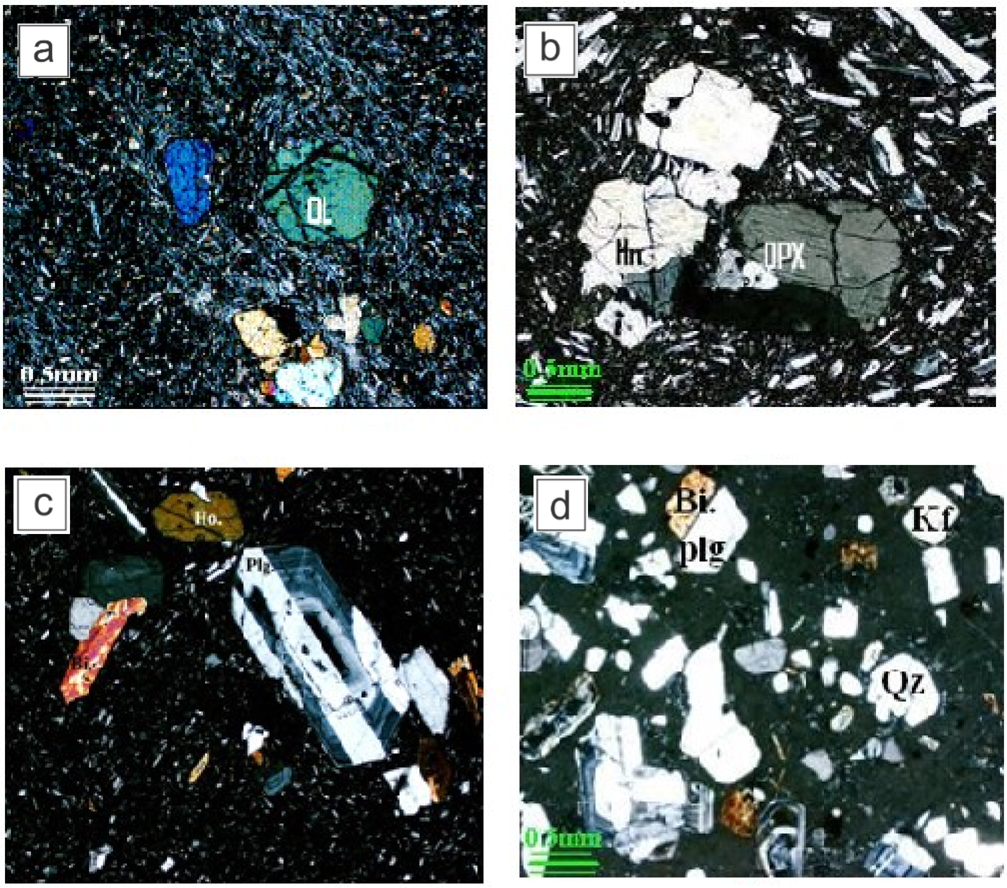

Fig 4. (a) Mugearite, (b) Andesite, (c) Dacite and (d) Rhyolite thin sections, XPL.

In the recent group, the prominent phenocrysts in andesites are plagioclase, orthopyroxene, clinopyroxene and hornblende; in dacites, plagioclase, hornblende, biotite and quartz; while in rhyolitic rocks they are quartz, plagioclase, potassium feldspar and biotite.

5 - Mineral chemistry and dating

Olivine crystals are found in both basalts and basaltic andesites. Olivine in these rocks is chrysolite from the chemical point of view, and the composition of these crystals has not revealed differences in the various spectrums of this rock group. In addition to basaltic rocks, pyroxene crystals are found in andesites. The composition of pyroxene is diopside in basalts, augite in basaltic andesites and enstatite in andesites. Amphibole crystals have been studied in dacitic rocks. Here, the composition of amphibole is magnesio hornblende to tschermakite hornblende. The composition of plagioclase phenocrysts in rhyolitic components is andesine, while the chemical composition of plagioclase phenocrysts in andesites, plagioclase microphenocrysts of basaltic andesites and scattered plagioclase microcrystals in basaltic rocks' mesostasis is labradorite. This assessment is reliable considering the fact that, commonly, the plagioclases that form volcanic rocks' mesostasis are more sodic than plagioclase phenocrysts in these rocks. These results show the distinctive composition of plagioclases from andesine to labradorite, and also show the calcium-rich nature especially in acidic to intermediate volcanic spectrum. As shown in Figure 5a, the age of andesitic sample with a sharp outcrop at 1.5 km southeast of Payhan village (no. 14610, N33°/26′ - E59°/49′) was calculated as 40.6 ± 1.2 MA, Upper Eocene by 40Ar/39Ar dating technique, and so synchronous with the early stages of the Pyrenean orogenic phase. Besides this, as shown in Figure 5b, we measured the age of a dacitic sample with the outcrop in southeast of Nowghab village (no. 01367, N33°/19′ - E59°/42′.05) as 20.7± 6.1 MA, Late Oligocene to Early Miocene, and so synchronous with Savian orogenic movement.

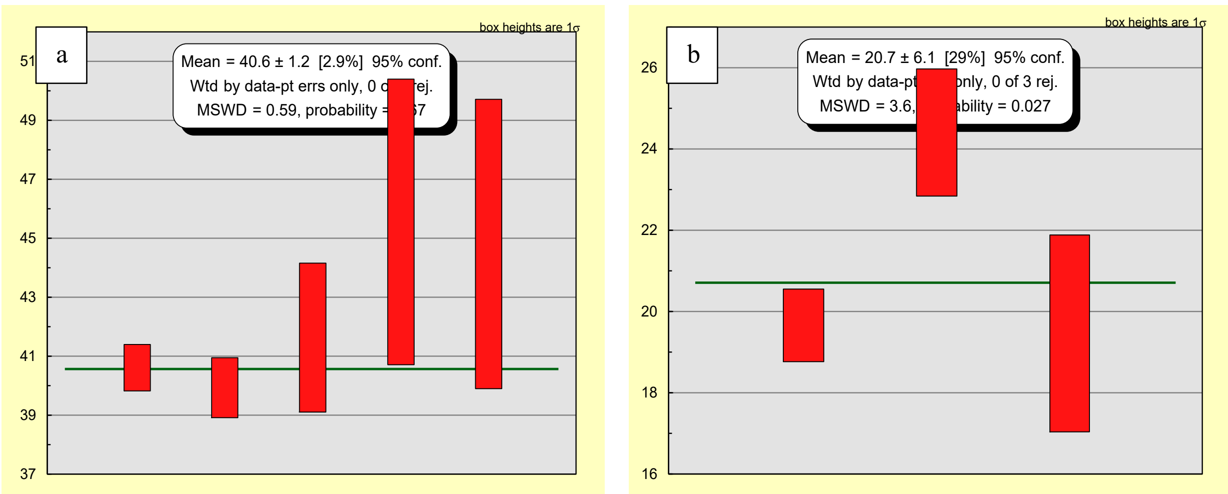

Fig 5. (a) Average age for sample 14610 measured according to microcrystaline mesostasis, (b) Average age of sample 01367 calculated by Amphibole crystals study.

6 - Geochemistry

As shown in Figure 6, the AFM (Irvine and Baragar 1971) and total alkali versus silica (Irvine and Baragar 1971) diagrams give magmatic series and natural definitions of the studied rocks. According to the mentioned diagrams, the acidic and intermediate volcanic rocks show a calc-alkaline nature, while the basic volcanic group in general, and especially with use of the total alkali versus silica diagram (Irvine and Baragar 1971), shows a tendency to an alkaline volcanic nature. As shown in Figure 7, the common subject in five of Harker's (1906) diagrams (CaO, Fe_2O_3t, FeOt, TiO_2 and Al_2O_3) is the remarkable descending trend as the result of the differentiation process. In all diagrams, a remarkable gap can be distinguished between mugearites, basaltic andesites and basaltic samples, and other volcanic rocks of the region. Here, CaO versus silica indicates a differentiated relationship between andesitic and rhyolitic rock series, and a precise study of Al_2O_3 versus silica shows that acidic to intermediate volcanic rocks of the northeast region of Birjand have more Al_2O_3 than basic rocks. This fact confirms the relation between these rocks and orogenic processes. This gap indicates that these two groups have different evolutionary histories and petrogenesis, and should be studied separately with consideration for all their genetic, evolutionary and age parameters.

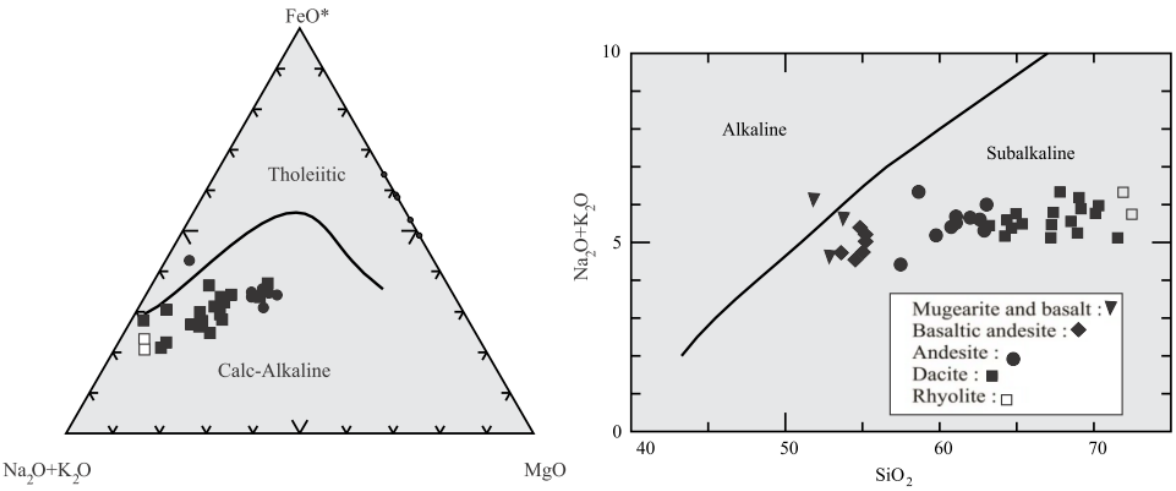

Fig 6. (a) AFM, Irvine and Baragar 1971 (b) Total alkali versus silica, Irvine and Baragar, 1971.

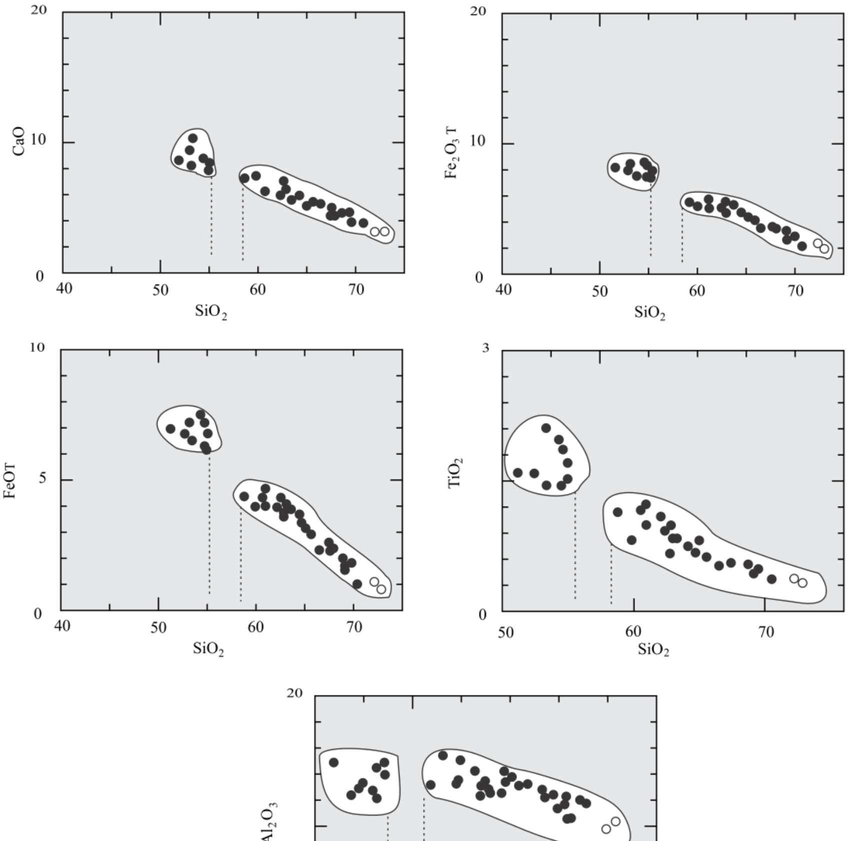

Fig 7. Harker variation diagram of some major oxide contents for the East of Northern Lut volcanic rocks

Based on a study with the main oxide versus differentiation index (Toronton and Tuttle 1960) variation diagrams mentioned in this study, a fault between two rock groups has appeared, and due to this fact there is no doubt that they would be different in at least one or more characteristics in at least one or more characteristics from among genesis, ascension meantime transitions, genesis environment and emplacement age. The amount of iron, especially in acidic to intermediate rocks, is low. As shown in Figure 8, in comparison with non-orogenic andesites (icelandites), the low amount of iron and increase in Al_2O_3 confirm that they belong to orogenic regions. The diagram of Zr rare element versus differentiation index shows Zr gradually decreasing when the differentiation index increases, as shown in Figure 8. This is a notable sign for Calc-alkaline rocks and confirms this nature in the acidic to intermediate rock group, clearly distinguishing them from basic rocks.

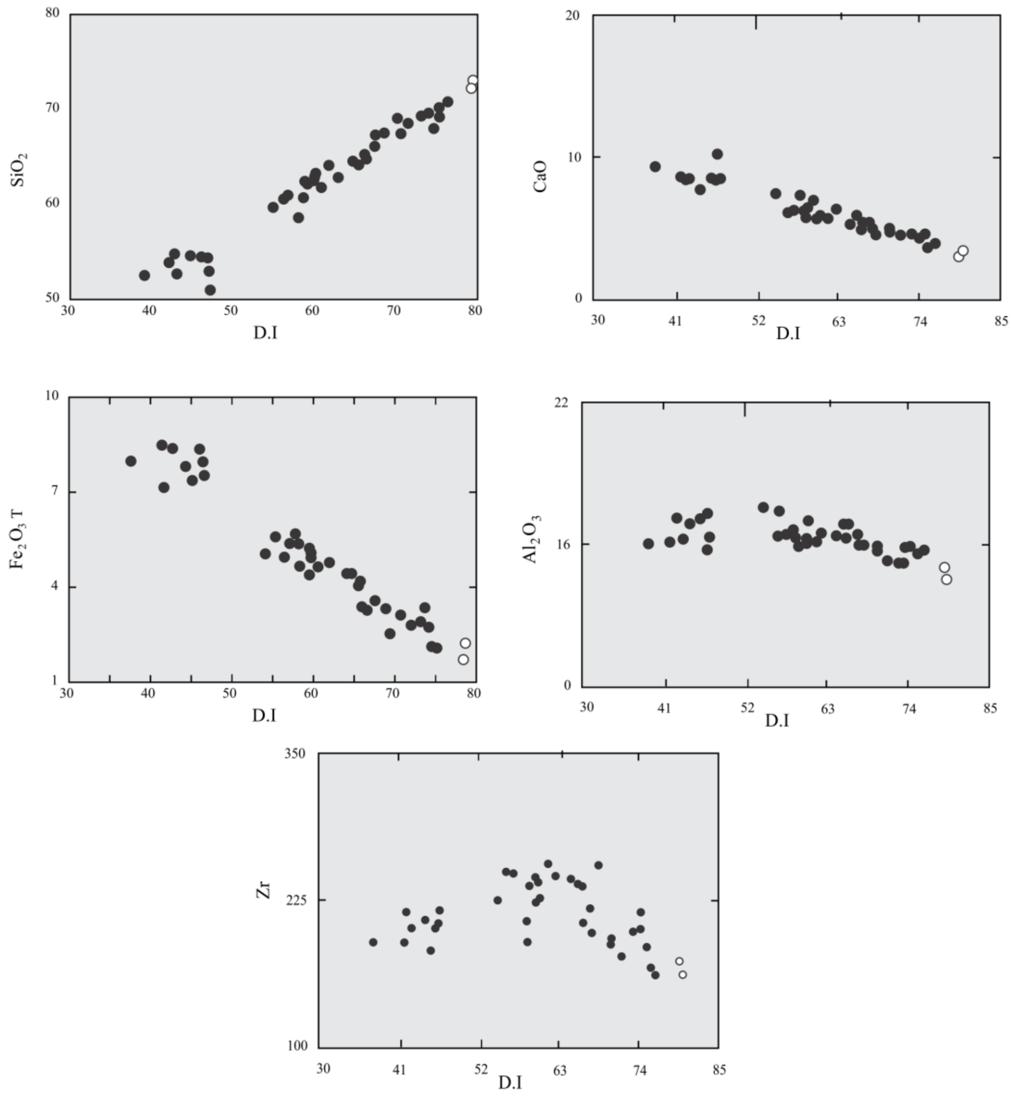

Fig 8. SiO_2, CaO, Fe_2O_3t & Al_2O_3 and Zr diagrams versus D.I. of Toronton and Tuttle (1960).

7- Petrogenesis

Emami (2000) has noted that northern Lut volcanism has been influenced by contamination, especially in terms of acid. Furthermore, Soffel et al. (1984) pointed out the incremental trend of the Rb/K ratio with increase in Rb amount as confirmation of meantime differentiation of crustal contamination, a process that is acceptable for the andesitic, dacitic and rhyolitic series of the region's volcanic rocks. As shown in Figure 9a, this subject is confirmed by La/Sm versus weight percent of silica (Richards et al. 2006).

Consideration of the northeast region of Birjand using the Ti/Zr versus Zr (ppm) diagram (Price et al. 1999), as shown in Figure 9b, also shows that the basic volcanic rocks of area are near to the mantle by nature, and they are approximately similar to MORB.

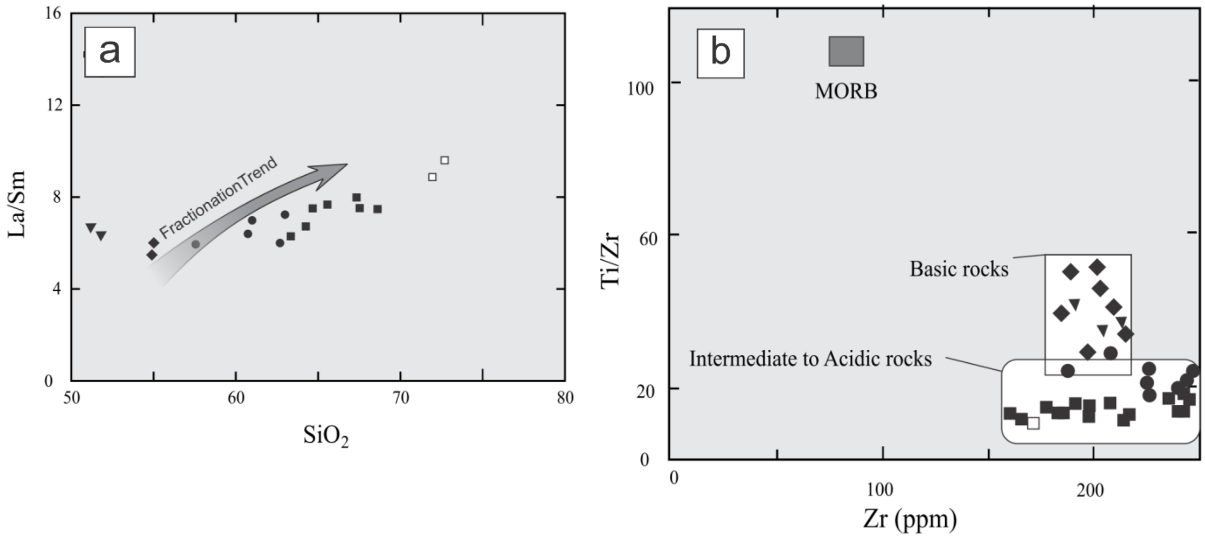

Fig 9. (a) La/Sm versus SiO_2 (wt%), Richards et al. (2006), (b) Ti/Zr versus Zr(ppm), Price et al. (1999).

The composition of other rocks is very different from MORB, and this obvious linear trend confirms their genetic relationship and separates them from basaltic compositions. Variation in a wide domain of a very high distribution index (D≥ 1) for the element Ba, which changes from 243 to 558 (ppm), also supports this subject and confirms the differentiation as a main parameter for genesis of acidic to intermediate extrusive rocks.

As shown in Figure 10, we have also used spider diagrams for the genetic assessment of the region's volcanic characteristics. According to the spider diagram proposed for the average composition of different rock types normalized with MORB, a negative Nb anomaly induces dependence with continental active margin-related subduction, a probable mechanism for mantle source metasomatism of a selective rich in LILE subducted phenomenon (Pearce and Parkinson, 1993). The negative Nb and Ti anomaly for intermediate to acidic rocks is more obvious for andesites and rhyolites, which can indicate that the origin contained rutile and amphibole as residue. Magma passing through the continental crust here suggests crustal contamination, a phenomenon that resulted in a high Rb/Sr ratio and an increase in Y and K_2O amounts as a result of AFC. Raeisi (2010) introduce Ba/Zr between 2 and 5 as a sign of contaminated continental basalts. This ratio is 1.42 for our basaltic rocks, and shows they have not been influenced by any notable contamination.

8 . Geodynamic situation

According to the Nb (ppm) versus the Y (ppm) variation diagram (Pearce et al. 1984), as shown in Figure 11a, the geotectonic situation of the northeast region of Birjand's dacitic and rhyolitic rocks is a continental volcanic arc with syn-collision.

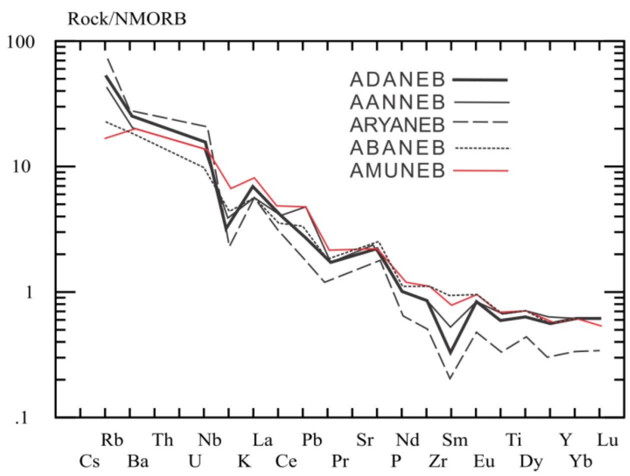

Fig 10. Spider diagram for all region rock types normalized with MORB (Pearce and Parkinson 1993). Average chemical composition of northeast region of Birjand dacites (ADANEB); Average chemical composition of northeast region of Birjand andesites (AANNEB); Average chemical composition of northeast region of Birjand rhyolites (ARYANEB); Average chemical composition of northeast region of Birjand basaltic andesites (ABANEB); Average chemical composition of northeast region of Birjand mugearites (AMUNEB)

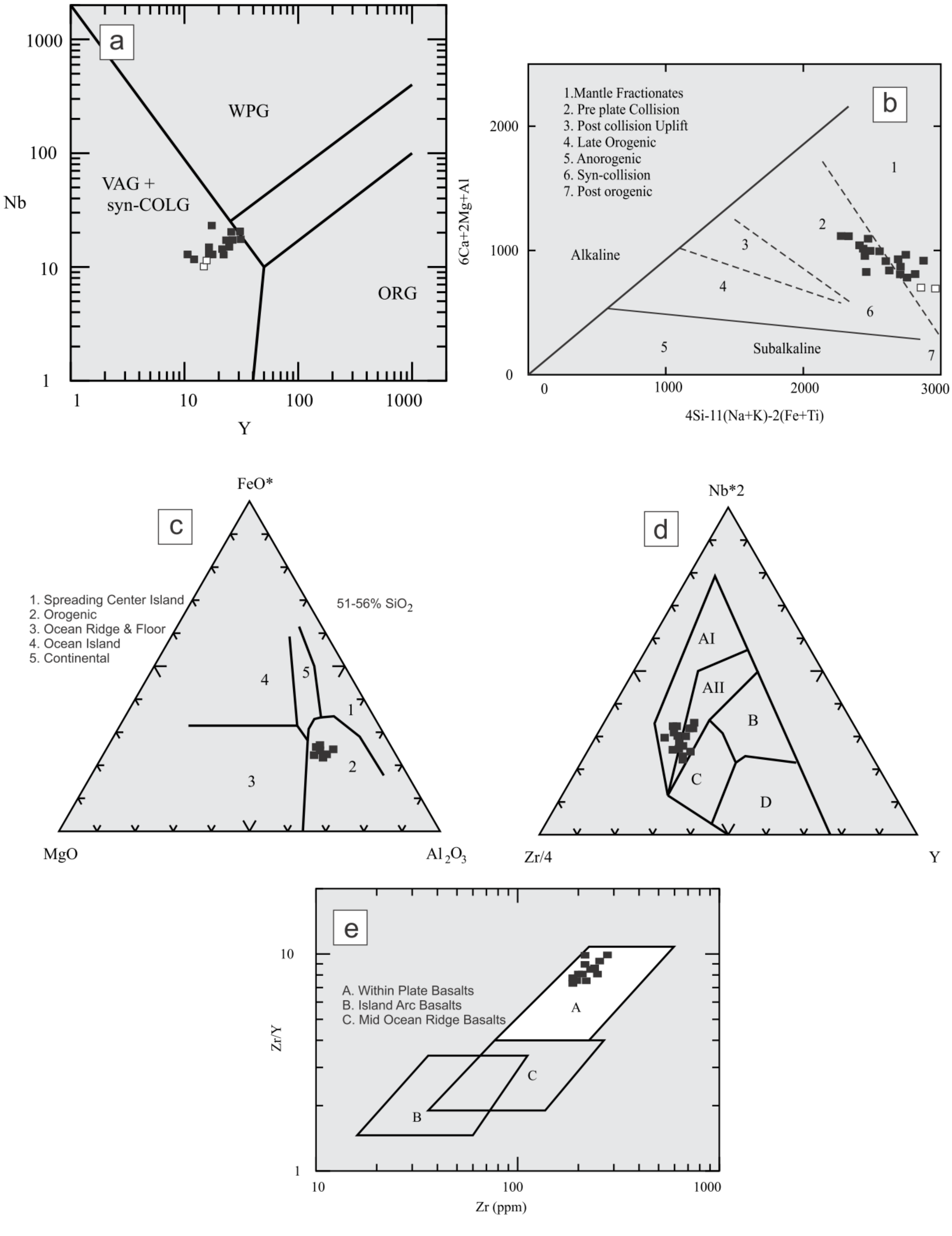

Fig 11. (a) Y(ppm) versus Nb(ppm), Pearce et al. (1984), (b) R2/R1, Batchelor and Bowden (1985) R1= 4Si-11 (Na + K)-2(Fe + Ti) and R2= 6Ca+2Mg+Al; (c) MgO - FeO*- Al_2O_3, Pearce and Gale (1977), (d) Zr/4 - Nb∗2 – Y triangular diagram for basalts (20%> CaO + MgO> 12%), Meschede(1986); AI: Intraplate alkali basalts, AII: Intraplate tholeiitic and alkali basalts, B: E – MORB, D: N – MORB and volcanic arc basalts and C: Intraplate tholeiites and volcanic arc basalts. , (e) Zr/Y versus Zr, Pearce & Norry (1979).

Based on the R2/R1 diagram (Batchelor and Bowden, 1985), the majority of dacitic rocks are pre-collision; therefore, due to the age of the dated dacitic sample, the Miocene should be considered for the collision event, as shown in Figure 11b. As shown in Figures 11c, d, e the MgO-FeO*-Al_2O_3 (Pearce and Gale 1977) and Nb∗2–Zr/4–Y (Meschede 1986) triangular diagrams and the Zr – Zr/Y (Pearce and Norry 1979) diagram show that all basaltic rocks of the region are intercontinental alkali basalt and are plotted in the location for orogenic basalts. Furthermore, as shown in Figure 12, based on La/Nb versus Ti (ppm) (Yilmaz et al. 2001), the common composition of basic rocks is close to MORB, while intermediate to acidic rocks are located in the area for melts influenced by subducted zone metasomatism (SZM).

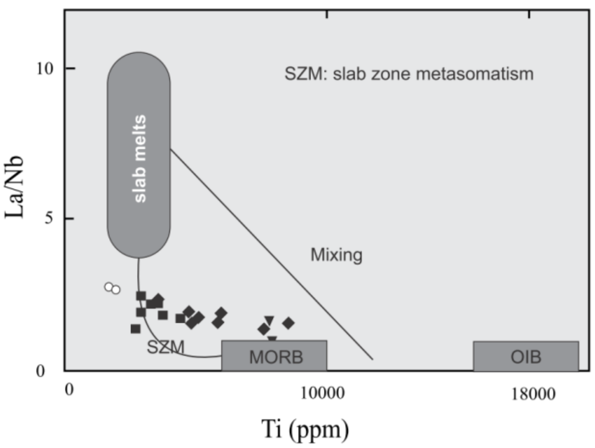

Fig 12. La/Nb versus Ti (ppm), Yilmaz et al (2001).

9. Evolution history and tectonomagmatic model

In relation to the genesis history of this rock set, and to introduce a tectonomagmatic model, we consider Eftekharnezhad's (1973) plan first, which described the existence of a flysch basin that resulted from Lower Cretaceous continental rifting between Lut and Helmand blocks. He believed that when the rifting in east Iran finished, the described oceanic crust subducted under Lut. Camp and Griffis (1982) and Tirrule et al. (1983) believed that rifting started between the Afghan (Helmand) block and Lut in the Cenomanian (early Upper Cretaceous), and has resulted in oceanic crust forming and flysch-type sediments being deposited. They proposed Maastrichtian for the beginning of the oceanic subduction under the Lut block and Middle Eocene for the two blocks' final collision.

Fotouhi Rad (2004) has reported that the general geological destination of the area was started by rifting in a unique continental block that has finally resulted in the east Birjand ophiolitic complex at the boundary of the Jurassic and Cretaceous, probably synchronous with the Makran basin or in the early Lower Cretaceous. After that, by changes in tectonic movements, rifting stopped and the oceanic crust started to subduct (Valanginian–Hauterivian in the Lower Cretaceous). Continuation in this convergent movement in the Upper Cretaceous to the Paleogene concluded the collision between the Lut and Afghan blocks.

Babazadeh and De Wever (2004), in a stratigraphy study of eastern Iran's Lower Cretaceous radiolarites, and Saccani et al.'s (2010) paper about the petrology and geochemistry of Nehbandan ophiolitic complex, point to an oceanic basin before the Lower Aptian between the two mentioned blocks. In similar studies, Babazadeh and De Wever argued for a pre-Maastrichtian dating for implacement for ophiolitic melange, and Saccani et al. (2010) indicated Late Albian for the beginning of the oceanic basin's closure, and under the Afghan block as the subduction direction. The existence of an oceanic basin between Lut and Helmand has generally been accepted, but the dispute is about the continental blocks' collision time. In this matter, Tirrule et al. (1983) have suggested Middle Eocene for the final blocks' collision.

Darvishzadeh (1991) has proposed Late Eocene for this event, and Emami (2000) also suggests Middle Eocene for the collision of the Lut block and the flysch zone. Berberian (1988) has argued for the oceanic strip's mutual subduction under both the Lut and Afghan blocks, and Middle Eocene for the blocks' contact. McCall (2002) in a paper about Makran's geology, through studying the geotectonic evolutions of Makran and eastern Iran's flysch zone southern terminal, has noted Early Oligocene as the oceanic basin's closing time in this area (in the part that he named the Saravan gulf). Furthermore, on the issue of the chemical nature of the region's volcanism, Aghanabati (2004) earlier pointed to an alkaline nature for Lut's basaltic rocks. Vosoughi Abedini (1997) has classified the basaltic rocks of the Mud and Ferdows regions in southern Khorasan Province (central-eastern Iran) as alkaline rocks with a binary geochemical character. In this line, Berberian (1988) also reported northern Lut volcanics as of a binary type. This idea that intermediate to acidic volcanic rocks of the northeast region of Birjand belong to a volcanic arc that resulted from the convergence and subduction between Lut and Helmand continental segments has clearly been inferred from subducted slab metasomatism and contamination with crustal materials. On the other hand, since in the Plioquaternary (Omrani and Nazary 2003), the forming time of basalts (probably Late Pliocene), the crust had considerable thickness, the magma forming these rocks has to be differentiated from basaltic andesites in terms of when it ascended and influenced crust materials' contamination. This contamination has influenced the main elements contained in these rocks, so in the study of total alkali versus silica they have to be located around the intervening curve of the calc-alkaline and alkaline compositions. Considering Sengor's (1990) classification of geotectonic evolutions with geotectonic and tectonomagmatic signs that have been defined for eastern Iran (with its strike-slip north-south fault systems that their trend in both terminals inclines to northwest-southeast direction) and this fact that in northern part such as our study area, fault systems transitionary change to left-lateral shear compressional east-west faults (and partly northwest-southeast), the tectonomagmatism and tectonic in continental fragment's collision stage is conform with continental margin asymmetric compressional slip orogenic belts.

In the northeast region of Birjand, we have dated andesitic and dacitic samples related to the continental active margin's calc-alkaline volcanics. According to these analyses, the andesitic sample belongs to the Upper Eocene and the dacitic sample is younger; its age is Upper Oligocene to Lower Miocene. According to Batchelor and Bowden (1985), the dated dacitic sample is of a pre-collision type. We propose seven stages for the area's geodynamic evolution.

1 - With convergence starting between Lut and Helmand continental fragments in the Middle Cretaceous (Late Albian to Cenomanian), in the flysch zone's western side the subduction begins under Lut.

2 - During this gradual process, as the result of the subducted slab's partial melting of the volcanic arc, calc-alkaline lavas with andesitic to rhyolitic composition are formed which reach the surface and also contaminate the relatively thick continental crust formations during ascent.

3 - The convergence process was reinforced and was more effective in the Alpine orogenic phase stages, and considerable volumes of volcanic rocks have formed in these time periods (for example, the dated andesitic sample was formed synchronously with the Pyrenean orogenic phase, and the dacitic sample formation time is contemporaneous with the Savian phase).

4 - The main collision event between continental fragments occurred in the Miocene, and after that the convergence's durability resulted in crustal shortening. In the later stage, post-orogenic molasse facieses have been deposited in some parts of the area as Pliocene conglomerate.

5 - When the crust became thicker, tensional fractures formed due to the Lut block's perimeter fault-related movements, and especially Nehbandan's fault-related right-lateral strike slip-faults, through which basaltic lavas ascended to the surface.

6 – The ascent of the mentioned lavas, meanwhile, in addition to the differentiation and formation of basaltic andesites, were relatively influenced by contamination in contact with crustal materials. All geochemical signs, which have few signs of the impression of alteration processes, and the stratigraphic situation of basaltic rocks and basaltic andesites show that these rocks are younger than the intermediate to acidic rocks. This is related to their position (above the Pliocene conglomerate, for example, north of the Payhan village region) which suggests they belong to the Late Pliocene (synchronous with the Wallachian orogenic phase).

7 - The final rising of the area occurred in Upper Pliocene. Quaternary sedimentary depositions, gentle folding and cutting, gully formation and the numerous river terraces are signs of geotectonic movements' continuation and tectonic activity.

Acknowledgments
We would like to appreciate from Prof. Dr. Joerg Erzinger, GFZ, German research center for geosciences, Potsdam, for XRF and ICP – AES analyses and Prof. Dr. Franz Neubauer, Paris Lordon University of Salzburg, Austria, for $^{40}Ar/^{39}Ar$ Geochronologie.

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