Journal of Geology and Mining Research Vol. 3(1), pp. 7-12, January 2011
Available online http://www.academicjournals.org/jgmr
ISSN 2006-9766 ©2011 Academic Journals

Full Length Research Paper

Comparison of rock units separation and fuzzy logic methods in neutralizing the syngentic effects in geochemical data, a case study in eastern part of Iran, Birjand

Ahmad Aryafar[1]*, Mohammad Shiva[1] and Soheil Zaremotlagh[2]

[1]Department of Mining, Faculty of Engineering, Birjand University, P.O. Box: 97175-376 Birjand, Iran.
[2]Department of Mining, Faculty of Engineering, Sistan and Baluchestan University, Zahedan, Iran.

Accepted 21 December, 2010

The elemental concentration variations in mineralization processes in the nature are mainly influenced by the syngenetic and epigenetic processes. By neutralizing the syngenetic effects, the epigenetic effects may delineate the mineralization of the interest elements. In the present study, two methods which were carried out in detecting the potential areas across the study area are compared; a) the method of separation of the lithological units comprising the determination of the median of every element in the relevant rock unit and calculating the enrichment index and using the X+2S for anomaly detection. b) Application of fuzzy c-means clustering (FCMC) which leads to the determination of the residual components of the geochemical signals. These two methods were applied to the results of a geochemical exploration project where 175 stream sediment samples were analyzed for 20 elements, using x-ray fluorescence spectrometry (XRFS). The comparison of the two sets of maps which were prepared by these methods indicated that, for most of the elements, there are very good coincidence in anomaly detection. The differences between two sets of maps lay in the intensity of the anomalies and there are no differences in anomaly locations.

Key words: Geochemical data, syngentic effect, fuzzy logic, rock unit separation.

INTRODUCTION

In stream sediment geochemical exploration or in litho-geochemical exploration, the variations of the element concentrations in the samples are somehow related to the two initial processes which are known as syngenetic and epigenetic processes. Since the epigenetic activation are more effective in mineralization process than the syngentic process, in data processing we try to highlight the geochemical signals of epigenetic processes which may lead to the mineralization detection. In some cases, the geochemical signals of the element concentration which may be related to the epigenetic process are covered by the initial enrichment of the element concentrations in the rocks. Owing to the presence of this problem among the results of the element analyses of the hundreds of samples, it is essential to separate the various lithological units of the catchments area, based on the geological map of the area, and neutralizing the effects of syngenetic processes using enrichment index for each separated rock units.

Then the new data are mixed and are ready for further data processing (Singh et al., 1997; Selinus and Esbenson, 1995; Shiva, 1998; Ranitisch, 2000). In this method, the samples are grouped according to the allocation of every sample to a specific rock. In case of stream sediment samples every sample is allocated to a specific type of rock which the sample might be originated from. The second method of neutralizing the syngenetic effects is the use of fuzzy logic, particularly

*Corresponding author. E-mail: ahariafar@yahoo.com.

Table 1. The number of samples which are allocated the relevant type of rocks.

Type of rocks	Symbol	No. sample
Filish	FI	18
Andesit- Tuff-Ignimbrite	AD-TI	17
Flish-Eslate	FE	13
Tuff-Ignimbrite	TI	9
Andesit-Filish	AD-FI	8
Andesit-Filish Eslate	AD-FE	7
Andesit- Marne Tuff- Tuff Ignimbrite	AD-MT-TI	6
Flish- Marne Conglomerate-Marne Tuff	FI-MC-MT	6
Andesit- Filish-Marne Conglomerate-Tuff Ignimbrite	AD-FI-MC-TI	6
Andesit- Marne Tuff	AD-MT	5
Andesit-Filish-Marne Conglomerate	AD-FI-MC	5
Flish-Marne Conglomerate-Marne Tuff-Tuff Ignimbrite	FI-MC-MT-TI	5

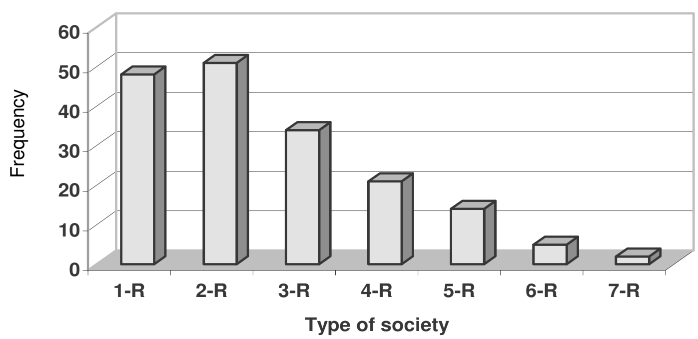

Figure 1. The histogram of the frequency distribution of the geochemical samples based on the number of rock types in the catchments area.

fuzzy c-means clustering (FCMC). Determination of the number of clusters is an important criterion in using the FCMC method. An empirical approach was tested to assign the adequate number of clusters in the study. Eight clusters were allocated to the data sets comprising 175 samples and 20 elements (variables).

Geology of the study area

Based on the 1:100000 scale geological map of Khousf, there are various lithological units across this area. Sandstones, conglomerates, Marn and tuffs are the main units in the central part of the study area, whereas Eocene – Oligocene volcanic bodies comprising andesite, tuffs and dacite are seen in the north and north-western part of the area. The intrusive igneous rock out-crop in the east and north-eastern part of the area.

Attribution of samples to the catchments area

In this study, every stream sediment sample was allocated to the specific rock are groups that, it might be originated from that rock. Following this procedure, all of the samples were put into their specific rock associations, which in this study are symbolically named as FI, UB, MC, FE, LI, AD, TI, MT, LV, Q. Table 1 indicates the number of samples which are allocated the relevant type of rocks (Aryafar, 2003). After separation of rock asso-ciations and their relevant samples, cluster analysis was applied to them and this lead to the creation of 14 independent associations. The histogram of the frequency distribution of the geochemical samples based on the number of rock types in the catchments area is shown in Figure 1.

Neutralizing the syngenetic effects

In order to neutralize the syngenetic effects, the background value of the element concentration was determined using the mean value or the median value for each element concentration. The use of median is more adequate than the mean, due to the independence of median from the type of distribution function. Then, the enrichment index for all of the elements in 14 rocks associations were calculated by the following relation (Davis, 1986):

$$e_i = c_i / c_m \tag{1}$$

Where, is enrichment index, is the element concentration and is the median for each element in its relevant rock association. These calculations lead to create a matrix of data, comprising 175 rows and 20 columns and ei as entries. The maps of enrichment index values were drawn for each element and the anomaly locations were determined based on the values greater than. Table 2 indicates the membership degrees of samples. Figure 2 indicates the Zn distribution map based on the enrichment index values.

In consequence, determination of geochemical signals using fuzzy c-means clustering method was applied to the data sets, in order to neutralize the element concentration variations caused by the syngenetic effects. The principles of the method are described by Kramar (1995) and Bezdek et al. (1984). The elements are allocated to the predetermined number of clusters by using fuzzy c-means clustering. In this study, the data matrix which is obtained from the initial operation is a matrix (the number of clusters are 8 and the number of elements are 20). The cluster centers, Cij are calculated using the following relation:

$$C_{ij} = \frac{\sum (\mu_{ki})^q \; x_{kj}}{\sum_{k=1}^{n} (\mu_{ki})^q} \tag{2}$$

Where: µik is the membership value of the sample k to the cluster i(i=1,2,...,n) and j=1,2,…,n); q is the degree of fuzziness and Xkj is the value of the variable j for the sample k. The membership values, µ, are calculated by using the following relation:

$$\mu_{ik} = \frac{(d_{ik}{}^2)^{-1/(q-1)}}{\sum_{k=1}^{c} (d_{ij}{}^2)^{-1/(q-1)}} \tag{3}$$

Where, dik is the distance of sample k to center of cluster, and q is the degree of fuzziness (Vriend et al., 1988). The dik are calculated by the following relation:

$$(d_{ik})^2 = \sum_{j=1}^{m} \left[(X_{kj} - C_{ij}) / S_j \right]^2 \tag{4}$$

Following the calculation of membership values, the new cluster centers are calculated. This procedure is iterative calculations which continue until the clusters remain stable.

Table 2. The membership degrees of sample to the related clusters in study area.

Serial	1	2	3	4	5	6	7	8
496	0.039	0.058	0.680	0.034	0.088	0.019	0.065	0.016
497	0.073	0.126	0.221	0.138	0.125	0.095	0.103	0.119
498	0.098	0.164	0.039	0.027	0.106	0.005	0.556	0.007
499	0.231	0.140	0.131	0.056	0.160	0.020	0.239	0.023
500	0.030	0.041	0.691	0.021	0.134	0.013	0.060	0.009
501	0.171	0.065	0.099	0.025	0.322	0.012	0.296	0.010
502	0.136	0.048	0.068	0.017	0.405	0.007	0.313	0.007
503	0.047	0.077	0.588	0.052	0.102	0.031	0.076	0.027
504	0.375	0.053	0.044	0.021	0.208	0.009	0.282	0.008
505	0.347	0.058	0.053	0.022	0.191	0.009	0.312	0.008
506	0.407	0.075	0.044	0.023	0.103	0.007	0.333	0.008
507	0.303	0.062	0.055	0.022	0.174	0.008	0.368	0.008
508	0.094	0.075	0.142	0.024	0.347	0.008	0.303	0.008
509	0.178	0.091	0.134	0.033	0.237	0.012	0.302	0.012
510	0.050	0.076	0.476	0.038	0.221	0.017	0.108	0.015
511	0.093	0.126	0.216	0.103	0.199	0.066	0.139	0.057
512	0.305	0.099	0.094	0.039	0.167	0.016	0.265	0.015
513	0.073	0.076	0.200	0.056	0.163	0.295	0.101	0.035
514	0.046	0.028	0.055	0.011	0.740	0.006	0.109	0.004
515	0.050	0.037	0.082	0.017	0.690	0.011	0.107	0.007
516	0.101	0.046	0.065	0.020	0.566	0.011	0.183	0.008
517	0.066	0.056	0.268	0.023	0.414	0.012	0.152	0.009
518	0.119	0.138	0.233	0.046	0.192	0.013	0.244	0.016
519	0.187	0.058	0.076	0.022	0.347	0.011	0.290	0.009
520	0.160	0.050	0.038	0.018	0.305	0.006	0.418	0.006
521	0.092	0.420	0.060	0.203	0.063	0.012	0.110	0.040
522	0.113	0.041	0.021	0.012	0.105	0.003	0.702	0.004
523	0.621	0.073	0.034	0.028	0.068	0.007	0.159	0.010
524	0.041	0.595	0.053	0.149	0.056	0.007	0.080	0.019
525	0.264	0.177	0.066	0.050	0.118	0.010	0.298	0.015
526	0.598	0.058	0.027	0.022	0.079	0.006	0.203	0.007
527	0.127	0.035	0.016	0.009	0.066	0.002	0.740	0.003
528	0.025	0.821	0.025	0.032	0.030	0.003	0.058	0.006
529	0.032	0.804	0.023	0.047	0.027	0.003	0.056	0.008
530	0.108	0.099	0.053	0.030	0.277	0.007	0.416	0.009
531	0.082	0.177	0.187	0.112	0.218	0.028	0.160	0.037
532	0.086	0.480	0.077	0.059	0.087	0.007	0.189	0.014
533	0.082	0.153	0.192	0.098	0.250	0.033	0.159	0.034
534	0.054	0.350	0.120	0.226	0.094	0.015	0.104	0.037
535	0.015	0.036	0.023	0.084	0.017	0.009	0.019	0.796
536	0.027	0.051	0.035	0.098	0.029	0.019	0.032	0.708
537	0.038	0.072	0.047	0.134	0.038	0.023	0.043	0.605
538	0.148	0.322	0.066	0.180	0.079	0.015	0.142	0.047
539	0.184	0.207	0.038	0.036	0.092	0.006	0.429	0.009
540	0.017	0.898	0.011	0.024	0.015	0.002	0.030	0.004
541	0.064	0.439	0.077	0.148	0.102	0.011	0.134	0.025
542	0.101	0.334	0.134	0.135	0.095	0.017	0.144	0.040

Table 2. Cont.

543	0.098	0.140	0.062	0.028	0.151	0.006	0.509	0.008
544	0.204	0.208	0.094	0.054	0.122	0.011	0.291	0.017
545	0.773	0.039	0.016	0.014	0.039	0.003	0.112	0.005
546	0.500	0.111	0.043	0.048	0.086	0.011	0.183	0.017
547	0.036	0.666	0.040	0.138	0.037	0.006	0.059	0.018
548	0.278	0.124	0.036	0.034	0.108	0.006	0.404	0.010
549	0.078	0.379	0.049	0.294	0.054	0.011	0.092	0.044
550	0.036	0.028	0.067	0.012	0.755	0.006	0.090	0.005
551	0.075	0.105	0.376	0.080	0.129	0.077	0.105	0.053
552	0.066	0.399	0.162	0.105	0.099	0.012	0.134	0.024
553	0.054	0.070	0.472	0.039	0.217	0.028	0.102	0.017
554	0.065	0.118	0.463	0.062	0.131	0.022	0.114	0.026
555	0.062	0.158	0.337	0.137	0.105	0.037	0.098	0.068
556	0.050	0.070	0.551	0.046	0.133	0.044	0.082	0.024
557	0.065	0.482	0.075	0.053	0.106	0.007	0.202	0.011
558	0.753	0.035	0.020	0.015	0.053	0.005	0.113	0.006
559	0.067	0.079	0.242	0.026	0.358	0.009	0.210	0.009
560	0.105	0.149	0.246	0.114	0.126	0.056	0.130	0.075
561	0.068	0.021	0.014	0.006	0.090	0.002	0.797	0.002
562	0.301	0.232	0.057	0.080	0.088	0.012	0.206	0.024
563	0.110	0.241	0.113	0.045	0.145	0.008	0.325	0.013
564	0.181	0.300	0.054	0.048	0.090	0.007	0.308	0.012
565	0.090	0.052	0.042	0.018	0.412	0.005	0.375	0.006
566	0.066	0.125	0.188	0.039	0.342	0.010	0.219	0.012
567	0.025	0.097	0.035	0.662	0.027	0.009	0.033	0.112
568	0.050	0.249	0.083	0.388	0.076	0.016	0.084	0.054
569	0.059	0.329	0.044	0.394	0.046	0.010	0.073	0.045
570	0.024	0.064	0.031	0.228	0.026	0.011	0.030	0.587
571	0.014	0.034	0.018	0.107	0.015	0.007	0.017	0.789
572	0.063	0.312	0.047	0.390	0.049	0.011	0.077	0.050
573	0.024	0.047	0.031	0.093	0.026	0.016	0.028	0.734
574	0.855	0.021	0.011	0.008	0.027	0.002	0.073	0.003
575	0.229	0.057	0.071	0.025	0.340	0.013	0.254	0.010
576	0.083	0.453	0.064	0.098	0.101	0.009	0.174	0.019
577	0.079	0.106	0.107	0.042	0.422	0.013	0.219	0.013
578	0.451	0.095	0.062	0.049	0.118	0.018	0.185	0.022
579	0.063	0.026	0.014	0.007	0.067	0.002	0.819	0.002
580	0.336	0.144	0.040	0.033	0.083	0.006	0.349	0.009
581	0.021	0.053	0.034	0.148	0.026	0.014	0.027	0.678
582	0.437	0.114	0.058	0.059	0.106	0.018	0.182	0.025
583	0.003	0.013	0.003	0.969	0.003	0.001	0.004	0.005
584	0.261	0.085	0.028	0.022	0.095	0.005	0.498	0.006
585	0.043	0.101	0.084	0.211	0.059	0.037	0.058	0.408
586	0.080	0.068	0.053	0.017	0.187	0.004	0.586	0.005
587	0.051	0.450	0.087	0.220	0.061	0.011	0.085	0.035
588	0.056	0.597	0.057	0.049	0.073	0.005	0.152	0.010
589	0.041	0.099	0.067	0.241	0.054	0.029	0.055	0.413
590	0.065	0.496	0.064	0.185	0.056	0.010	0.092	0.032
591	0.035	0.758	0.033	0.059	0.035	0.004	0.065	0.010

Table 2. Cont.

592	0.367	0.178	0.051	0.076	0.092	0.013	0.200	0.024
593	0.127	0.397	0.049	0.165	0.075	0.011	0.145	0.031
594	0.070	0.464	0.041	0.244	0.051	0.009	0.090	0.030
595	0.081	0.617	0.034	0.069	0.054	0.006	0.128	0.012
596	0.021	0.079	0.024	0.757	0.023	0.007	0.028	0.062
597	0.105	0.303	0.054	0.277	0.076	0.015	0.121	0.050
598	0.039	0.741	0.025	0.078	0.035	0.004	0.067	0.011
599	0.086	0.130	0.150	0.063	0.338	0.024	0.188	0.021
600	0.199	0.056	0.053	0.023	0.363	0.010	0.287	0.009
601	0.394	0.067	0.046	0.029	0.178	0.011	0.266	0.011
602	0.699	0.043	0.020	0.016	0.057	0.004	0.156	0.005
603	0.258	0.106	0.066	0.051	0.218	0.018	0.265	0.019
604	0.093	0.385	0.052	0.221	0.077	0.012	0.126	0.034
605	0.038	0.676	0.041	0.120	0.039	0.006	0.063	0.017
606	0.020	0.022	0.038	0.020	0.033	0.828	0.025	0.014
607	0.141	0.348	0.067	0.166	0.078	0.014	0.143	0.042
608	0.062	0.060	0.090	0.050	0.094	0.536	0.073	0.036
609	0.314	0.095	0.076	0.052	0.197	0.028	0.215	0.023
610	0.512	0.078	0.048	0.038	0.111	0.014	0.182	0.016
611	0.652	0.029	0.016	0.010	0.062	0.003	0.225	0.003
612	0.348	0.120	0.037	0.029	0.082	0.005	0.368	0.009
613	0.038	0.014	0.008	0.004	0.035	0.001	0.900	0.001
614	0.079	0.524	0.044	0.065	0.083	0.007	0.185	0.012
615	0.241	0.283	0.050	0.095	0.090	0.011	0.208	0.024
616	0.170	0.316	0.043	0.053	0.092	0.007	0.307	0.012
617	0.033	0.102	0.040	0.470	0.034	0.013	0.042	0.266
618	0.015	0.071	0.015	0.833	0.015	0.004	0.020	0.026
619	0.051	0.113	0.091	0.223	0.070	0.044	0.069	0.340
620	0.025	0.086	0.032	0.654	0.028	0.010	0.033	0.131
621	0.041	0.183	0.066	0.505	0.058	0.015	0.065	0.066
622	0.047	0.134	0.047	0.445	0.043	0.015	0.056	0.213
623	0.031	0.126	0.028	0.682	0.028	0.008	0.039	0.058
624	0.054	0.198	0.040	0.523	0.044	0.011	0.064	0.065
625	0.019	0.070	0.022	0.769	0.020	0.006	0.025	0.070
626	0.058	0.050	0.062	0.019	0.622	0.007	0.175	0.007
627	0.094	0.102	0.178	0.064	0.328	0.047	0.159	0.028
628	0.068	0.152	0.152	0.216	0.114	0.054	0.101	0.142
629	0.834	0.027	0.012	0.010	0.030	0.003	0.082	0.003
630	0.011	0.014	0.025	0.012	0.019	0.895	0.015	0.009
631	0.252	0.060	0.059	0.025	0.282	0.010	0.304	0.009
632	0.315	0.052	0.024	0.014	0.072	0.003	0.516	0.004
633	0.312	0.054	0.054	0.022	0.258	0.010	0.280	0.009
634	0.340	0.073	0.069	0.032	0.207	0.017	0.250	0.013
635	0.698	0.040	0.027	0.016	0.069	0.006	0.139	0.006
636	0.358	0.056	0.055	0.023	0.221	0.011	0.267	0.009
637	0.092	0.068	0.222	0.038	0.373	0.044	0.144	0.018
638	0.231	0.060	0.082	0.026	0.323	0.015	0.252	0.011
639	0.073	0.103	0.217	0.100	0.115	0.207	0.095	0.091
640	0.096	0.139	0.320	0.090	0.134	0.042	0.131	0.048

Table 2. Cont.

641	0.058	0.081	0.560	0.038	0.127	0.018	0.103	0.016
642	0.031	0.037	0.074	0.034	0.051	0.706	0.039	0.028
643	0.056	0.231	0.177	0.248	0.101	0.026	0.098	0.064
644	0.222	0.084	0.053	0.030	0.207	0.008	0.385	0.010
645	0.040	0.516	0.040	0.272	0.039	0.007	0.060	0.025
646	0.042	0.136	0.087	0.377	0.057	0.024	0.060	0.217
647	0.053	0.346	0.117	0.261	0.071	0.015	0.088	0.048
648	0.057	0.159	0.387	0.061	0.168	0.014	0.136	0.019
649	0.046	0.204	0.101	0.408	0.071	0.019	0.075	0.076
650	0.398	0.050	0.041	0.017	0.140	0.006	0.342	0.006
651	0.168	0.062	0.076	0.029	0.416	0.017	0.220	0.012
652	0.063	0.080	0.466	0.031	0.195	0.013	0.140	0.012
653	0.019	0.024	0.824	0.012	0.071	0.007	0.037	0.005
654	0.539	0.063	0.049	0.027	0.111	0.011	0.188	0.011
655	0.538	0.067	0.048	0.027	0.101	0.009	0.200	0.010
656	0.085	0.088	0.120	0.082	0.106	0.353	0.094	0.073
657	0.089	0.093	0.124	0.088	0.110	0.317	0.098	0.080
658	0.082	0.341	0.096	0.103	0.153	0.014	0.188	0.022
659	0.083	0.146	0.192	0.123	0.188	0.078	0.134	0.055
660	0.703	0.054	0.023	0.021	0.055	0.005	0.132	0.007
661	0.103	0.123	0.282	0.042	0.204	0.015	0.217	0.015
662	0.377	0.096	0.061	0.031	0.116	0.009	0.298	0.011
663	0.040	0.330	0.033	0.468	0.036	0.007	0.056	0.029
664	0.028	0.053	0.038	0.101	0.031	0.021	0.034	0.693
665	0.164	0.243	0.060	0.083	0.146	0.012	0.274	0.020
666	0.089	0.505	0.041	0.160	0.059	0.008	0.113	0.025
667	0.255	0.097	0.069	0.049	0.239	0.020	0.252	0.019
668	0.042	0.032	0.080	0.014	0.722	0.009	0.095	0.006
669	0.140	0.064	0.101	0.030	0.432	0.021	0.199	0.013
670	0.095	0.086	0.214	0.055	0.266	0.117	0.138	0.029

In this research, in result of the multiplication of the two matrices, (175×8) and (8×20) generated matrix of (175×20). The FCMC method calculates the matrix of (175×20) which resembles the background concentration of the elements in the sample locations. The residual matrix is calculated from the following subtraction:

$$\sigma_{kj} = X_{kj} - \sum_{i=1}^{c} \mu_{ik} c_{ij} \quad (5)$$

The FCMC method has been applied to eliminate the syngenetic component from the geochemical data in Khousf. 1:50000 sheets. The sufficient clusters have been assigned using the K-mean cluster and lithological units' types in study area. The matrix of membership degree has been presented in Table 2. Finally, the calculated residual values using Equation (5) has been mapped. In Figure 3, the residual values for Zn has been

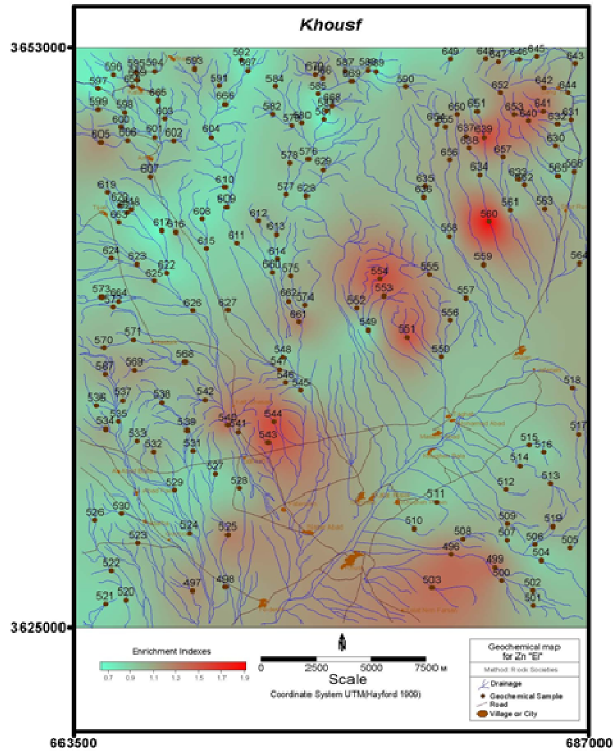

Figure 2. The Zn distribution map based on the enrichment index values.

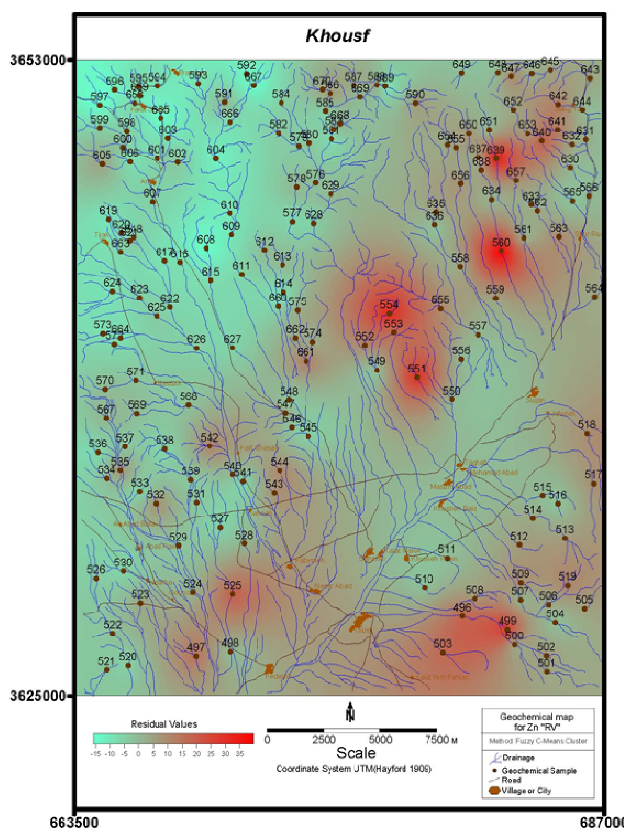

Figure 3. The Zn distribution map based on the residual values.

illustrated.

CONCLUSIONS

The fuzzy c-mean clustering (FCMC), using MATLAB software, was successfully applied the results of 175 stream sediment analyses in delineating the anomaly locations (residual matrix). The comparison the residual maps of this method with the maps generated by the method of Rock Units Separation, using enrichment index, indicated that there is a relatively good coincidence between these two series of maps. The results of such studies can be used in order to optimize the geochemical exploration programs in semi detailed or detailed exploration steps.

ACKNOWLEDGMENT

The author's would like to express their appreciations to the authorities of the Geological Survey of Iran who provided the facilities of mutual relations between GSI and the University of Birjand. The financial support of the Geological Survey of Iran is gratefully thanked.

REFERENCES

Aryafar A (2004). The analysis of the geochemical data in order to recognize the promising area in Khusf 1:50000 sheets, MSc. Thesis, the Shahrood University of technology, Shahrood, Iran.

Bezdek JC, Ehrlich RR, Full W (1984). FCM: the fuzzy c-means clustering algorithm. Comput. Geosci., 10: 191-203.

Davis JC (1986). Statistics and Data Analysis in Geology, John Wily &Sons, New York, pp. 646

Kramar U (1995). Application of limited fuzzy clusters to anomaly recognition in complex geological environments. J. Geochem. Explor., 55: 81-92.

Ranitisch G (2000). Application of fuzzy clusters to quantify lithological background concentrations in stream-sediment geochemistry. J. Geochem. Explor., 71: 73-82.

Selinus OS, Esbensen K (1995). Separating anthropogenic from natural anomalies in environmental geochemistry. J. Geochem. Explor., 55: 55-66.

Shiva M (1998). Stream Sediment Geochemical Exploration in the Arid Environment of East Iran, Ph.D Thesis, the University of Natingham, UK

Singh M, Ansari AA, Muller G, Singh IB (1997). Heavy metal in freshly deposited sediments of the Gomati River (a tributary to the Ganga River): effects of human activities. Environ. Geol., 29: 246-252.

Vriend SP, Van Gaans PFM, Middelburg J, De Nijis A (1988). The application of fuzzy c-means cluster analysis and nonlinear mapping to geochemical datasets: examples from Portugal. Appl. Geochem., 3: 213-224.