RED COLOURING OF THE UPPER RED FORMATION IN CENTRAL PART OF ITS BASIN, CENTRAL ZONE, IRAN

A. Amini*

Department of Geology, Tehran University, Tehran, Islamic Republic of Iran

Abstract

This study attempts to investigate the origin of red pigments, time of reddening, and processes responsible for red colouring of the Upper Miocene age Upper Red Formation, the most important clastic unit in central Iran. Mineralogical composition and textural properties of the studied sequences show that the Upper Red Formation sequences were not red when deposited, although some parts of red pigments were derived from the source region. This study clearly shows that both detrital and diagenetic pigments contributed in red colouring of the formation but diagenetic forms were more significant.

Introduction

In early sedimentological studies, the red colour of red beds was often related to their iron oxide content, including hematite, limonite, goethite, or mixtures of these with other iron oxides. Recent studies has clearly shown that the colour of red beds is not only the result of the presence of iron, but also due to ferric hydroxide which had enough time to dehydrate and turn to the red anhydride form, hematite [4,10,15,18,20,28-31,33]. Such a transformation may occur in the source region [15,24], during transportation [18], or after deposition [28,29,33]. The origin of pigments in red beds has been the subject of considerable controversy among geologists for the past 50 years. In early studies, it was believed that the hematite as a main component of pigments was formed in a lateritic soil and was subsequently transported to desert basins, associated with evaporites which usually form in such basins [15]. According to this hypothesis, hematite is formed in wet tropical or sub-tropical source areas so that it can be used as an indicator of warm and moist source regions. Based on this hypothesis, hematite as main cause for red colouring, was mainly detrital and sediments were red when deposited. Some examples of recent red sediments coloured by laterite detritus on the coastal piedmont of Tabasco in southern Mexico [15] were used as evidence to support this hypothesis. More recent studies took greater emphasise on post-depositional origin of red pigments [13,23,28-30,33]. Based on this hypothesis, hematite forms after deposition due to alteration of iron bearing detrital minerals, therefore hematite is mainly authigenic and sediments were not red when first laid down. This hypothesis claims that hematite may be formed in hot, arid, or semiarid climates.

The Upper Red Formation (URF) sequences; interbedded sandstone, mudstone, and conglomerate, with local layers of limestone, evaporites, and marl, are dominantly red in colour. The term “red beds” is appropriate for most sequences, based on the definition given in the literature [11]. This formation provides the best examples of red bed sequences in Central Iran with a wide variation in lithology, colour, and thickness.

Keywords: Red beds; Upper Red Formation; Central Iran; Clastic diagenesis

* *E-mail: ahamini@khayam.ut.ac.ir*

Both the first- and second-cycle deposits [25] are observed in the URF sequences, hence the red colouring of the formation seems to have an interesting and complex story, similar to which has been barely discussed in the literature. The origin of red pigments, time of pigmentation and processes responsible for reddening of the URF are discussed in this paper. This study provides significant information about the provenance, palaeoclimate, diagenetic history, and depositional environment of the formation.

Geological Setting

Based on a hypothesis, which explains the evolution of Iran from the standpoint of plate tectonic, the southwest of Iran (Khouzestan platform) is believed to be a part of the Arabian Plate, which subducted underneath Central Iran along the NW-SE Zagros Thrust belt. The subduction commenced by the late Kimmeridgian compressional phase, resulted in closure of the High Zagros Alpine Ocean, and probably continued till recent time [19]. Final closure of the High Zagros Alpine Ocean is related to the Late Cretaceous Laramide phase, following which Central Iran underwent regional metamorphism, intense volcanism, and extensive folding and uplifting [2,3]. The extensive Eocene volcanic activity of Central Iran, as the major post-collisional event, is related to subduction along the Zagros Thrust [5,7-9,14]. The post-collisional convergence of Arabian and Asian plates, on the other hand, resulted in progressive folding, faulting, and gradual rise of the mountain belts which established the present day physiographic features of Central Iran [3]. During the Middle and Late Alpine orogenic movements, folding and uplifting of the mountain belts continued, followed by subsidence in the central part of the zone [2,3]. As a result of these movements, most parts of Central Iran became land with inter-mountain basins. The Upper Red Formation is one of the most important Tertiary clastic units to which components were supplied from the rising mountains and deposited in the inter-mountain subsiding basins (Fig. 1). The Upper Miocene age terrigenous deposits of the formation were laid down in a large southeast-opening, wedge-shaped, fault-bounded basin in Central Iran [1]. The basin was dominantly bounded to the north/northeast by Eocene pyroclastics and to the south/southwest by Eocene volcanics. Apart from the Eocene volcanics, the top members of the Qum Formation had intermittent outcrops both in the north and south margins of the URF basin. They had significant role in providing carbonate lithics to the URF basin.

Methodology

This study is part of a wider project, which investigates the provenance and depositional environment of the URF in Central Iran. Two thick sections, 5100m and 1800m from the north and south margins respectively, provided data on composition, texture, and depositional structures and to study them in terms of diagenesis, provenance, and depositional environment. This was established by a thorough description of the rocks in the field and laboratory work on collected samples. After reconnaissance on nearly all outcrops reported in previous studies, the Yazdan and Rud-e-Shour Sections were selected as representative of lower and upper parts of the formation in the south margin respectively. The Bone-e-Kuh and Evan-e-Kay sections were selected as representative of the north margin successions (Fig. 1). Sampling in selected sections was carried out mainly based on the lithological variation. About 400 oriented samples from the Yazdan and Rud-e-Shour Sections, 380 samples from Evan-e-Kay, and 100 samples from the Bon-e-Kuh Sections were collected. After a rapid scanning of the samples, 160 samples from south margin and 172 samples from north margin were selected for detailed description of texture, composition, and diagenetic studies. Mineralogical composition, grain size and colour variation of constituent lithofacies, their lateral and vertical extent, the relationship of the lithofacies to neighbouring units, the nature of their bounding surfaces, and their sedimentary structures were the major aspects investigated in the field studies. In this basis, sedimentological lithofacies logs were constructed for selected sections [1]. Scanning Electron Microscope coupled with X-Ray analysis and petrographic studies were used in this study. All samples with appropriate red colour were investigated for chemical composition and textural properties of the pigments. Mineralogical composition was determined by X-Ray powder diffraction analysis and Scanning Electron Microscopy. Scanning Electron Microscope, model JSM6400, equipped with computer based energy-dispersive X-Ray (EDX) analyser (Link EXL) was used. Textural properties were studied by polarizing microscope and SEM. For textural analysis of minerals in SEM, accelerating voltage of 20 kv, a sample current of 1.5 nA, and work distance of 15 mm were applied. For chemical analysis, an acceleration voltage of 15 kv, a sample current of 1.5 nA, and electron-beam diameter of sub-micron, and work distance of 39 mm were applied. The frequency of the minerals was calculated by point counting using Gazzi-Dickinson method [35].

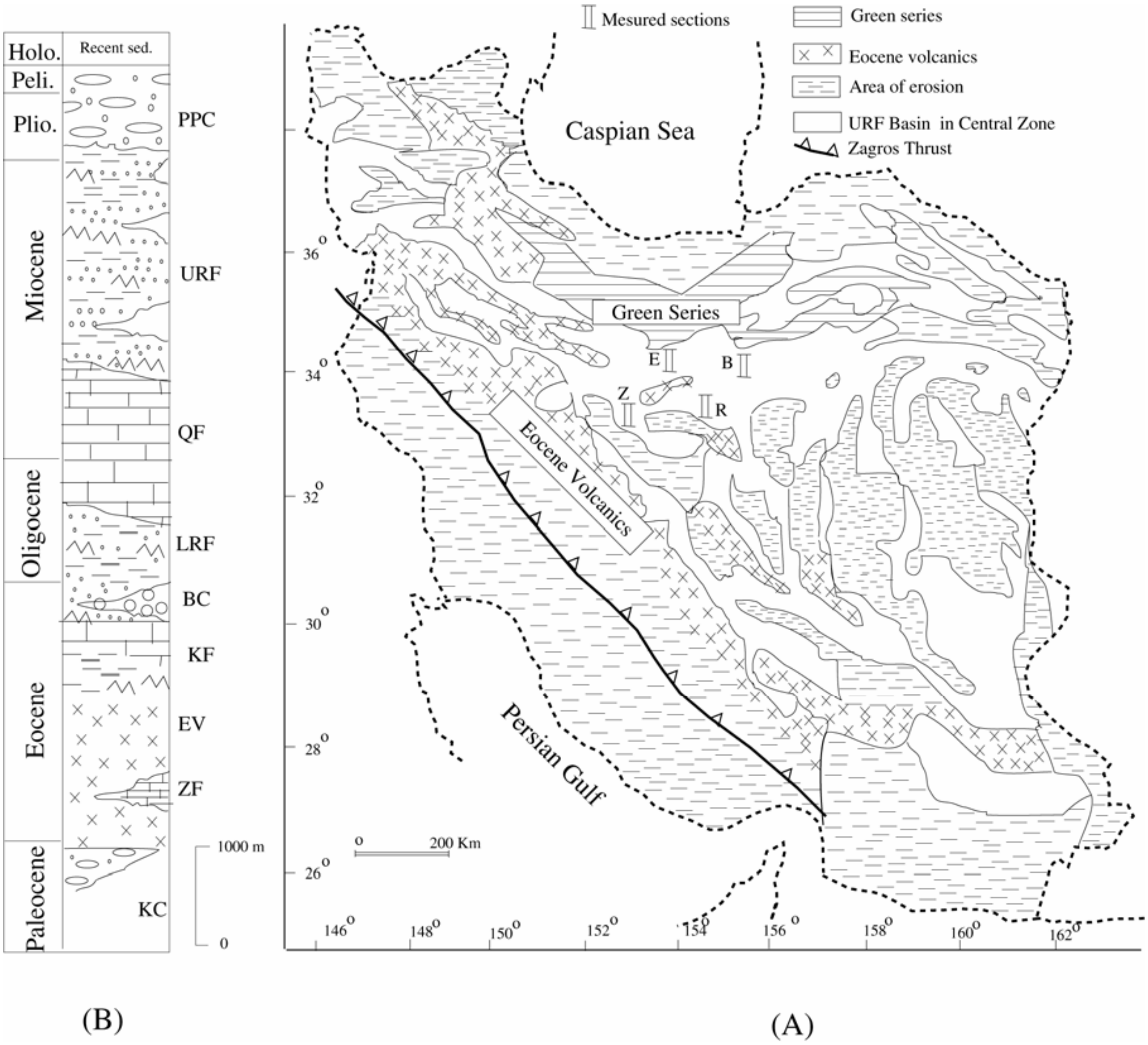

Figure 1. A) Palaeogeography of the URF basin in the Central Iran and position of the Eocene volcanics and "green series" as major buildings of the rising mountains (Modified from Berberian & King 1981). Z= Yazdan Section, R = Rud-e-shore Section, E = Evan-e-kay Section, B = Bon-e-kuh Section B) The simplified Cenozoic stratigraphic column of the Central Zone. KC = Kerman Conglomerate, EV = Eocene volcanics including pyroclastics, ZF = Ziarat Formation, KF = Kond Formation, BC = Basal Conglomerate, LRF = Lower Red Formation, QF = Qum Formation, URF = Upper Red Formation, PPC = Plio-Pleistocene Conglomerate.

Results and Discussion

Colour of Sediments

The iron oxide pigments in the URF red beds show a wide variety in form, either amorphous, cryptocrystalline, poorly crystallised yellow-brown ferric hydrate (limonite), or intermediate and well crystallised ferric oxide (hematite). In the south margin sequences, more than 80% of the constituent beds are red or in associated colours; red-brown, pink, yellow-brown, and brown; compared to 65% in the north. The non-red sediments are mainly green, grey, khaki, or in associated colours. The intensity of the red colour, in a certain rock type, increases with increasing depth. In terms of grain size, higher intensity of red colouring is recorded in finer-grained facies (see plate 1a). However, the upper parts of the measured sections with higher proportion of mudstone and gypsiferous mudstone are brighter in places. Gypsum and associated evaporites within mudstone are related to local playas developed on flood plain [1]. This is probably related to the high gypsum content of the mudstones in the upper zones and some degree of bleaching near the surface. In a given single facies, the interstitial materials, matrix and cement, are more stained in red than the coarser portion.

Plate 1. A) Hematite bearing, well to moderately rounded, red mud clasts in a non-red sandstone host, evidence for detrital origin of red pigments. B) Oxidized wood debris in non-red sandstone, evidence of post-depositional development of red pigments. Scale in centimetre.

This is true for all facies through all parts of the measured sections. The conglomerates are dominantly green to khaki in field observation and the red colouration is restricted to the matrix and cement. Bleaching of the sediments, more common in gypsiferous facies, is observed in some outcrops. This is probably due to an excess of iron-reducing agent such as organic material and/or hydrogen sulphide [22].

The main colours of the sediments and distribution of the red beds in the measured sections were fully discussed in [1].

Fe-bearing Minerals

The following Fe-bearing minerals, occurring as minor constituents in the URF rocks, are considered to be involved in producing iron precursors for pigmentation of the red beds. The abundance of the minerals in different rock types is given in Table 1. A slight increase in the frequency of the Fe-bearing minerals with decreasing petrofacies (petrographic lithofacies) size was detected both in the south and north margins (see Table 1).

Detrital opaques. Detrital opaque minerals are commonly detectable in the URF rocks both in hand specimen and polished section. Detrital magnetite, defining the cross bedding in some sandstone, can be easily distinguished in the field and hand specimen by a magnet. In terms of composition, the detrital opaque oxides dominantly fall into magnetite-ulvöspinel and

Table 1. Principle characteristics of the major rock types in the south (a) and north (b) margins of the URF Basin. Qm = monocrystalline quartz, Qp = polycrystalline quartz, Ch = chert, F = feldspar, Lv = volcanic lithic, Lc = carbonate lithics, Mc = mud clast, Opq = opaque minerals, Fe/Mg = Fe/Mg minerals, Zeol. = Zeolites, Cal = Calcite, Anal. = analcime: G = Conglomerate, VCS = Very Coarse sandston, Cs = Coarse Sandstone, MS = Medium Sandstone, FS = Fine sandstone, FVS = Very Fine Sandstone, SD = Standard deviation

Major	**Framework content (%)**							**Matrix**	**Cement content (%)**				**Total**
rocks	Qm	Qp/ch	F	Lv	Lc/Mc	Opq.	Fe/Mg	**(%)**	Zeol.	Cal.	Iron	Anal.	**cement**
(a)													
G	R	-/1	3	77	11/3	3	2	14	37	20	15	28	21
VCS	R	-/1	9	75	4/2	6	3	3	45	13	7	35	31
CS	R	-/R	10	71	3/1	12	3	7	60	7	11	22	45
MS	R	-/R	20	57	2/2	16	3	12	53	6	15	16	46
FS	2	-/R	16	57	2/3	18	2	14	58	17	14	11	56
VFS	R	-/1	10	56	2/2	28	1	20	62	8	13	17	55
Mean	0.5	-/R	12	67	4/2	13	3	10.9	58	8	13	21	42.8
SD	0.67	-/-	5.8	8.5	3/0.7	6.7	0.6	5.8	8.4	5.4	2.8	7.6	18.4
(b)													
G	9	-/6	15	61	4/1	3	1	7	58	32	10	--	24
VCS	7	-/7	27	54	1/R	3	1	10	34	33	33	---	23
CS	11	5/5	25	40	6/1	6	1	8	17	62	21	2*	28
MS	15	2/5	26	30	11/3	5	3	6	21	46	21	7/5*	26
FS	15	3/4	30	22	12/2	4	4	24	10	59	22	2/7*	32
VFS	17	2/4	30	11	17/5	10	4	42	1	60	36	----	21
Mean	14	3/5	27	28	11/2	7	3	19.5	16	53	25	3/4	26.5
SD	2.5	0.7/1	3.3	13	4.3/8	2.3	1.01	14.4	12.7	9.1	7.5	3.1/2	4.22

illmenite-hematite solid solution series, so called Fe-Ti oxides. A few examples of pseudobrookite solid solutions, chromite and rutile were observed. Representative SEM analyses of their composition are given in Table 2.

Fe-Silicates. Pyroxene, predominantly augite, is the main Fe-silicate in the south margin facies. It is an accessory component in nearly all samples ranging in abundance from rare (<1%) to 2%. Representative SEM analyses of the composition are given in Table 3. Amphibole and chlorite are rare in the south margin facies not exceeding 1% in abundance. Glauconite is rarely observed in some samples. In the north margin facies, biotite, and chlorite are the main Fe-silicates. Amphibole detritals are few. Glauconite is also recognisable in a few samples. All Fe-silicates are considered together in point counting as Fe-Mg content of the facies (Table 1).

Volcanic glasses. Volcanic glasses are the most common grains in the facies of both margins (Table 1). Their compositional analysis reveals their high iron content. Their alteration to iron oxide cement is commonly observed both in petrographic and SEM studies (Pl. 2.a).

Iron oxide minerals. Apart from detrital opaques discussed before, some iron oxides; dominantly limonite, goethite, and hematite; occur as grains coating and mixed with interstitial matrix. The minerals are dominantly observed in shallow buried facies but are rare or absent in samples from deeper parts of the formation. Their similar occurrence in the recent sediments, derived from the URF source region, reflects that they are at least partially detrital in origin. SEM and petrographic evidences reflect that such minerals have been source of some part of the red pigments in the studied rocks.

The Origin of Red Pigments

The red pigments in the URF rocks occur as coating on framework grains, interstitial matrix/cement, filling in fractures, replaced in Fe-bearing minerals and

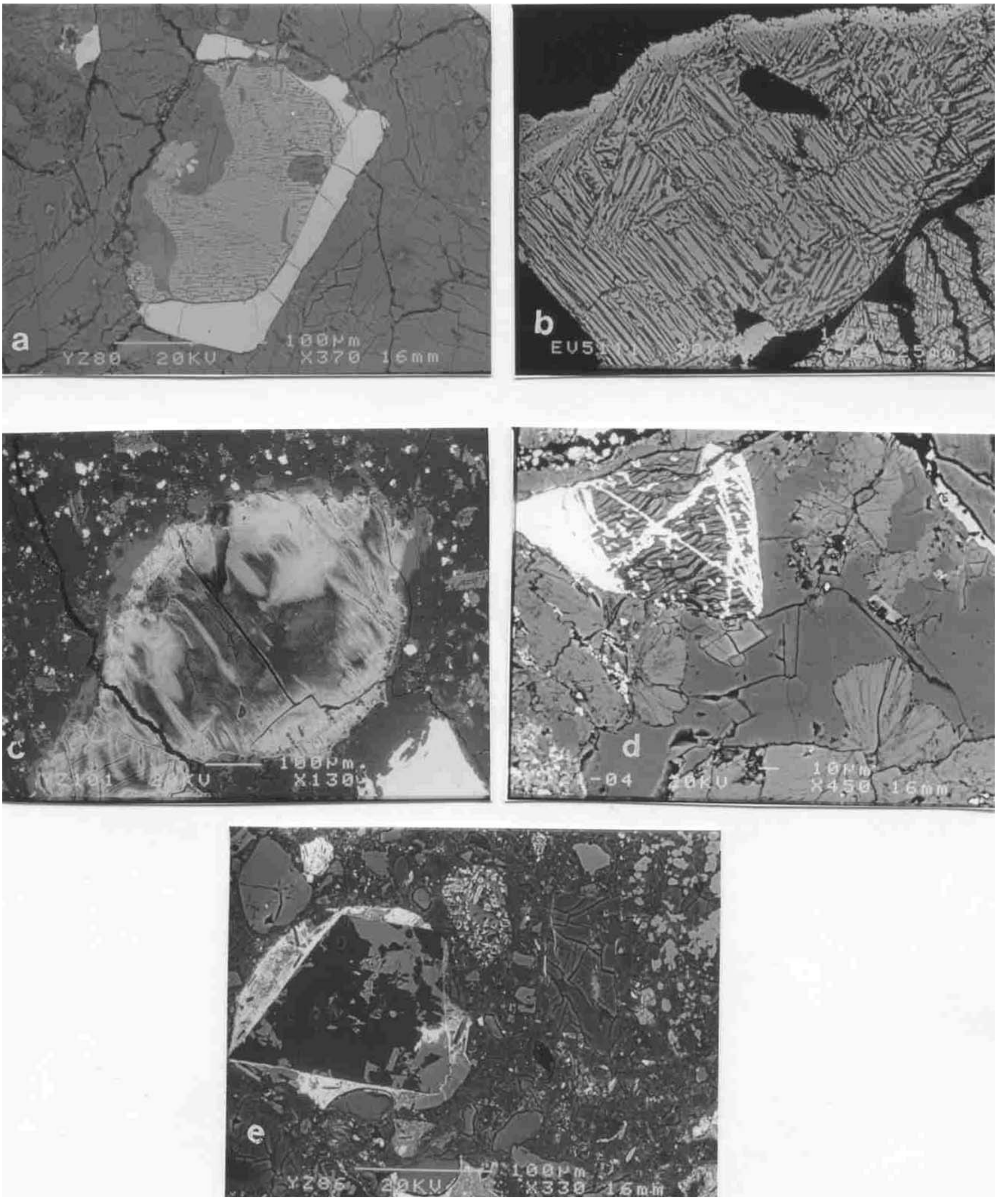

Plate 2. a) SEM micrograph of hematite surrounding a volcanic lithic. b) Development of hematite halos around a Fe-Ti oxide mineral, intergrowth of ilmenite in titanomagnetite. c) SEM micrograph illustrating the alteration of augite to hematite. d) Replacement of a clino-pyroxene by hematite as detected by SEM. e) Hematite coating on a detrital feldspar that is dominantly replaced by analcime.

Table 2. Representative SEM (equipped with EDX) analyses of detrital opaques

Sample	Y2701	Y3707	E4506	E4904	E4911	E5111	E5813	Y1060	Y106	E4908	E5105	E4920	E5801	Y3612
	Wt%									Wt%				
SiO2	0.33	0.32	0.43	0.23	0.22	-	0.38	-	0.15	0.15	0.22	0.22	0.21	0.14
Al2O3	8.76	1.74	1.15	2.57	1.47	0.64	0.61	0.36	-	2.01	1.66	2.62	-	0.15
TiO2	1.96	8.53	4.05	15.06	13.93	8.81	51.84	39.26	49.77	41.809	46.279	46.174	53.487	46.75
FeO	24.26	38.09	33.67	40.98	43.84	40.56	40.813	31.03	16.535	31.43	36.92	34.12	41.98	34.515
Fe2O3	54.86	47.48	55.82	35.65	37.66	47.32	0.00	26.143	6.773	21.11	8.14	8.69	0.00	8.396
MgO	5.33	0.44	0.59	2.19	0.36	0.41	2.16	2.23	2.30	1.58	3.00	4.28	2.12	1.17
CaO	-	-	-	0.17	0.23	-	0.17	-	-	-	-	0.49	0.11	-
MnO	1.48	0.38	0.24	0.46	-	-	1.28	0.89	22.69	0.43	0.32	-	1.90	5.83
Cr2O3	0.21	-	0.21	0.20	-	-	-	-	-	-	-	1.59	0.28	-
ZnO	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	97.18	96.99	96.15	97.50	97.71	97.74	97.27	99.92	98.22	98.53	96.53	98.18	100.08	96.95
	Number of cations on the basis of 32 O.									Number of cations on the basis of 24 O.				
Si	0.10	0.10	0.13	0.07	0.07	-	0.08	-	0.108	0.03	0.05	0.04	0.04	0.029
Al	2.98	0.64	0.43	0.91	0.53	0.23	0.15	0.083	-	0.48	0.40	0.61	-	0.037
Ti	0.43	1.99	0.96	3.41	3.22	2.05	7.88	5.93	7.526	6.30	7.08	6.84	7.96	7.272
Fe2+	5.86	9.89	8.86	10.33	11.25	10.51	6.897	5.216	2.781	5.27	6.28	5.62	6.94	5.971
Fe3+	11.93	11.09	13.22	8.08	8.70	11.02	0.00	3.955	1.025	3.19	1.25	1.29	0.00	1.307
Mg	2.30	0.20	0.28	0.98	0.16	0.19	0.65	0.669	0.695	0.66	0.91	1.26	0.62	0.362
Ca	-	-	-	0.06	0.08	-	0.04	-	-	-	-	0.10	0.02	-
Mn	0.36	0.10	0.06	0.12	-	-	0.22	0.147	3.866	0.07	0.06	-	0.32	1.02
Cr	0.05	-	0.05	0.05	-	-	-	-	-	-	-	0.25	0.04	-
Zn	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	24.00	24.00	24.00	24.00	24.00	24.00	15.91	16.00	16.00	16.00	16.00	16.00	15.95	16.00

volcanic grains, or mixed with clay minerals. They are considered to originate from three major sources:

a) Direct derivation from the source region
b) Dehydration of yellow to yellow-brown ferric hydroxides
c) *In situ* alteration of Fe-bearing minerals

a) Direct Derivation from the source region. The following lines of evidence suggest that some parts of the red pigments in the URF deposits is inherited from the source region:

1) Presence of red mud clasts in the light red to yellow-brown channel sandstones (Pl. 1.a) indicate that they have been eroded from previously exposed (overbank or inter-channel areas) mudstones. The fact that they are more red-stained than their host sandstones suggests that the iron had concentrated in the mudstones prior to erosion [17].

2) Unstable iron-bearing minerals are largely destroyed by surface weathering in the rocks that are considered as a source for the URF deposits [1]. Such an extensive alteration undoubtedly provided some red pigments or precursors for red pigmentation in the sediments before they reached to the deposition site [21,25]. Seasonal fluctuation in the moisture of the facies is presumably responsible for such weathering in the source region [21].

3) Using petrographic techniques and XRD analysis, iron oxides in the form of hematite, limonite and goethite were detected in the recent sediments that have been derived from the rocks determined as URF sources (Fig. 2). Iron-rich clays were also distinguished in these sediments. SEM analyses of the finer fraction of the sediments showed that the pigments are present mainly as coatings on the surface of the clay size fraction. The bright red to pink colour of the recent sediments in field observation, more obvious in the south margin, is also believed to be mainly due to the detrital red pigments.

4) Finer fractions of the URF deposits contain more iron and are more intensively red-stained by hematite. The greater proportion of pigmentary hematite in the finer grained petrofacies has been interpreted as a result

Table 3. Representative SEM (equipped with EDX) analyses of detrital pyroxene

Sample	**Y2201**	**Y5101**	**Y7401**	**Y7402**	**Y8502**	**Y9101**	**Y1020**	**Y1060**	**Y3708**	**Y3709**	**Y3710**	**Y3711**	**Y3712**	**Y3713**
	Wt%													
SiO2	53.12	50.96	50.78	48.26	51.68	49.95	51.27	52.35	50.27	50.03	47.33	48.91	49.69	49.41
Al2O3	1.47	2.81	2.85	2.84	2.33	1.94	0.85	-	1.29	0.96	3.93	3.33	2.04	1.93
Na2O	0.93	0.31	0.45	-	0.38	-	0.56	0.33	0.47	0.38	0.43	0.55	-	0.45
TiO2	0.29	0.89	0.7	0.52	0.72	0.56	-	0.22	0.43	0.36	0.7	0.48	0.46	0.51
FeO	4.63	12.88	8.34	7.19	11.06	10.69	16.38	10.47	9.87	11.71	4.72	8.73	9.17	10.57
Fe2O3	2.2	1.07	1.07	1.31	-	0	-	-	1.75	1.32	3.21	1.13	0	-
MgO	17.07	14.43	15.1	14.49	14.62	13.38	11.17	13.25	13.01	12.06	13.2	13.29	14.19	13.08
CaO	19.5	16.9	19.66	19.04	19.33	19.11	18.6	21.88	19.67	19.3	21.06	19.37	19.62	19.76
MnO	0.35	0.46	0.2	-	0.37	0.41	0.83	0.41	0.49	0.56	0.28	-	0.25	0.43
Cr2O3	-	-	-	-	-	-	-	-	-	-	-	0.2	-	0
Total	99.56	100.7	99.15	93.65	100.5	96.04	99.66	98.91	97.25	96.68	94.86	95.99	95.42	96.14
	Number of cations on the basis of 6 Oxygen.													
Si	1.94	1.9	1.89	1.91	1.92	1.94	1.97	1.99	1.94	1.96	1.85	1.9	1.94	1.93
Al	0.06	0.12	0.13	0.13	0.1	0.09	0.04	-	0.06	0.05	0.18	0.15	0.09	0.09
Na	0.07	0.02	0.03	-	0.03	-	0.04	0.02	0.04	0.03	0.03	0.04	-	0.03
Ti	0.01	0.03	0.02	0.02	0.02	0.02	-	0.01	0.01	0.01	0.02	0.01	0.01	0.02
Fe2+	0.14	0.4	0.26	0.24	0.34	0.35	0.53	0.33	0.32	0.38	0.16	0.28	0.3	0.35
Fe3+	0.06	0.03	0.03	0.04	-	0	-	-	0.05	0.04	0.1	0.03	0	-
Mg	0.94	0.81	0.84	0.86	0.81	0.78	0.64	0.75	0.75	0.71	0.77	0.77	0.82	0.76
Ca	0.77	0.68	0.79	0.81	0.77	0.8	0.76	0.89	0.81	0.8	0.88	0.81	0.82	0.83
Mn	0.01	0.01	0.01	-	0.01	0.01	0.03	0.01	0.02	0.02	0.01	-	0.01	0.01
Cr	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-
Total	4	4	4	4	4	3.98	4.01	4	4	4	4	4	3.99	4.02

of depositional concentration of brown ferric hydroxide precursors in the flood plain environment, which eventually aged to hematite [10,24,27]. On the basis of this hypothesis, prevailing of oxidizing conditions on flood plains favoured transformation of ferric hydroxides to hematite. In this regard, depositional processes mainly controlled concentration of ferric hydroxide precursors in finer sediments, although reddening of sediments was mainly carried out after deposition. Moreover, the fact that hematite is present in the recent sediments in acceptable amount (Fig. 2) shows that some part of the red pigments, although minor, must have derived from the source region.

On the other hand, association of the red beds with evaporite minerals, calcrete, and palaosol horizons reflect a semi-arid to arid condition in the region. Such an association rejects the development of deeply weathered red soil in the source region [24,25]. Moreover, abundance of nearly fresh feldspars and augite in the URF rocks suggests that climatic weathering in the source area would have not been intense enough to produce heavy red colour. These unstable minerals would have not survived in the source area if weathering were producing iron-rich soils [6]. Subsequently, it is considered that the detrital portion of the red pigments was partially derived from pre-existing red beds. This result is in agreement with the contribution of the lower Red Formation (LRF), consisting of red mudstones and shales, in the source region [1].

b) Dehydration of Ferric-hydroxides. The brown to yellow-brown hydrated iron oxides, collectively called limonite [27,28] were distinguished both in the URF rocks and the recent sediments derived from the region which is nominated as a source for these rocks. They are more common in the fine-grained facies, occurring as grains coating or detrital ferric oxides. Moreover the partial alteration of the Fe-bearing minerals in the source region shows that the URF sediments contained some limonite content when first deposited. Several investigations on the origin of red beds; e.g. [4,16,25-29] have shown that fine-grained limonite is thermodynamically unstable and converts to hematite

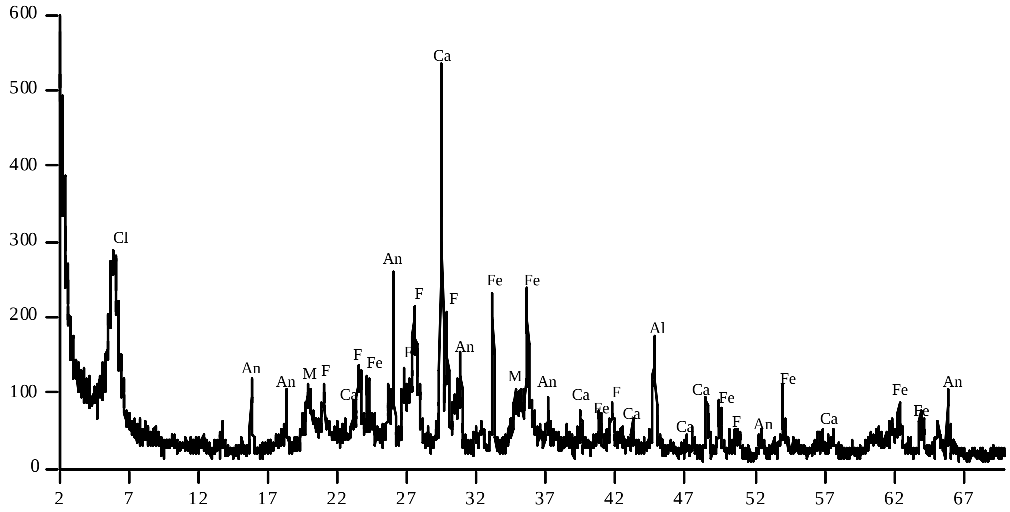

Figure 2. X-Ray diffractogram illustrating the considerable amount of hematite (Fe) content in the recent sediments derived from the URF source region. Cl= clay minerals, An= analcime, M= mica, Ca= calcite, F= K-feldspar.

with ageing sediments under practically all geological conditions. The oxidizing and alkaline environment and temperature, indicated by abundant oxidized wood debris (Pl. 1.b) and evaporite minerals, favoured such transformation in the URF basin [12]. Scarcity or absence of the limonite in deep facies is most likely related to such a process.

c) Interstitial Alteration of Fe-bearing Minerals. The colour of the recent sediments derived from the region that is considered as a source for URF rocks reflects that the minor amount of detrital red pigments was not adequate enough to produce such a red colour in the URF deposits. Accordingly, the main colouring of the sediments must have occurred after deposition. The following signs are indicative of post depositional development of hematite pigments in the Upper Red Formation rocks.

1) Development of hematite halos around iron bearing detrital grains (Pls. 2.a & 2.b). The halos are observed most commonly around volcanic glasses/shards, augite, and biotite. The last two minerals are most abundant Fe-silicates in these rocks.

2) Abundance of partially altered Fe-silicates and Fe-Ti oxides into hematite in the studied rocks (Pl. 2.c).

3) Different stages of replacement of augite, biotite, and chlorite by hematite and presence of hematite in shell fragments or in-filling their intragranular porosity (Pl. 2.d).

4) Development of irregular hematite coating on detrital grains which shows no evidence of abrasion (transportation). In some samples the coating is absent at the grains contact (Pl. 2.e).

5) Development of hematite as cement in pore spaces, intragranular porosity of the reworked fossils, and in-filled fractures. Iron oxide rim cement, mainly hematite, is a commonly observed surrounding iron bearing mineral. Overgrowth on some iron oxide minerals is observed. Increase in the Fe cement content of the petrofacies with increasing depth is also considered as a function of diagenesis.

6) Presence of euhedral crystals of hematite, detected by polarizing microscope and SEM from deeper facies.

7) Increase in the intensity of the red colour of successively deeper facies suggests more reddening of the sediments in deep burial diagenesis (Fig. 3) [28,29].

8) Presence of biotite and augite that are pseudomorphed by hematite in some samples.

9) The positive correlation between clay content, dominantly diagenetic in origin and red colour shows that the alteration of fine-grained Fe-bearing minerals in diagenetic environment has provided significant hematite in the sediments.

10) Oxidation of titanomagnetite to illmenite is a common phenomenon in the opaque-rich deposits (Pl. 2.b). This process probably has provided some hematite in the sediments in an oxidizing environment.

$$2\,[2FeO, TiO_2] + 1/2\,O_2 \Rightarrow 2\,[FeO, TiO_2] + Fe_2O_3 \qquad (I)$$

11) Abundance of the red pigments correlates with the paucity of the unstable iron bearing minerals in the studied petrofacies. Moreover, higher altered petrofacies are more red-stained. Such an association indicates the significance of diagenetic red pigmentation in the URF sequences.

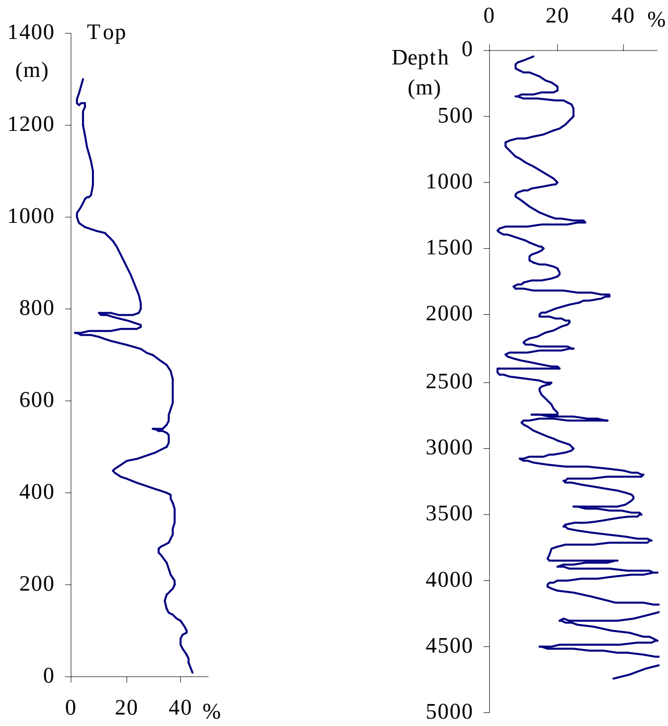

Figure 3. Iron oxide cement distribution in the Upper Red Formation Sandstones throughout the Yazdan (left) and Bon-e-Kuh sections.

12) Different stages of calcite and zeolite replacement by iron oxide cement show that the reddening of the sediments was probably one of the late diagenetic processes.

13) Development of Fe-rich calcite cement, more common in the north margin facies, and replacement of some Fe-silicates by ferroan calcite cement are indicative of additional amount of iron in the pore water [12].

14) Exclusively oxidized wood debris, occurring as red nodules in non-red host rocks (Pl. 1.b) undoubtedly show post depositional development of the red pigments.

15) Restriction of red colouring in cement or interstitial material of highly porous facies reflects digenetic origin of the pigments.

Time of Reddening and processes responsible for pigmentation

Major characteristics of the URF rocks, discussed above, show that they were not entirely red when deposited. The pigments responsible for reddening of the deposits, although inherited from the source region to some extent, were mainly developed in the diagenetic environments. Significance of diagenetic processes on red pigmetation is reflected in distribution of iron oxide cements throughout the sections (Fig. 3). Development of the pigments occurred by crystallization of amorphous or poorly crystalline precursors, dehydration of the ferric hydroxides, and interstitial alteration of the Fe-bearing minerals.

The interstitial alteration of the iron bearing minerals, probably was the most common process responsible for pigmentation, which started by dissolution of the grains by hydrolysis [28]. Stages of the Fe-bearing minerals dissolution are observed in petrographic studies and their details are clearly shown by SEM. The iron released from that process most likely precipitated as hematites in an oxidizing, alkaline pore water [28,29,33]. The main iron oxide cement content of the formation seems to be developed by this process. The iron might have also precipitated as a red precursor ferric oxide which, on ageing, converted to hematite [12,33].

$$FeO.OH \text{ (goethite)} \Rightarrow 1/2\ Fe_2O_3 \text{ (hematite)} + 1/2\ H_2O \qquad (II)$$

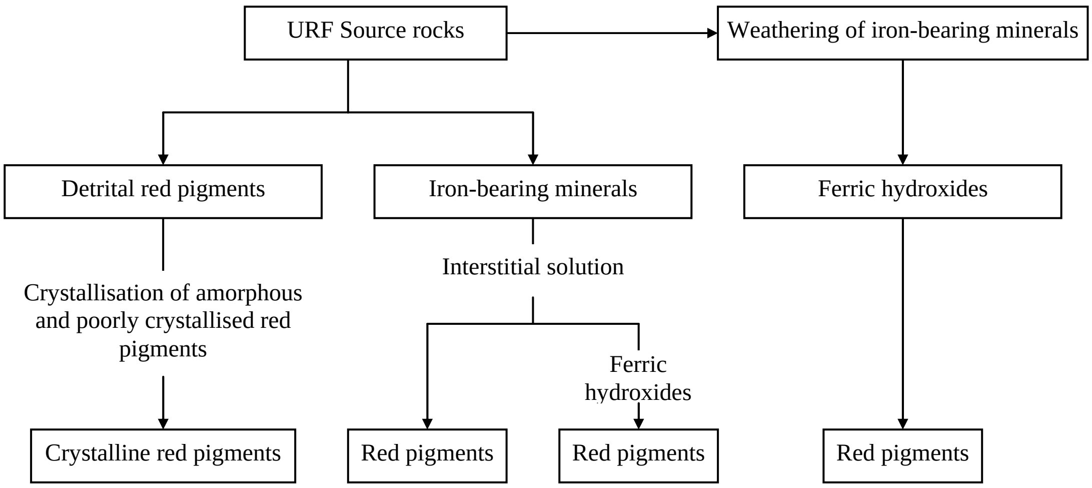

Figure 4. Diagram summarises major processes responsible for red pigmentation in the URF rocks.

In coarse-grained facies, where reddening is mainly observed in the matrix portion, it seems that mechanical infiltration of iron-rich clay into the pore spaces was responsible for some part of pigmentation [34].

In situ replacement of iron-bearing minerals and volcanic glasses by iron-rich clays is a process by which pigmentation in some samples can be explained. In a few samples the entire grain, biotite or augite, is replaced by iron-rich clay. Replacement of wood debris by hematite is another example of this process (Pl. 1.b).

Development of authigenic hematite in pore space and red iron-bearing clay minerals, although less frequently, are processes that explain the red pigmentation of some samples [32]. Processes responsible for development of the red pigments in the studied rocks are summarised in Figure 4.

Conclusion

This study demonstrated that the red colouring of the URF had occurred in several stages. Some part of the red pigments inherited from the pre-existing red beds. This is more significant in the south margin sections. The Lower Red Formation rich in red mudstones had a significant roll in providing the detrital red pigments in the URF basin. Dehydration of limonite to hematite in an oxidizing and alkaline condition during transportation and/or in early stages of diagenesis is responsible for some other part of red pigmentation. The major part of reddening occurred in diagenetic environment through interstitial alteration of Fe-bearing minerals. This is more significant in north margin sections. The following characteristics of the formation favoured development of red pigments:

– Abundance of Fe-Ti oxides; volcanic glasses, Pyroxene, iron oxides, amphibole, biotite, chlorite, and some glauconite; in the source material.
– Fluctuation of the available moisture in the basin, with superficial weathering in rainy seasons and oxidizing condition in dry periods.
– Minimal bleaching of the deposits after reddening due to scarcity of the iron reducing factors, such as organic material, in the diagenetic environment.

Due to different sources of red pigments in different sections, discrimination of detrital from diagenetic forms and significance of each part are essential for any further investigation on depositional environment and diagenetic history.

Colour variation of the rocks through the measured sections is probably a function of relative abundance of red pigments, which in turn was a function of availability of Fe-bearing minerals and diagenetic features. More intensive reddening of the south margin deposits is probably due to more hot and dry climate, sparse vegetation, and more alkaline ground water. This supposition is supported by development of local swamp deposits in the north margin.

Finer grained facies, with higher proportion of detrital opaques, Fe-bearing minerals, and iron-rich clays, were more susceptible to red pigmentation, whereas in coarse-grained facies, pigmentation was limited to the iron-rich part, matrix or cement.

In certain types of lithofacies, fine sandstones for example, those that were exposed to diagenetic processes for a longer period, older sediments, contained more red pigments. This factor reflects the significance of the diagenetic processes in distribution of the iron oxide cement and red colouring in the studied samples.

Acknowledgements

This study is a part of authors' Ph.D. thesis that was financially supported by the Ministry of Science, Research and Technology of Islamic Republic of Iran. Especial thanks are expressed to three unknown referees for their interesting comments.

References

1. Amini, A. Provenance and depositional environment of the Upper Red Formation, Central Zone, Iran. Ph.D. thesis, Manchester University, 320 pp., (1997).
2. Berberian, M. Continental deformation in the Iranian plateau. Geological Survey of Iran, Report No. 52, 626 pp., (1983).
3. Berberian, M. and King, G. C. P. Toward the paleogeography and tectonic evolution of Iran. *Can. Jour. Sci.*, **18**: 210-65, (1981).
4. Berner, R. A. Goethite stability and the origin of red beds. *Geochemica et Cosmochemica Acta*, **33**: 267-73, (1969).
5. Brookfield, M. E. The emplacement of giant ophiolite nappes: I. Mesozoic-Cenozoic examples. *Tectonophysics*, **37**: 247-303, (1977).
6. Clark, J. Field interpretation of red beds. *Geol. Soc. Am. Bull.*, **73**: 423-28, (1962).
7. Dewey, J. F., Pitman, W. C., Ryan, W. B. F. and Bonnin, J. Plate tectonic and evolution of the Alpine system. *Geol. Soc. Am. Bull.*, **84**: 3137-80, (1973).
8. Farhoudi, G. A comparison of Zagros geology to island arcs. *Jour. Geol.*, **86**: 323-34, (1978).
9. Foster, H., Continental drift in Iran in relation to the Afar Structures. In: Pilger, A. and Rosler, E. (Eds.), Afar between continental and oceanic rifting, Vol. II, Schweizerbatsche Verlagsbuchhandlung, Stuuttgart, 182-90, (1976).
10. Friend, P. F. Clay fractions and colour of some Devonian red beds in the Catskill Mountains, USA. *Q. Jour. Geol. Soc. Lon.*, **122**: 273-92, (1966).
11. Hatch, F. H. and Rastal, R. H. In: Bates, R. L. and Jackson, J. A. (1980), Glossary of Geology. 2nd ed., Am. Geol. Institute, Virginia, 751 pp., (1965).
12. Hubert, J. F. and Reed, A. A. Red-bed diagenesis in the east Berlin Formation, Newark group, Connecticut Valley. *Jour. Sed. Petrol.*, **48**: 175-84, (1978).
13. Judd, J. B., Smith, W. C., Pilkey, O. H. The environmental significant of iron stained quartz grains on the southern United States Atlantic shelf. *Marine Geology*, **8**: 355-62, (1970).
14. Jung, D., Kursten, M., and Tarakian, M. Post-Mezozoic volcanism in Iran and its relation to the subduction of Afro-Arabian plate under the Eurasian Plate. In: Pilger, A. and Rosler, E. (Eds.), Afar between continental and oceanic rifting, Vol. II, Schweizerbatsche Verlagsbuchhandlung, Stuuttgart, 175-81, (1976).
15. Krynine, P. D. Petrology, stratigraphy, and origin of the Triassic sedimentary rocks. In: Turner, P. (1980), Continental red beds. Developments in Sedimentology, **29**, Elsevier Scientific Pub., 562 pp., (1950).
16. Langmuir, D. Particle size effect on the reaction Goethite = Hematite + Water. *Am. Jour. Sci.*, **271**: 147-56, (1971).
17. Macpherson, J. C. Genesis of variegated red beds in the fluvial Aztec siltstone (Late Devonian), south Victoria land, Antarctica. *Geol.*, **27**: 119-42, (1980).
18. Miller, D. N. and Folk, R. L. Occurrence of detrital magnetite and ilmenite in red sediments, New approach to significance of red beds. *Am. Ass. Petrol. Geol.*, **39**: 338-45, (1955).
19. Nowroozi, A. A. Seismo-tectonics of the Persian Plateau, Eastern Turkey, Caucasus and Hindu-Kush regions. *Bull. Seism. Soc. Am.*, **61**: 317-41, (1971).
20. Schluger, P. R. Petrology and the origin of red beds of Perry Formation, New Brunswick, Canada and Maine USA. *Jour. Sed. Petrol.*, **46**: 22-37, (1976).
21. Schmalz, R. F., Formation of red beds in modern and ancient deserts (Discussion). *Geol. Soc. Am. Bull.*, **79**: 277-80, (1968).
22. Schwertmann, U. Transformation of haematite to goethite in soils. *Nature*, **232**: 624-25, (1971).
23. Turner, P. Continental red beds. Developments in Sedimentology, Vol. 29, Elsevier Scientific Pub., 562 pp., (1980).
24. Van Houten, F. B. Origin of red beds. some unsolved problems. In: Nairn, A. E. M. (Ed.), Problems in palaeoclimatology. Proc. NATO paleoclimate Conf., Inter-science pub. Inc. 647-60, (1964).
25. Van Houten, F. B. Iron oxide in red beds. *Geol. Soc. Am. Bull.*, **79**: 399-416, (1968).
26. Van Houten, F. B. Iron and clay in tropical Savanna Alluvium: a contribution to the origin of red beds. *Geol. Soc. Am. Bull.*, **83**: 2761-72, (1972).
27. Van Houten, F. B. Origin of red beds; a review, 1961-1972. *Ann. Rev. Earth Planet. Sci.*, **1**: 39-61, (1973).
28. Walker, T. R. Formation of red beds in modern and ancient deserts. *Geol. Soc. Am. Bull.*, **78**: 353-68, (1967a).
29. Walker, T. R. Colour of recent sediments in tropical Mexico. A contribution to the origin of red beds. *Ibid.*, **78**: 917-20, (1967b).
30. Walker, T. R. Formation of red beds in moist tropical climates. A hypothesis. *Ibid.*, **85**: 633-38, (1974).
31. Walker, T. R. and Honea, R. M. Iron content of modern deposits in the Sonoran Desert: a contribution to the origin of red beds. *Ibid.*, **80**: 535-44, (1969).
32. Walker, T. R., Ribbe, P. H. and Honea, R. M. Geochemistry of Hornblende alteration in Pliocene red beds, Baja California, Mexico. *Ibid.*, **78**: 1055-60, (1969).
33. Walker, T. R., Waugh, B., Grone, A. J. Diagenesis in first cycle desert alluvium of Cenozoic age, southwest US. and northwest Mexico. *Ibid.*, **89**: 19-32, (1978).
34. Waugh, B. Diagenesis in continental red beds as revealed by Scanning Electron Microscopy. In: Whalley, W. B. (Ed.), Scanning Electron Microscopy in the study of sediments. Published by Geo Abstracts limited, University of East Angelia, England, 329-46, (1978).
35. Zuffa, G. G. Optical analyses of arenites: influence of methodology on compositional results. In: Zuffa, G. G. (Ed.), Provenance of arenites. NATO-ASI, Series 148, D. Reidel, Dordrecht, 165-89, (1985).