Iranian Int. J. Sci. ***3****(1), 2002, p.43-67*

Sandstone Petrofacies Expressions of Source and Tectonic Controls on Sedimentation in a Back-arc Basin, Central Zone, Iran

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(Received: 7/7/2001 ; accepted:11/27/2001)

Abstract

Detail description of texture and composition of 880 samples from Upper Red Formation sandstones in central part of its basin directed to identification of major petrofacies. On this basis, 17 petrofacies in the south and 16 petrofacies in the north successions were distinguished and described comprehensively. Major components variation of petrofacies through measured sections is used for analysis of source region and diagenetic history. A distinct diversity in the source rocks composition is indicated from component variation analysis. Major characteristic of the petrofacies and detrital mode analysis of sandstones indicate deposition in a back arc setting in which block faulting controlled accommodation development. Active tectonic setting of the basin is responsible for textural properties of the petrofacies. Composition of the petrofacies and its variation through measured sections was mainly controlled by source rocks characteristics. Diagenetic features of the petrofacies are significant enough to necessitate thorough diagenetic study prior to and depositional and/or provenance investigation.

Keywords: *Petrofacies, Upper Red Formation, Central Iran, sedimentation and tectonic*

Introduction

Texture, chemical composition, and sedimentary structures of sandstones have been considered as the fundamental properties providing information on their geological history (e.g. Krynine 1948; Folk *et al.* 1970; Folk 1974; Pettijohn *et al.* 1987; Tucker 1991; Carozzi 1993). Results from detailed description of rocks provide a basis that is essential in understanding of provenance, diagenetic history, and depositional environment. Analysis of textural elements such as sorting, maturity, pore system, size and shape of the particles, roundness and surface features, and arrangements of the detrital constituents provide information on the conditions of depositional environment, tectonic setting, and transportation history. The mineralogical composition of detrital fraction is the most powerful indicator for determination of source rocks, tectonic setting, weathering, and palaeoclimate history. Sedimentary structures are extremely important in the interpretation of depositional environments and are mainly used for establishing stratigraphic order of sedimentary units and palaeocurrent directions. To date, no detailed study on these aspects of the Upper Red Formation (URF) sandstones has been conducted. By petrofacies analysis of the URF sandstones, texture and composition of these rocks are fully discussed. Such a study is both essential in providing a basis for further investigation on the formation, and significantly reflects the role of source rocks and tectonic on the URF basin evolution. This paper also aims to practice a logical method for petrofacies analysis of clastic rocks in Central Iran.

Methodology

From consideration of facies definitions in the literature; e.g. Weller 1958; Cant & Walker 1976; Bates & Jackson 1980; Walker 1984; and Reading & Levell 1996; the term petrofacies (petrographic lithofacies) is applied here for a unit of rock distinguished primarily on the basis of texture and composition. Such an application helps to avoid any confusion with the term "lithofacies" which is defined mainly on the basis of rock characteristics in the field. The petrofacies analysis of the formation is done on the samples collected from four representative sections. After reconnaissance on nearly all outcrops reported in the literature, the Yazdan and Rud-e-shor Sections in the south and Bone-kuh and Evan-e-key Sections in the north margins were selected as representative of the formation (Fig.1). Overall, 400 oriented samples from the south margin sections and 480 from those of north were collected for detailed description of texture and composition. The petrofacies from north and south margins are discussed separately to determine any difference in the nature of their source and tectonic setting.

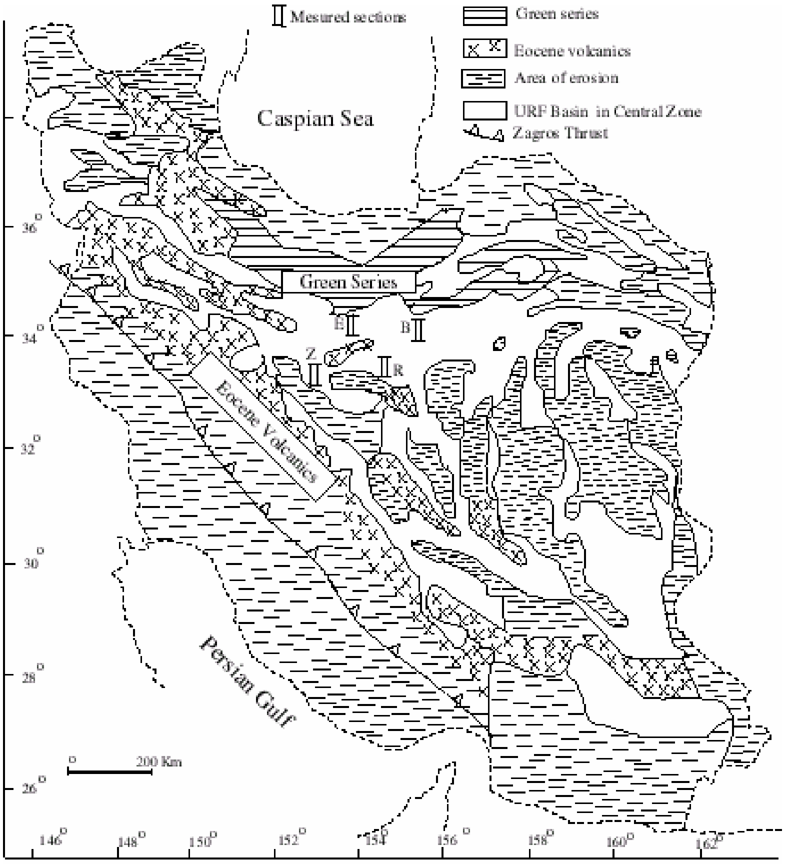

Figure 1- Palaeogeography of the Upper Red Formation Basin in Central Iran and position of measured sections (Modified from Berberian and King, 1981). Z = Yazdan, R = Rud-e-shore, E = Evan-e-key, B = Bon-e-kuh

Textural properties of the sandstones were examined by polarizing microscope and SEM, where necessary. 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. The geochemical composition was determined by petrographic techniques, XRD, and SEM. A scanning electron microscope equipped with computer based energy–dispersive X-Ray analyzer (EDX) was used. Clay size fractions of the sandstones were separated and prepared for XRD analysis based on the methods described by Moore and Reynolds (1989). All frequency determination carried out by point counting technique using Gazzi-Dickinson method (cf. Ingersoll *et al.,* 1984; Suttner and Basu 1985). In each thin section 500 points were counted. For each petrofacies, on average, 10 thin sections were studied and mean values of the major constituents were calculated. Categories used for point counting are given in table 1. Sorting of the petrofacies was estimated by comparison with charts introduced by Harrell (1984). Maturity of the petrofacies was measured based on the method of Folk (1974). The roundness of framework grains was estimated on the basis of Power's (1953) scale. Chemical staining with Na cobaltinitrate, using the method of Houghton (1980), was applied for initial distinction of K-feldspar from plagioclase. Different plagioclase minerals were discriminated based on their mineralogical composition using SEM. All the sections with carbonate content were stained using the method of Dickson (1965, 1966) to determine the mineralogy and Fe contents of the carbonates.

All collected samples were initially classified on the basis of grain size into very coarse to very fine sandstone using the scale of Wentworth (1922). The sandstones were primarily classified on the basis of the scheme proposed by Pettijohn *et al.* (1987). Due to limitations in the classification for detail description of rocks, some modifications are applied. The grains size, cement composition, textural maturity, and unusual constituents were considered to devise a comprehensive term for each petrofacies. The remarkable advantage of this method is that the applied term yields nearly a comprehensive information about the rock types and makes any further description unnecessary.

Table 1. Categories used for sandstone point counting and recalculated mode parameters (after Dickinson, 1982).

Qp = Polycrystalline Quartz
Qm = Monocrystalline Quatrz
Q = Qp + Qm Q = Total Quartz
P = Plagioclase Grains
K = Potassium feldspars
F = K + P F = Total Feldspar grains
Lv = Volcanic lithics
Ls = Sedimentary lithics
Lc = Carbonate lithics
L = Lv + Ls L = Total unstable lithic fragments
Lt = L + Qp Lt = Total aphanitic rock fragments

Major Petrofaies of Southern Margin

Detailed description of texture and composition led to identification of 17 petrofacies which abundance and characteristics are given in figure 2 and table 2 respectively.

Table 2. Major characteristics of south margin petrofacies. Mc = mud clast, Opq = Opaque minerals, Fe/Mg = Ferro-magnesian minerals, Zeol. = zeolite minerals, Ca = Calcite, Iron = Iron oxide cement, anal. = analcime. Other symbols are the same as those in table 1.

Petro-facies	Framework content (%)							Matrix	Cement content (%)				Total cement
	Qm	*Qp*	*F*	*Lv*	*Lc/Mc*	*Opq.*	*Fe/Mg*		*Zeol.*	*Cal.*	*Iron*	*Anal.*	
VCS1	1	-	5	58	31/-	4	1	3	-	53	14	33	15
VCS2	1	-	5	76	-/8	8	2	2	94	4	2	-	52
VCS3	R	-	11	78	2/-	6	3	3	48	8	6	38	32
CS1	R	-	8	75	3/-	11	3	1	49	7	12	32	49
CS2	R	-	14	67	2/1	14	2	21	74	6	12	8	39
CS3	R	-	10	63	1/12	12	2	11	71	10	8	11	36
MS1	7	-	17	19	46/-	8	3	24	-	82	16	2	12
MS2	R	-	32	52	1/-	13	2	25	57	17	20	6	39
MS3	R	-	30	55	6/-	7	2	16	5	23	40	32	26
MS4	R	-	13	64	1/-	19	3	4	60	9	11	20	55
MS5	R	-	15	30	1/25	17	2	13	75	2	5	18	60
FS1	13	-	19	30	33/-	4	1	3	10	79	11	-	34
FS2	1	-	24	55	1/-	17	2	28	72	13	12	3	50
FS3	R	-	9	64	R	25	2	4	56	9	15	20	64
VFS1	2	-	25	33	-/19	20	1	64	-	10	90	-	3
VFS2	3	-	5	68	1/-	21	2	2	77	2	9	12	81
VFS3	2	-	8	64	-/1	34	1	17	53	11	15	21	55

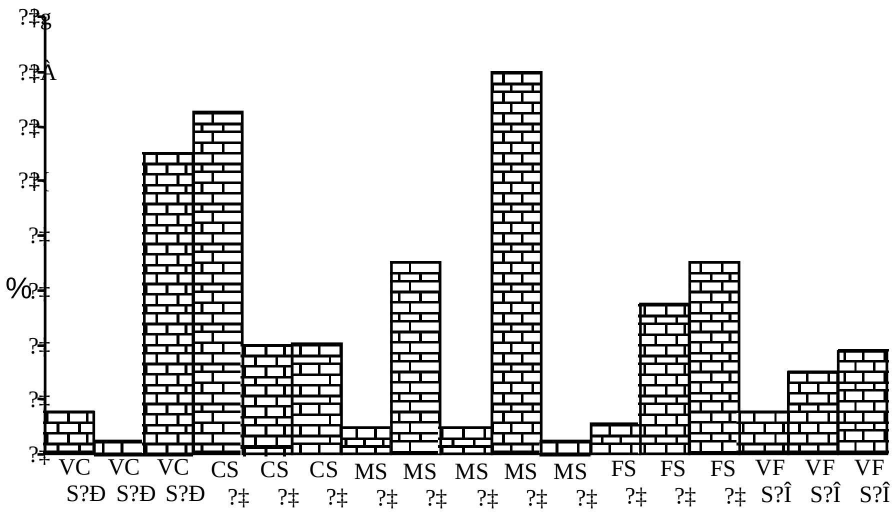

Figure 2 Frequency histograms showing the abundance of major petrofacies in the south margin sections.

Petrofacies VCS1: It is a grain supported, calcite and analcime cemented, submature, carbonate bearing, very coarse volcanic arenite. Feldspar grains are dominated by twinned and zoned plagioclase. Pyroxene is the main Fe/Mg mineral present. The petrofacies occurs mainly in the lower part of the measured sections and is marked by low level of cementation (table 2). Calcite cement is mainly in blocky and fracture-filling forms. Analcime occurs as pore-filling cement and as replacement of volcanic lithics or feldspars. Minor ferruginous cement occurs as fissure filling and grains coating.

Petrofacies VCS2: This is a clast supported, mainly zeolite cemented, submature, mud clasts bearing, very coarse volcanic arenite. High degree of cementation (52%) and presence of about 8% mud rip-up clasts in its framework mark the petrofacies. Zeolite minerals, as dominant cement, occur in blocky and poikilotopic forms. Calcite cement is presented in minor amount mainly replacing the carbonate lithics.

Petrofacies VCS3: The petrofacies is a grain supported, moderately (Ave. 32%) cemented, submature, very coarse volcanic arenite (Plate

1.a). It is characterized by predominance of volcanic lithics (Lv/L=0.98) and near absence of mud clasts. Analcime and other zeolites are the main cements, dominantly occurring in blocky or poikilotopic forms. Volcanic lithics are characterized by aphanitic and microlithic texture with phenocrysts of plagioclase. Replacement of volcanic glasses/lithics by zeolite is commonly observed. Calcite and ferruginous cements are minor interstitial materials of the petrofacies.

Petrofacies CS1: It is a grain supported; zeolite or analcime cemented; submature; coarse volcanic arenite (Plate 1.b). Abundance of blocky and poikilotopic zeolite and/or analcime cements and low matrix content characterize the petrofacies. Quartz is rare or absent. Calcite occurs mainly as replacement of plagioclase grains.

Petrofacies CS2: It is a grain supported, zeolite cemented, and poorly sorted, immature, coarse-grained lithic greywacke. The lithics are represented by microlithic or aphanitic volcanic lithics and glasses. Zeolite minerals are the main cements. Analcime, calcite, and ferruginous cements present in minor amounts. The matrix is mainly in pseudomatrix (Dickinson 1970) form.

Petrofacies CS3: This petrofacies is characterized by the presence of mud rip-up clasts in its framework (Ave. 12%). It is a grain supported, zeolite cemented, poorly sorted, submature, mud clasts bearing, coarse volcanic arenite. The petrofacies comprises a considerable amount of matrix (Ave. 11%), and cement (Ave. 36%).

Petrofacies MS1: This petrofacies is marked by prevalence of carbonate lithics (46%) and high matrix content (24%). It is a grain supported, calcite cemented, poorly sorted, immature, medium lithic greywacke. Calcite is the main interstitial material both in cement and matrix forms.

Petrofacies MS2: It is a grain supported, dominantly zeolite cemented, immature, medium lithic greywacke. Volcanic lithics (52%) and feldspar grains (32%) are the major framework constituents. The iron-rich matrix is present in nearly all samples in a considerable amount (Ave. 20%). Zeolite minerals, as the main cement, appear in radial, microgranular, fracture-filled, and blocky forms. Replacement of calcite by zeolite and zeolite/calcite by ferruginous cement is observed in some samples.

Petrofacies MS3: This petrofacies is a grain supported; mixed iron oxide, analcime, and calcite cemented; poorly sorted, immature; medium lithic greywacke. It is distinguished from petrofacies MS2 by its cement content. Their other characteristics are nearly similar (Table 2). Zeolite is rare or absent (Ave. 5%). Replacement of calcite cement by iron oxide minerals and zeolites by analcime are commonly observed.

Petrofacies MS4: This is the most common petrofacies in the south margin (Fig. 2). High quantity of volcanic lithics (Lv/L=0.98), appreciable amount of opaque minerals (19%), and low matrix content (Ave. 4%) characterize the petrofacies. It is a grain supported mainly zeolite cemented, submature, medium volcanic arenite (Plate 1.c). Zeolite cement appears in poikilotopic, radial, granular, and fracture-filled forms. Replacement of zeolite by analcime and calcite is observed. In some samples authigenic clay minerals occur in thin layers coating the volcanic lithics/glasses.

Petrofacies MS5: This petrofacies is characterized by 25% mud clasts in its framework (Ls/L=0.45). It is a grain supported, zeolite cemented, immature, mud clast bearing, medium volcanic arenite. Other factors of the petrofacies are comparable to those of MS4 except lower Lv in the framework (Ave. 30%) and higher matrix content (Ave. 13%).

Petrofacies FS1: The petrofacies is characterized by prevalence of carbonate lithics in its framework (Lc/L= 0.52) and high calcite cement (Ave. 79%). It is a grain supported, calcite cemented, poorly sorted, immature, quartz bearing, fine calclithite. Carbonate matrix has endured relatively a high degree of re-crystallization in most of its volume. The petrofacies presumably was matrix supported when deposited.

Petrofacies FS2: It is a grain supported, zeolite cemented, poorly sorted, immature, fine lithic greywacke. It is distinguished from other petrofacies by its high matrix content (28%) which is dominantly carbonate in composition. Aphanitic volcanic lithics and volcanic glasses are the main framework constituents (55%). Quartz grains and opaque minerals are present in appreciable amounts, 24% and 17% respectively. Zeolite and analcime pseudomorphs after plagioclase are commonly observed. Clay minerals, coating the framework grains, are present in most samples of the petrofacies.

Petrofacies FS3: It is a grain supported, zeolite cemented, immature, fine volcanic arenite. The petrofacies is marked by predominance of volcanic lithics (Ave. 64%), opaque minerals (25%), and high degree of cementation (55%) (Plate 1.d). Analcime and ferruginous cements occur in noticeable amounts, Ave. 20% and 15% respectively. Development of authigenic clays and iron oxides around the volcanic glasses, replacement of plagioclase by zeolite and calcite, devitrification of glass, and alteration of Fe/Mg minerals to iron oxides are common diagenetic features.

Petrofacies VFS1: This is a matrix supported, rarely cemented (iron oxides and calcite), poorly sorted, immature, mud clasts-bearing, very fine volcanic arenite. Volcanic glasses are the main framework content. It is characterized by high iron-rich matrix (Ave. 64%); low degree of cementation; and noticeable amount of individual feldspars and opaques, 25% and 20% respectively.

Petrofacies VFS2: This petrofacies is marked by prevalence of volcanic glasses in the framework (Lv/L=0.99) and high degree of cementation (81%). It is a grain supported, zeolite cemented, poorly sorted, immature, very fine volcanic arenite. Alteration of glass to clay minerals, replacement of carbonate lithics and plagioclase grains by zeolite cement, and re-crystallization of carbonate matrix are common diagenetic events. Cross- lamination, picked out by opaque detritals, is observed in some samples.

Petrofacies VFS3: It is a grain supported, zeolite cemented, poorly sorted, immature, very fine lithic greywacke. The average Lv/L ratio is 0.99, which reflects scarcity of sedimentary lithics. This is probably due to their disintegration to matrix in early diagenesis. Cross-lamination and graded bedding are common. Burrows, filled with analcime and zeolite cements are commonly observed.

Major Components Variation

Variation of major components through the measured sections is recorded best in very coarse and coarse sandstones. For this reason the analysis of components variation is made mainly on these groups of

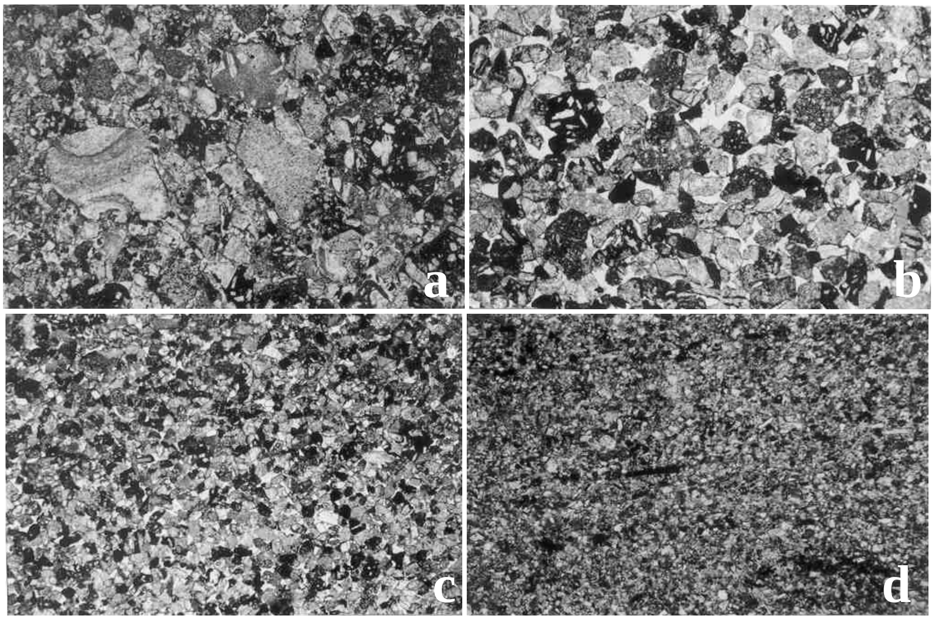

Plate 1 - Plane-polarized, transmitted light photograph representing examples of Petrofacies VCS3 (a), CS1 (b), MS4 (c), and FS3 (d) from south margin sections. Magnification is X 20.

rocks. Any remarks of other groups of rocks are explained where necessary. There is no significant difference between components variation of very fine and fine sandstones, except that carbonate lithics are rare or absent and individual minerals have higher frequency in the first group. For this reason the very fine sandstones are excluded from discussion here.

The distribution of carbonate lithics in very coarse and coarse sandstones is nearly similar. They are common in the lower (0-200$_m$ above the base) and upper (1000-1200$_m$ above the base) parts but rare or absent in the rest of the section (Fig. 3). In medium and fine sandstones they are significant only in the lower part of the section, nearer to the basin margin, but rare or absent in the rest of the section.

The volcanic lithics frequency in very coarse sandstones remains nearly constant through the whole section. In coarse sandstones, with nearly similar frequency, they show higher variation. Nevertheless the general pattern of the grains variation is similar to that of very coarse sandstones. Their distribution pattern in medium and fine sandstones is nearly similar to those of coarser petrofacies. Two major changes in frequency of volcanic lithics distribution in all types of sandstone are evident (Fig. 3). They are less common in the lower (0-100$_{m}$ above the base) and upper (1000-1200$_{m}$ above the base) parts but common in the rest of the section.

Individual grains, including quartz, feldspar, Fe-Mg minerals, and opaques are not common in south margin petrofacies (Table 2). They show higher frequency in fine-grained lithofacies. Quartz is significant only in the fine sandstones of the lower part of the sections, up to about 200$_{m}$ above the base. In the coarser rocks, quartz is rare in the lower part and absent in the rest of the sections. Its distribution pattern almost correlates with that of carbonate lithics.

Calcite cement variation correlates with that of carbonate lithics, more evident in the very coarse and coarse sandstones. Zeolite is the dominant cement of all rock types. Its variation, although depends on the volcanic lithics frequency, seems to be highly effected by diagenetic processes. The analcime frequency contrasts with that of zeolites in all rock types. Ferruginous cement occurs in all petrofacies, although in minor amount. A slight increase in its frequency with increasing depth is observed.

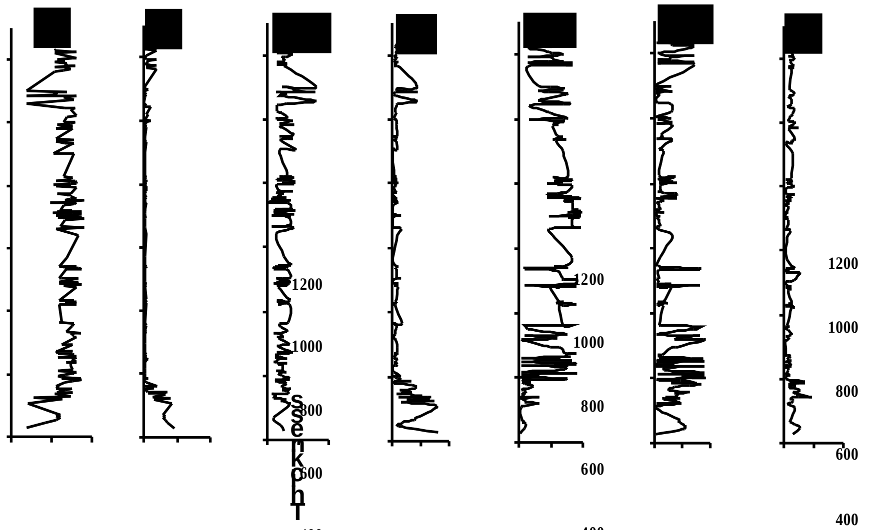

Figure 3 - Variation of major components in VCS and Cs through south margin sections. Lv = Volcanic lithics, Lc = Carbonate lithics, IND. = individual grains comprising quartz, feldspars, Fe-Mg minerals and opaque minerals, Ca = calcite cement, Zeol. = Zeolite cement, Ana. = Analcime cement, Fe = Iron cement.

Major Petrofacies of Northern Margin

The north margin sandstones are marked by prevalence of medium-size petrofacies (Fig. 4). Describing the texture and composition in detail, 16 petrofacies were distinguished in these rocks which characteristics are given in table 3. In mineralogical terms, disregarding grain size, calcite-cemented litharenites are the predominant petrofacies. In comparison with those in the south, the north margin petrofacies are richer in quartz, feldspar, carbonate lithics and chert but contain less volcanic lithics and zeolites(Table 3).

Petrofacies VCS3: The main characteristics are those described in the south margin but with higher feldspars, carbonate lithics, calcite cement, and lower volcanic lithics and lack of analcime.

Petrofacies VCS4: It is a grain supported, ferroan calcite and zeolite cemented, poorly sorted, submature, very coarse-grained, feldspar bearing volcanic arenite. Ferruginous cement and pseudomatrix are noticeable (Table 3).

Table 3. Major characteristics of north margin petrofacies. Symbols are the same as those in tables 1 and 2.

Petro-facies	Framework content (%)							Matrix	Cement content (%)				Total cement
	Qm	*Qp*	*F*	*Lv*	*Lc/Mc*	*Opq.*	*Fe/Mg*		*Zeol.*	*Cal.*	*Iron*	*Anal.*	
VCS3	3	-/5	18	65	5/-	3	1	8	65	18	17	-	17
VCS4	5	-/3	27	57	3/-	5	R	10	35	45	19	1	21
VCS5	2	-/6	46	41	2/-	3	R	11	5	24	71	-	35
CS4	12	7/7	10	54	3/2	4	1	7	11	81	8	-	30
CS5	20	8/10	15	32	8/1	4	2	4	10	85	3	2	25
CS6	7	3/3	32	40	7/1	6	1	10	20	45	35	-	22
CS7	17	5/4	25	18	13/8	7	3	8	3	90	5	2	45
MS6	12	2/4	27	37	7/3	5	3	6	26	50	22	2*	21
MS7	15	3/5	24	22	17/5	5	4	5	13	69	9	5*/2†	28
MS8	10	1/6	30	25	2/16	5	5	16	18	58	21	3†	15
MS9	8	1/2	45	34	2/-	6	2	8	4	23	73	-	50
FS4	13	3/2	30	23	13/4	8	4	36	4	51	33	12	28
FS5	16	2/3	39	11	17/3	7	2	52	13	67	20	-	10
FS6	11	4/2	31	29	10/3	7	3	12	17	66	16	1	39
VFS4	19	1/3	33	16	10/4	9	5	48	4	70	20	6*	27
VFS5	20	2/3	24	11	25	11	4	37	1	62	34	2*/1†	15

* Gypsum
† Silica

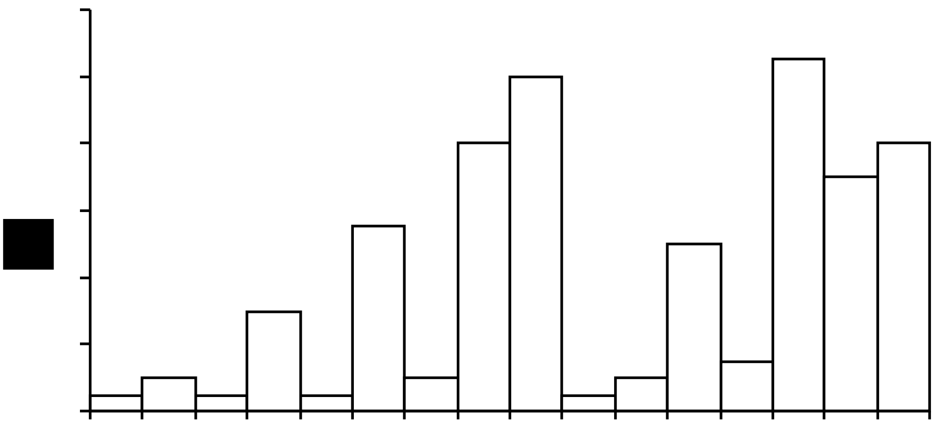

Figure 4 - Frequency histograms showing the abundance of major petrofacies in the north margin sections.

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6

4

Petrofacies VCS5: This petrofacies is characterized by feldspar detritus and ferruginous cement. It is a grain supported, ferruginous cemented, poorly sorted, submature, very coarse lithic arkose. Aphanitic to microlithic volcanic lithics are dominant rock fragments (Lv/L=0.89). Re-crystallization of carbonate matrix to calcite cement, alteration of volcanic glass to chert, re-crystallization of chert to micro-granular quartz, and feldspar overgrowth are common diagenetic features.

Petrofacies CS4: It is a grain supported, calcite cemented, poorly sorted, submature, coarse volcanic arenite. Most volcanic lithics have microlithic or glassy texture. Aphanitic porphyric lithics are few. Chert grains are common.

Petrofacies CS5: It is a grain supported, calcite cemented, poorly sorted, submature, coarse-grained, quartz-bearing volcanic arenite (Lv/L=0.54). Chert grains make up about 10% of the framework grains. Remnants of pelagic fauna are preserved in some chert grains. Re-crystallization of chert into micro-granular quartz is observed in some samples. Quartz overgrowth is common. Silica cement, filling in pore space or replacing shell fragments, is locally developed in these rocks.

Petrofacies CS6: This is the most common coarse sand-size petrofacies and is a grain supported, calcite and ferruginous cemented, poorly sorted, submature, feldspar bearing volcanic arenite (Lv/L=0.74) (Plate 2a). The petrofacies comprises pseudomatrix in noticeable amount (Av. 10%).

Petrofacies CS7: This petrofacies is marked by dominance of sedimentary lithics (Ls/L=0.52) and prevailing calcite cement (Ave. 90%). It is a grain supported, ferroan calcite cemented, poorly sorted, immature, coarse grained, feldspar bearing sedimentary lithic arenite. Carbonate lithics, chert grains, and mica-bearing shale fragments are the main sedimentary lithics. Re-crystallization of carbonate matrix to calcite cement is the most common diagenetic feature.

Petrofacies MS6: It is a grain-supported, dominantly calcite cemented, poorly sorted, immature, feldspar-rich medium volcanic arenite. Ferruginous and zeolite cements present in appreciable amounts (Table 3). Laminated shale fragments with biotite flakes are common. Carbonate lithics with Oligo-Miocene fauna are locally observed (Plate 2b).

Petrofacies MS7: It is a grain supported, dominantly ferroan calcite cemented, poorly sorted, submature, feldspar-rich sedimentary lithic arenite. Carbonate lithics are the main sedimentary lithics. They have micritic texture in which micro-fauna and shell fragments are locally preserved. Alternation of finer grains with coarser opaque minerals in plane-parallel laminae is locally observed (Plate 2c). Laminated shale fragments are present. Gypsum occurs as main cement in few samples.

Petrofacies MS8: This is a grain supported, dominantly calcite cemented, poorly sorted, immature, medium lithic greywacke. Mica-bearing laminated shale fragments are the major sedimentary lithics. In some samples orientation of the shale fragments along the bedding surfaces is observed. The plane-parallel lamination is recorded in some samples.

Petrofacies MS9: The petrofacies is marked by average73% ferruginous cement and 45% feldspar detritus. It is a grain supported, ferruginous cemented, poorly sorted, immature, medium lithic arkose. Andesine, twinned and zoned in most samples, is the dominant feldspar. Microcline is presented in a small amount. Sanidine, distinguished by polarizing microscope and SEM was observed in a few samples.

Petrofacies FS4: This is a matrix supported, dominantly calcite cemented, poorly sorted, immature, fine lithic greywacke. Calcite cement is exclusively enriched by ferric oxides. Abundant mica flakes mark the shale fragments. Gypsum occurs as a fracture-filling cement in most samples. Iron oxide minerals, clay minerals, calcite, evaporite minerals, and fine mica individuals are major constituents of the matrix.

Petrofacies FS5: It is a matrix-supported, calcite-cemented, poorly sorted, immature, fine feldspathic greywacke. The petrofacies is marked by more than 50% matrix that is mineralogically similar to that of FS4. Some part of the matrix is thought to be the result of sedimentary lithics disintegration (pseudomatrix). On the other hand, presence of cross-lamination, plane-parallel lamination, and graded bedding indicate its primary origin in most samples.

Petrofacies FS6: This is a grain supported, dominantly calcite cemented, poorly sorted, immature, fine-grained, feldspar-bearing litharenite. Volcanic glasses are dominant rock fragments (Lv/L=0.60). Feldspar detritals are chiefly plagioclase with a few examples of microcline. Matrix and cement are enriched by iron oxides. Red mud rip-up clasts are locally observed.

Petrofacies VFS4: The petrofacies is characterized by 48% matrix and 70% ferroan calcite cement. It is a matrix supported, ferroan calcite cemented, poorly sorted, immature, very fine feldspathic greywacke. Micro-scale cross lamination and graded bedding are commonly observed (plate 2d). Plant root remnants and burrows are locally observed.

Petrofacies VFS5: This is a matrix supported, calcite and ferruginous cemented, poorly sorted, immature, very fine lithic greywacke. It is distinguished from the former petrofacies by dominance of Lv and Ls. Carbonate lithics, mud clasts, and shale fragments are the main sedimentary lithics. Other features are similar to those of VFS4.

Major Components Variation

Major components variation in very coarse and coarse petrofacies throughout the measured section is given in figure 5. Lack of significant differences in the components of the very fine sandstones throughout the section excludes them from consideration. In contrast with the south margin, quartz, feldspar and chert detritals present in noticeable amount in nearly all petrofacies, for this reason their distribution pattern are shown separately.

Carbonate lithics are common in the petrofacies up to 2500m above the base but rare or absent in those of 2500-4000m. Their frequency increases again in the petrofacies of 4000-5000m above the base (Fig. 5). Volcanic lithics remain nearly high throughout the section. A diversity in frequency of both volcanic and carbonate lithics is recorded in the middle part of the section, around 2500m above the base. Palaeocurrent studies show no significant change in the direction of sediment transport for this part of the section (Amini, 1997). Individual contents of the petrofacies; quartz, feldspar, opaque

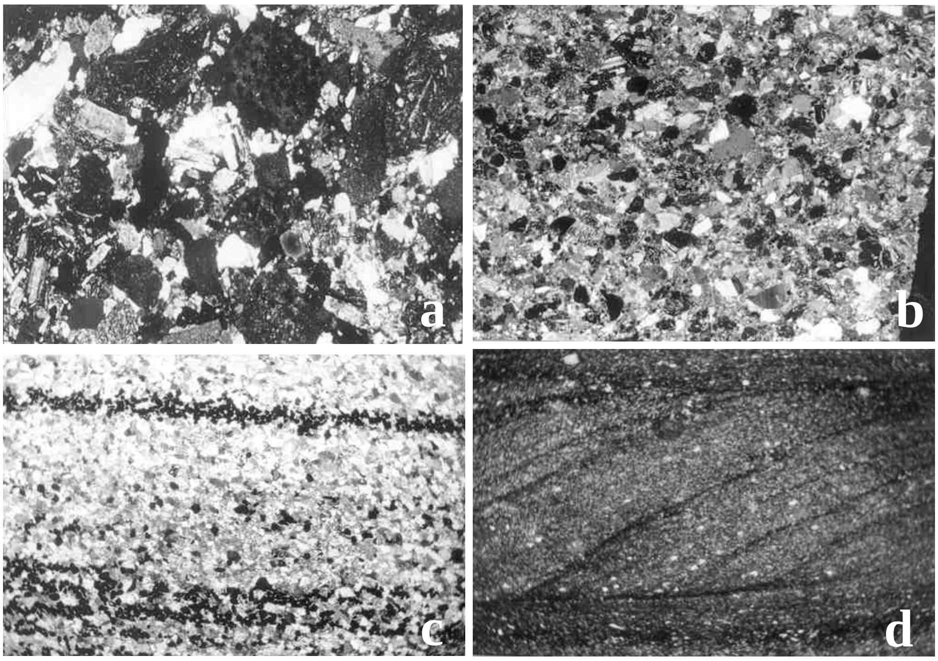


Plate 2 - Transmitted light photograph of Petrofacies VCS5 (a), PPL; CS6 (b), XPL: MS6 (c), XPL: and MS7 (d), XPL. Magnification for all is X 20.

minerals, and Fe/Mg minerals; remain quite high through the whole section. No significant variation through the section, in different petrofacies, was observed although their frequency increases with decreasing petrofacies grain size.

A slight increase in frequency of feldspars with increasing depth is observed. Distribution patterns of quartz and chert are similar to that of carbonate lithics. Calcite is the dominant cement in all rocks, through the entire section. Its variation is comparable to that of the carbonate lithics. Variation of major constituents in medium and fine sandstones slightly differs from that of very coarser lithofacies. The major change in source rocks composition is reflected in their distribution, more apparent in coarse and very coarse sandstones.

Zeolite distribution in very coarse, coarse and medium sandstones correlates with that of the volcanic lithics. In the fine sandstones, the zeolites occur in lower amounts with some anomalies in their distribution. A slight increase in iron oxide content with increasing depth is recorded in all sections.

Discussion

South

Occurrence of the carbonate lithics mainly in the lower part of the sections is probably related to their chemical instability during transportation. Carbonate lithics with short traveled distance and coarse size could survive where as others would disintegrate into silt/clay size grains. Abundance of carbonate matrix in medium and fine sandstones confirms this indication. Presence of Lc bearing lithofacies in the upper part most likely reflects reoccurrence of carbonate rocks in the source area. This probably was due to normal faulting in basin margin, characteristic of a back arc setting (Fig. 6).

Difference in distribution patterns of volcanic lithics in very coarse and coarse sandstones with those of medium and fine sandstones may be related to their different sources. The former group, dominantly aphanitic porphyric in texture, seems to be delivered from volcanic lavas whereas the latter, with microlitic or glassy texture, is from pyroclastic rocks. More significance of the former group reflects that the south margin facies were mainly originated from a volcanic source.

Clear correlation of quartz frequency with that of carbonate lithics probably reflects their origination from similar source. They are most likely originated from tuffaceous limestones of the upper members of the Qum Formation (Okhravi and Amini, 1998).

Higher proportion of calcite cement in medium and fine sandstones is probably related to more availability of carbonate precursors in silt to clay size. Finer carbonate lithics were more susceptible to water-grains reaction. Re-crystallization of carbonate matrix seems to be the main process responsible for calcite cement development in these rocks (Amini, 1997).

The discrepancy in zeolite and analcime cements probably suggests that replacement of zeolite by analcime, as indicated in petrographic and SEM observations (Amini, 1997), was a common diagenetic event in this area. Analcime presents both in shallow and deep lithofacies. Its distribution pattern reflects that some part of analcime was carried in to the basin from source area in solution form. Those in deeper lithofacies developed in diagenetic environment by alteration of volcanic lithics or zeolites. The distribution pattern of ferruginous cement reflects the significance of diagenetic processes in its development.

The diversity in frequency of both volcanic and carbonate lithics is probably related to a major change at the source with volcanic rocks becoming a more significant contributor, producing more lithics for middle part of the section. These rocks gradually lose their significance as a source toward the top of the section (Fig.5).

North

Based on the frequency and distribution patterns of the volcanic lithics and individual grains, with volcanic affinities, it seems that the studied rocks benefited mainly from a pyroclastic source. High proportion of individual minerals with volcanic affinities supports the predominance of pyroclastic rocks in the source region.

The frequency patterns of calcite and zeolite cements most likely suggest strong effect of framework grains in controlling the cements' composition. Distribution of zeolite cements in different rocks, their relation with volcanic lithics, and their increment with increasing depth suggest that they are dominantly diagenetic in origin.

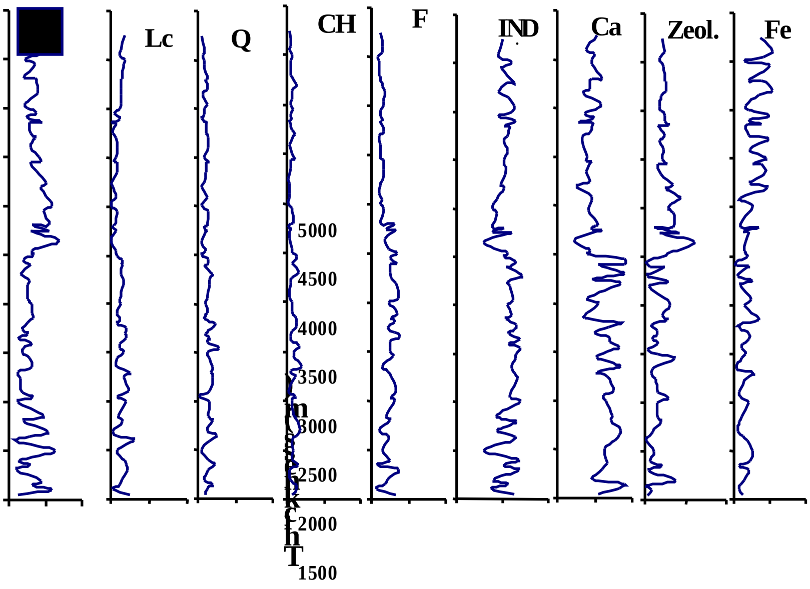


Figure 5 - Variation of major components in VCS and CS through north margin sections. Q = Quartz, F= Feldspars, CH = chert grains, Opq. = Opaque minerals. Other symbols are the same as those in figure 3.

Higher proportion of iron oxides cement in the deeper facies shows significance of diagenetic processes on their development. This result supports the idea that the reddening of the URF was dominantly carried out in the diagenetic environment (Amini, 2001).

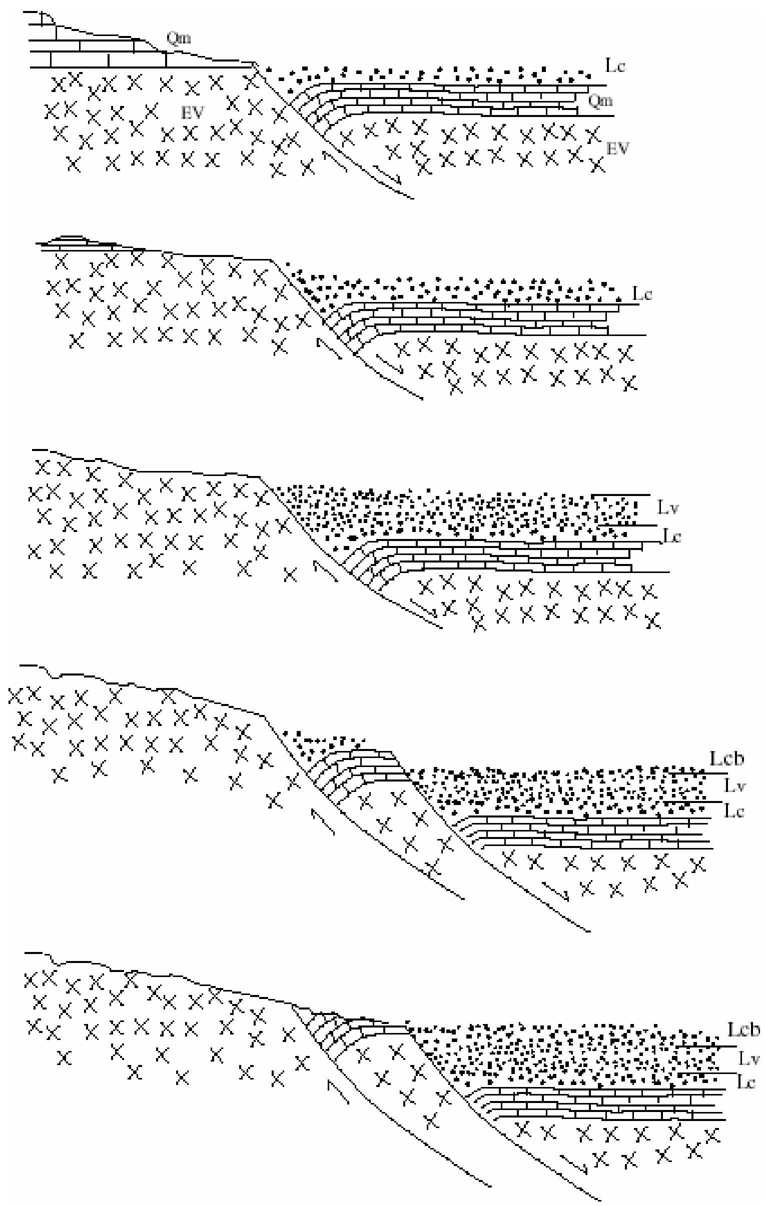
A general decrease in the Lc frequency from base to top is observed in all sections. It is related their unstability during transportation. The lithofacies in the upper parts of the sections with lower Lc content are related to distal and those with higher Lc content to the proximal parts of a fluvial system respectively. Reoccurrence of Lc in the petrofacies of the upper part, although in low amount, reflects diversity in the source region. It is probably due to progressive block faulting, similar to that of south with higher accommodation development (Fig. 6). Such a conclusion is identical from both Lv and individual grains' distribution.

Abundance of fine to medium sand-size quartz and feldspar indicates their pyroclastic origin. Chert detritals and some quartz grains were probably originated from tuffaceous limestones, similar to the south. Lower frequency of feldspar in deeper lithifacies is related to their instability in diagenetic environment. Higher abundance of carbonate lithics in the north margin lithofacies shows higher contribution of Qum Formation in providing grains in to URF basin. More abundant individual grains in the north margin lithofacies show the volcaniclastic nature of source rocks. Such a result along with geochemical variation of petrofacies through measured sections reflect that Eocene "green series" remained the major source for the whole formation in this part of the basin.

Distribution patterns of major constituents, especially volcanic and carbonates lithics show that the Upper Red Formation Basin was a fault-bounded basin in which accommodation development was mainly controlled by block faulting. Reoccurrence of Lc in upper part of the sections supports such an indication (Fig. 6). Moreover, results from modal composition analysis on provenance diagrams (Dickinson et al., 1993) shows that the sandstones were mostly derived from a dissected magmatic arc (Fig. 7). Such results also characterize a back arc setting for the Upper Red Formation Basin. Higher displacement of the bounding faults due to their reverse nature in the north margin provided more accommodation space for deposition. This is responsible for thicker sediment prisms of the formation in north margin.

Results from Lc and calcite cement variation in the studied sections show that in the south margin lithofacies carbonate cement was mainly derived from disaggregation and dissolution of carbonate lithics. In the north margin lithofacies apart from carbonate lithics, calcic plagioclases played an important role in calcite cement development.

Analcime occurs nearly in all parts of the sections, more common in deeper lithofacies. Its distribution pattern shows that most of analcime in the studied sections is the result of zeolites, volcanic lithics, or plagioclase alteration. Difference in its frequency in the north and south sections is a function of source materials composition. Moreover, higher abundance of volcanic glasses and deeper diagenetic environments provided better conditions for its development.



Results from petrographic and geochemical studies show that

Figure 6 - Schematic diagrams illustrate the occurrence of Lc

dominated (Lc), Lv dominated (Lv), and Lc bearing (Lcb) lithofacies in the lower, middle and upper part of the formation respectively. Qm = Qum Formation, EV = Eocene volcanics

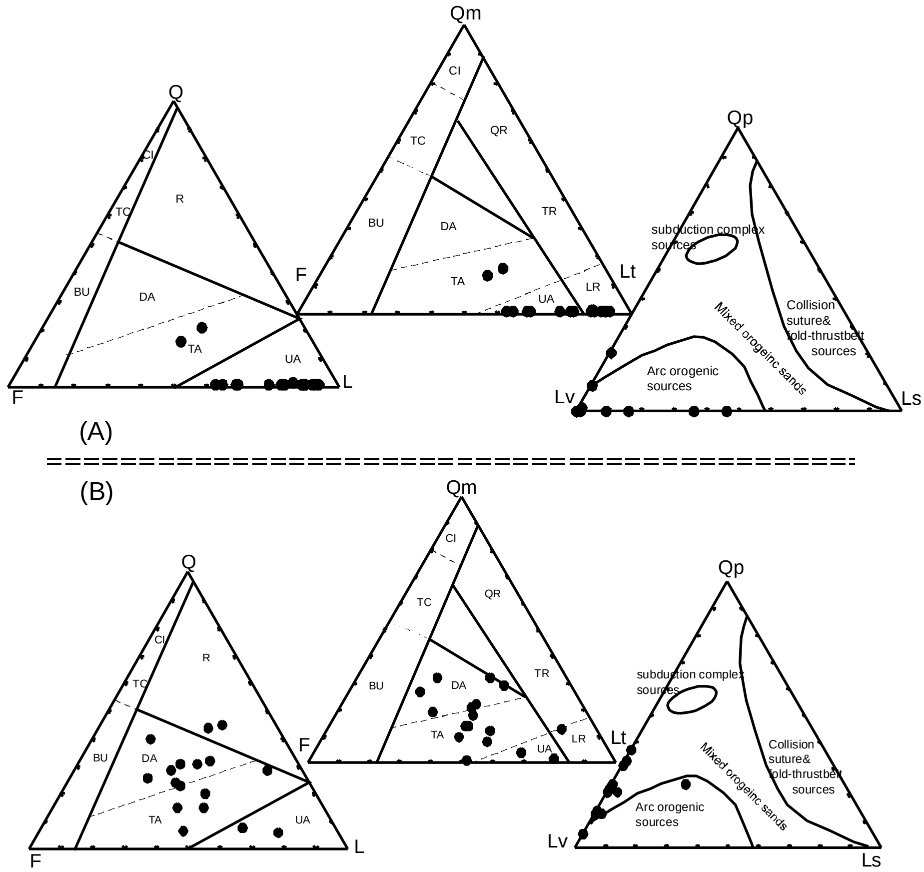


Figure 7 - Detrital modes of south (A) and north (B) margin sandstones on provenance diagrams of Dickinson et al., 1983. CI = Craton interior, TC = Transitional continental, BU = Basement Uplift, R = Recycled orogen, QR = Quartzose recycled, TR = Transitional Recycled, LR = Lithic recycled, DA = Dissected arc, TA = Transitional arc, UA = Undissected arc, Each point represents mean value of 20-30 analyses.

individual grains are mainly the result of Lv and Lc disaggregation during transportation. So that, their higher frequency in the lithofacies can be related to tectonically active phases in the region (periods in which region was tectonically more active). Their higher frequency in the north margin is both related to the nature of source rocks (pyroclastics) and higher tectonic activity of the region. Results from distribution patterns of Lc, Lv, and individual grains reflect the rejuvenation of surrounding faults during deposition of the studied rocks in both margins of the basin.

Results from this study clearly shows that accommodation development was mainly controlled by block faulting in a back arc setting.

Conclusions

Petrofacies analysis of the URF sandstones clearly shows that sedimentation was occurred in a back-arc setting. Accommodation necessary for sedimentation was mainly provided by fault activities in the basin margins. The nature of fault activities during sedimentation and diversity in the source area can be judged by component variation of the petrofacies.

Acknowledgements

Some part of data for this paper is taken from author's Ph.D. thesis that was financially supported by MSRT. The author is most grateful for interesting comments from three unknown referees.

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