Geol. Soc. Malaysia, Bulletin 39, July 1996; pp. 81-90

Anomalous quartzarenites of a Lower Cretaceous rift basin: Wadhwan Formation of Western India

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Abstract: The Wadhwan Formation represent, an anomalous quartz-arenite which was deposited in the Lower Cretaceous Saurashtra rift basin. The sandstones plot near the Qt and Qm poles of the standard triangular provenance diagrams of Dickinson (1985).

A critical analysis of the various factors that might have modified the original detrital composition of Wadhwan sandstones indicates that tropical weathering under warm and humid conditions and long residence time at the sediment water interface in a shallow marine environment destroyed the labile grains and enriched the sandstones in quartz. Recycling, transportation processes and diagenesis did not modify the original detrital composition significantly.

INTRODUCTION

Detrital mineral composition of a sandstone is primarily controlled by source rock composition and plate tectonic setting. However, several other processes such as climate and weathering, depositional reworking and diagenesis also affect the relative abundance of detrital grains in terrigenous sediments (Suttner, 1974). Weathering and depositional reworking are highly effective modifying agents of detrital composition on cratons or in passive continental margins as a result of low rates of erosion and sedimentation. The chances of destruction of labile detrital constituents are increased due to long residence time in the soil horizon or at the sediment/water interface of shallow marine environments (Suttner *et al.*, 1981). In some cases, total dissolution of grains of feldspar, rock fragments and heavy minerals by corrosive meteoric or subsurface waters severely modify original sand composition and produce 'diagenetic quartzarenites' (McBride, 1985). All these processes which modify the original sand composition make the sandstone highly quartzose and sometimes to the extent that the signatures of source rocks and tectonic setting are entirely masked resulting in an anomalous sandstone.

Sands deposited in incipient rift belts are shed from fault-bounded uplifts of continental basement rocks (Dickinson and Suczek, 1979). High relief and rapid erosion of the uplifted sources give rise typically to quartzo-feldspathic sands of classic arkosic character. The highly quartzose sandstones of the Wadhwan Formation deposited in the Lower Cretaceous Saurashtra rift basin are anomalous sandstones in as much as their detrital composition does not match their tectonic setting. In this paper various factors that might have modified the original detrital composition of the Wadhwan sandstones have been critically examined and their anomalous nature is explained.

GEOLOGICAL SETTING

The Saurashtra basin developed in Early Cretaceous coinciding with uplift of northerly Kutch basin (Jurassic). The elongated Saurashtra rift basin (Fig. 1) extending southwest to northeast from Gujarat coast to Aravalli over a length of nearly 400 km and bounded by major faults to north and south (Biswas, 1982; Varadarajan and Ganju, 1989) represents a pericratonic composite rift system (Sengor *et al.*, 1978).

According to Cannon *et al.* (1981) and Tankard *et al.* (1982) the beginning of plate separation in other parts of the Gondwana land during Jurassic and Early Cretaceous was marked by the formation of pericratonic rift basins which were similar to the pericratonic rifts (Kutch and Saurashtra) of India.

Both of these basins (Kutch and Saurashtra) may represent parts of an elongated extensional trough where up and down rifting during Jurassic-Cretaceous time brought about basin formation and sedimentation, first in northern part (Jurassic of Kutch) and latter in southern part (Early Cretaceous of Saurashtra) (Casshyap and Aslam, 1992).

The Saurashtra basin comprises Mesozoic and Tertiary sedimentary rocks and the Deccan Trap basaltic flows, the later covering the major part of the Saurashtra Peninsula (Fig. 1). The Mesozoic sedimentary rocks outcrop only in the northeastern part of the Saurashtra peninsula. In the outcrop area, the Mesozoic sequence is nearly 600 m thick. Besides the outcrop around Surendranagar, these rocks extend in subsurface below the Alluvium (Recent) and Deccan basalt (Late Cretaceous) towards the eastnortheast-westsouthwest and north and south.

The Mesozoic sedimentary rocks which are exposed in the northeastern part of the Saurashtra basin comprise two formations: Dhrangadhra Formation and Wadhwan Formation, which are unconformably overlain by the Deccan Traps of Late Cretaceous age. Thin Neogene and Quaternary deposits occur along the Arabian Sea Coast of the Saurashtra peninsula. The generalised complete stratigraphic sequence of Saurashtra peninsula is given in Table 1.

The Dhrangadhra Formation which is more than 500 m thick mainly comprises coarse clastics with minor amount of shale and clay. The overlying Wadhwan Formation, about 50 m thick, is made up of brick red to reddish brown sandstones with small pockets of shales, and at places thin brownish grey limestones are developed. The Wadhwan Formation is overlain by Deccan Trap basalt flows. The Mesozoic sedimentary sequence of the Saurashtra basin ranges in age from Late Jurassic to Early Cretaceous (Upper Tithonian to Albian: 145–97 Ma). The Dharangadhra and Wadhwan Formations are correlated with Bhuj Formation and Ukra Member of Bhuj Formation. Marine fossils of Wadhwan Formation reported by Chiplonkar and Borokar (1975) were correlated with the fossils found in the Bagh beds and upper part of Nimar Sandstone (Chiplonkar *et al.*, 1977). Thus the Wadhwan and Bagh sediments may be synchronous in age.

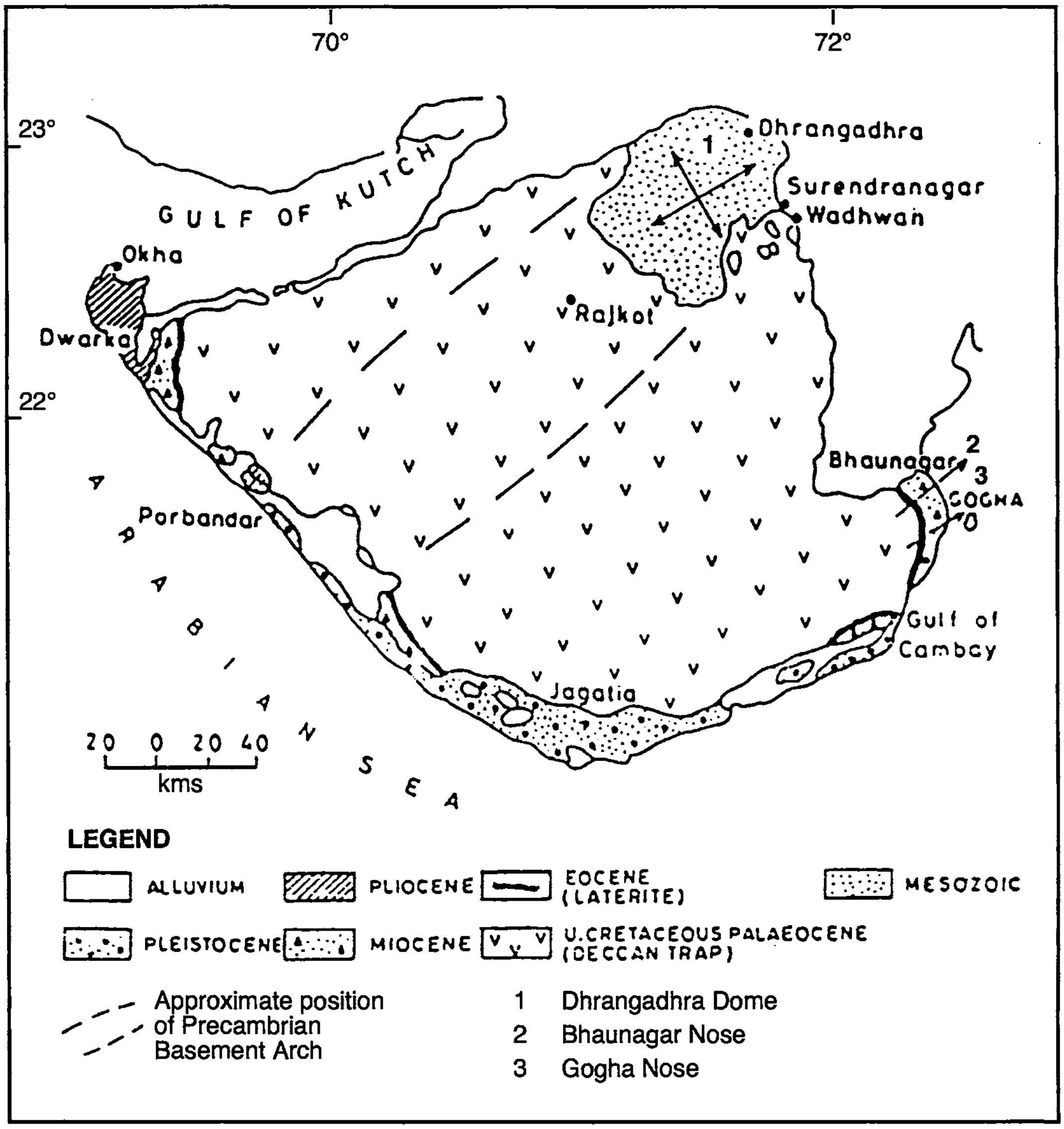

Figure 1. Geology and tectonic map of Saurashtra Peninsula (after Biswas and Deshpande, 1983).

Table 1. Generalised stratigraphic sequence of the Saurashtra peninsula (after Biswas and Deshpanda, 1983).

AGE	FORMATION
Recent to subrecent	Alluvium
Unconformity	
Quaternary	Porbandar Formation
Unconformity	
Mio-Pliocene	Dwarka Formation
Early Miocene	Gaj Formation
Unconformity	
Paleocene (?)	Laterites
Unconformity	
Late Cretaceous	Deccan Trap Formation (Basaltic flows)
Unconformity	
Early Cretaceous	Wadhwan Formation Dhrangadhra Formation
Unconformity	
Precambrian	Basement

METHODOLOGY

Detrital composition of the Wadhwan sandstones was evaluated both quantitatively and qualitatively in thin sections. About 200–300 grains per thin section were counted for quantitative analysis and for determining the modal composition of rocks under investigation. The study is based on examination of thin sections and scanning electron microscopy.

FRAMEWORK GRAINS

The sandstones of the Wadhwan Formation are composed of mainly quartz of several varieties followed by micas, rock fragments, feldspars and heavy minerals as minor constituents. The average composition of the sandstones is: quartz, 98.24%; rock fragments, 1.0%; feldspars, 0.19%; and other minor constituents (mica and heavy minerals etc.), 0.57%. The sandstones are medium to fine grained and moderately sorted (64.0%) to poorly sorted (36.0%) quartzarenites. The grains are generally subangular to subrounded. On the basis of Folk's (1980) classification the various types of quartz recognized include common quartz, 88.62%; vein quartz, 3.96%; recrystallized metamorphic quartz, 4.25% and stretched metamorphic quartz, 3.15%.

Both muscovite and biotite occur as tiny flakes. The percentage of mica is very low in the Wadhwan sandstones, averaging about 0.19% of the detrital constituents. However, muscovite is more common than biotite.

Feldspars are present only in some samples and constitute 1.0 to 2.0% of the detrital component averaging 9.19%. The feldspar grains belong to mainly orthoclase. The grains are weathered. Kaolinite is common in the Wadhwan sandstones and possibly formed by the weathering of feldspars grains.

The rock fragments comprise 1.0 to 3.0% and average 1.0%. They comprise sedimentary (mainly chert and some siltstone) and low rank metamorphic rocks fragments (phyllite and quartzite).

Heavy minerals were observed in about one third of the total samples. Heavy minerals constitute 1.0 to 2.0% and average 0.31%. Opaque, tourmaline and zircon are the main types of heavy minerals.

CLAY MATRIX

Percentage of clay in the Wadhwan sandstones generally range from 1.0 to 7.0%, and average about 1.6 percent. Both allogenic and authigenic clays are present. The authigenic kaolinite is dominant and shows well developed crystalline habit and book form as is clearly seen in SEM photographs (Fig. 2) which distinguish it from allogenic clay. The allogenic kaolinite shows irregular aggregates of plates which have rugged outlines (Fig. 3).

CEMENT (AUTHIGENIC)

In the Wadhwan sandstones three types of cementing materials occur which include iron oxides, silica and calcite, in order of abundance.

Iron oxide is most abundant cementing material which forms 2.0 to 25.0% (average 6.5%) by volume of the rocks and occurs in the form of a thin coating around detrital grains as well as patches which show corrosion of detrital grains and replacement along fractures (Fig. 4). Corroded quartz grains suggest the presence of an earlier calcite cement which was replaced by iron oxide. In some thin sections oversized pore spaces are seen to be lined with a thin coating of iron oxide. The oversized pore spaces have resulted from destruction and leaching of labile framework grains, possibly feldspars. Iron oxide cement was possibly derived from weathering and leaching of the overlying traps. The thin iron oxide coating on detrital grains is possibly inherited from the source rocks.

Silica cement ranges from 1.0 to 4.0% and averages about 1.86%. It occurs mainly in the form of overgrowths on detrital quartz grains which

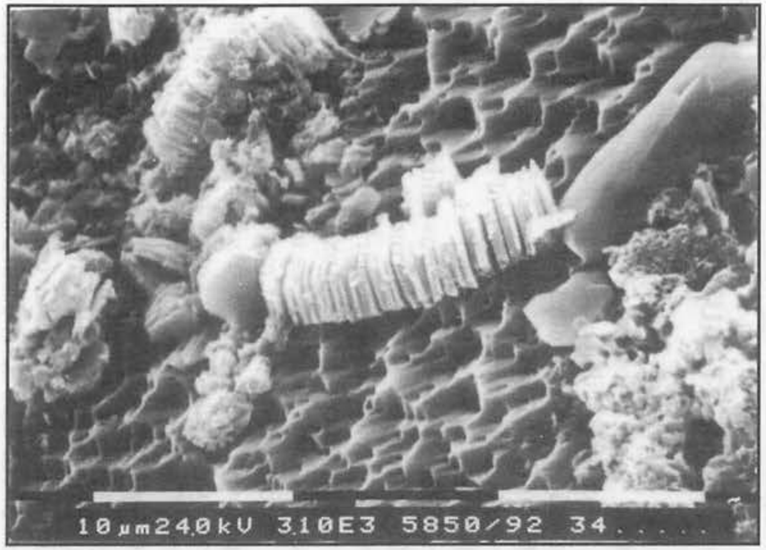

Figure 2. Scanning electron micrograph of the Wadhwan sandstone showing well developed hexagonal plates of authegenic kaolinite arranged in vermicular form.

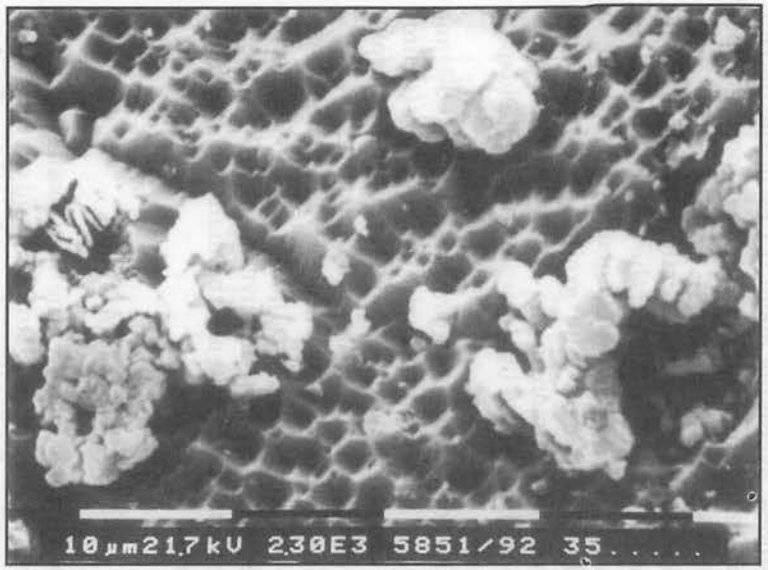

Figure 3. Scanning electron micrograph of the Wadhwan sandstone showing irregular aggregates of allogenic kaolinite with rugged plate outlines. Incipient silica overgrowths are seen on quartz grain surfaces.

Figure 4. Photomicrograph of Wadhwan sandstones showing iron oxide cement filling up intergranular spaces and fractures within the detrital quartz grains (x 90, uncrossed).

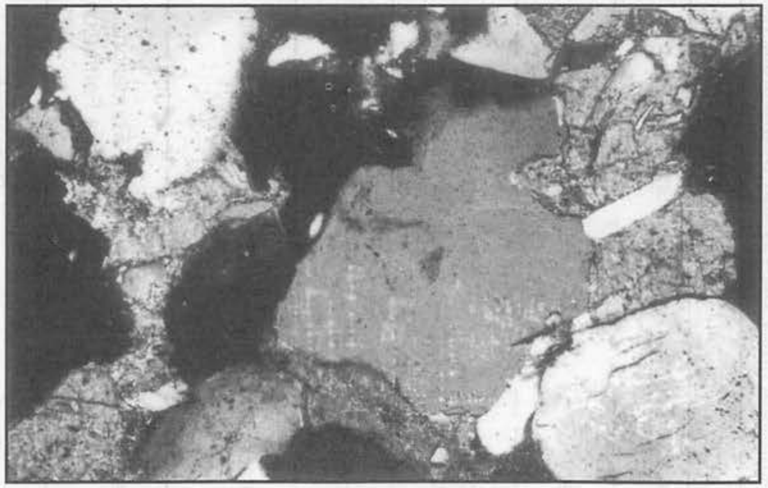

Figure 5. Photomicrograph of Wadhwan sandstone showing rare carbonate cement which has corroded detrital quartz grains (x 90, crossed).

partially fill up the intergranular spaces. SEM micrographs of quartz grain surfaces show incipient silica overgrowth (Figs. 2 and 3).

Calcite cement occurs in few samples of the Wadhwan Formation which are white coloured. In thin section calcite cement shows patchy distribution. Its percentages range from 2.0 to 21.0% and average about 0.63%. The calcite cement has partially replaced detrital grains which are marked by corroded boundaries (Fig. 5).

FACTORS CONTROLLING THE DETRITAL MINERALOGY OF THE WADHWAN SANDSTONES

Detrital mineralogy does not depend only on a single factor but a group of factors are responsible for detrital composition of a sandstone which include the types of source rocks, distance of transport, tectonism, palaeoclimate, paleogeography and depositional environments and diagenetic modifications of the original detrital constituents.

Identification of the source area

The Cretaceous rocks of Saurashtra including the Wadhwan sandstones were deposited in a failed rift and a schematic model of its tectonic setting and broad paleogeography have been reconstructed by Casshyap and Aslam (1992). The commencement of Cretaceous sedimentation in the Saurashtra rift was marked by the deposition of shoreline conglomerate and interbedded sandstone and shale around Himatnagar near Aravalli highlands (Casshyap *et al.*, 1983). The study area lies about 150 kilometer southwest of Himatnagar. Towards southwest sedimentation continued in the subsiding distal parts of the rift. A considerably thick clastic sequence was deposited within the rift which shows an increasing proportion of fine clastics to the southwest along the length of the basin.

The paleogeographic reconstruction of the Saurashtra rift suggests that the provenance of the Wadhwan sandstones was located towards the northeast, in the Aravalli highlands a few hundred kilometers from the study area.

Distance of transport

The detrital grains of the Wadhwan sandstones are in the sand size range and in all probability they have undergone transportation for a distance of a few hundred kilometers. The Wadhwan sandstones are deficient in feldspars and one possible reason for this deficiency may be the transportation of sediment by high gradient streams and rapid destruction of feldspars by abrasion. Since deposition of the Wadhwan sandstones took place in a tectonically active rift, presence of high gradient stream is quite likely within the basin. However this premise does not stand to scrutiny because rock fragments which could have been destroyed more easily are more common than the feldspars. Therefore some factor other than transportation was responsible for the paucity of feldspars in the Wadhwan sandstones.

Palaeoclimate

The palaeogeographic reconstruction of the earth at 100 m.y. (Thomson and Barron, 1981) suggests that during the Lower cretaceous the study area was located at latitude 44° south of the equator and within the wide humid tropical belt with luxuriant plant life that extended up to 45° north and south of the equator. Therefore the Precambrian basement rocks which provided sediments to the Saurashtra rift must have undergone rigorous weathering under humid tropical conditions resulting in destruction of much of the feldspars and labile constituents. Palaeoclimate was possibly a very important factor in the formation of highly quartzose sandstones of the Wadhwan Formation. Akhtar and Ahmad (1991) have demonstrated the active role played by tropical climate in the deposition of quartz rich Nimar Sandstone which is believed to be equivalent in age to the Wadhwan Formation.

Depositional environments

The Lower Cretaceous rocks of the Saurashtra rift basin represent deposits of a general transgression proceeding from SW to NE consequent upon progressive downwarping with intermittent rifting of the basin. A large part of the lithofacies of the rift-fill represents deposition in the nearshore coastal delta plain with a gradual northeastward transgression recognized by the facies changes from the basal deposits to the upper most Wadhwan Formation. The Wadhwan Formation represents localized deposition in estuaries and embayments as part of continuing marine transgression. The highlands to the east and northeast supplied the clastic sediments into the estuarine environment. Deposits of shoals and sand bars are represented by the associated pebbly coarse sand.

Depositional reworking effects the relative abundance of detrital gains in terrigenous sediments (Suttner, 1974). The most effective modification of sandstone composition may take place in those environments where rates of erosion and sedimentation are low. A long residence time at the sediment water interface of shallow marine environments enhances the destruction of labile detrital grains (Suttner *et al.*, 1981). The sandstones of Wadhwan Formation which are mostly texturally submature were deposited in rather protected environments of estuaries and embayments. Because of the protected environment and lack of reworking, the labile grains remained at the sediment water interface for a long time and were destroyed.

Diagenetic modifications

The depositional composition of sands may be altered by diagenetic processes which must be taken into consideration while making provenance interpretation (McBride, 1985). The diagenetic modifications include loss of detrital framework grains by dissolution, alteration of grains by replacement or recrystallization, and the loss of identity of certain ductile grains during compaction which give rise to pseudomatrix.

The presence of highly weathered feldspar grains as well as oversize pores indicate dissolution of detrital grains in the Wadhwan sandstones. We have estimated that about 2% of the existing porosity of the Wadhwan sandstones has resulted from dissolution of detrital grains, mainly feldspars. The process of replacement has not been very effective in modifying the detrital composition of the Wadhwan sandstones. The replacement of quartz grain by carbonate and iron oxide is only partial and localized and hence composition of the original grain is determinable. Therefore this factor has not been much of a problem in provenance interpretation of the Wadhwan sandstones. A study of grain contacts of the Wadhwan sandstones indicates that the sandstones have not suffered much compaction during burial and their original texture and fabric has not been modified to any appreciable extent by the process of compaction.

Plate tectonic setting

The use of quantitative detrital modes, calculated from point counts of thin section, to infer sandstone provenance is now well established (Dickinson, 1985). The detrital modes of sandstone primarily reflect the different tectonic setting of the provenance but various other factors which effect sandstone composition are relief, climate, transport mechanism, depositional environment and diagenetic change.

In accordance with Dickinson's (1985) scheme the detrital modes of the Wadhwan sandstones were identified and recalculated to 100 percent as the sum of Qm, Qp, P, K, Lv and Ls (Table 2). The sandstones do not contain intrabasinal grains (Zuffa, 1980).

Two complementary triangular diagrams (Fig. 6A, B), each of which involves a different set of grain populations, were employed for the analysis of the data on detrital modes of the Wadhwan sandstones.

Table 2. Classification and symbols of grain types (after Dickinson, 1985).

A.	Quartzose Grain (Qt = Qm + Qp)		
	Qt	=	Total quartz grain
	Qm	=	Monocrystalline quartz
	Qp	=	Polycrystalline quartz
B.	Feldspar Grain (F = P + K)		
	F	=	Total feldspar grains
	P	=	Plagioclase grains
	K	=	K-Feldspar grains
C.	Unstable lithic fragments (L = Lv + Ls)		
	L	=	Total unstable lithic fragments
	Lv	=	volcanic/metavolcanic lithic fragments
	Ls	=	Sedimentary/metasedimentary lithic fragments
D.	Total lithic fragments (Lt = L + Qp)		
	Le	=	Extrabasinal detrital lime clasts (not included in L or Lt)

Qm (monocrystalline quartz) is the dominant detrital mode and forms 79 to 98 percent in various samples, averaging 91.6 percent. Qm grains are mostly subrounded.

Qp (polycrystalline quartz) includes recrystallized metamorphic quartz and stretched metamorphic quartz. Qp ranges from 2.0 to 21.0 percent in various samples, averaging 7.1 percent.

K-feldspar grains are not common in the Wadhwan sandstones and were observed in very few samples. The feldspar grains consist of weathered orthoclase and their percentages range from 1.0 to 2.0 percent in the few samples in which the grains occur. The feldspar grains average about 0.19%.

Ls (rock fragments) comprises 1.0 to 3.0 percent of the detrital fraction. They include metasedimentary/sedimentary lithic fragments of phyllite, quartzite, chert, sandstone and siltstone etc.

On the standard Qt-F-L plot, the studied samples lie in the continental block provenances with sources on stable cratons because most of the points fall near the Qt pole (Fig. 6A). On the Qm-F-Lt plot most points lie in the transition zone between the fields of continental block provenances and recycled orogen provenances. The points are mostly located on the Qm-Lt leg of the triangular diagram (Fig. 6B).

The petrofacies analysis of the Wadhwan sandstones suggest their sources on stable craton (Fig. 6A). The main sources for craton-derived quartzose sands are low-lying granitic and gneissic exposures, supplemented by recycling of associated

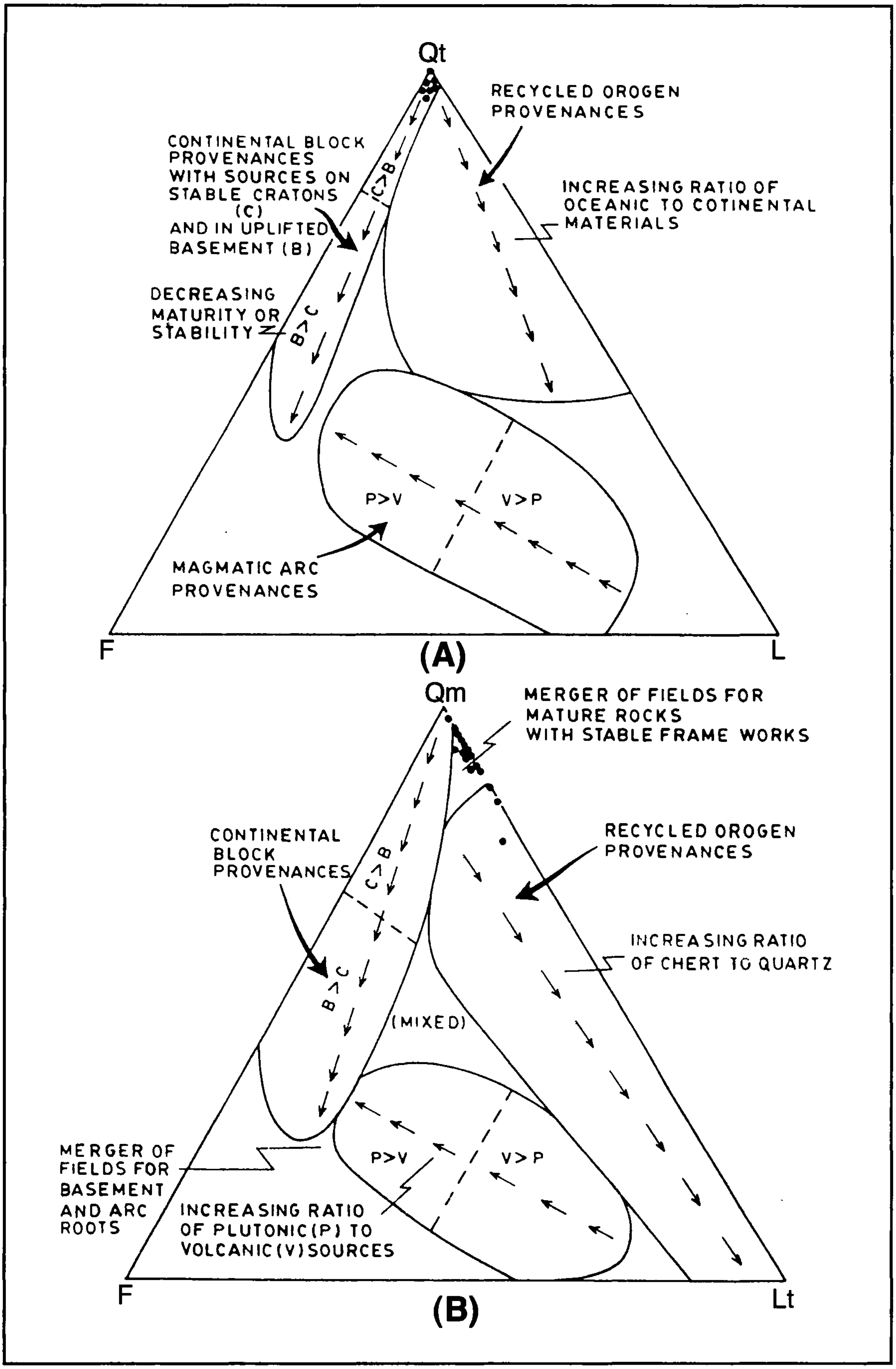

Figure 6A, B. Classification of Wadhwan sandstones (based on the scheme of Dickinson, 1985).

flat lying platform sediments. It has been mentioned elsewhere that the source rocks of the Wadhwan sandstones, located northeast of the study area, consisted of Precambrian metasediments and granite-gneisses of Delhi and Aravalli Supergroup.

The location of the study area within a humid tropical belt during the lower Cretaceous (Thomson and Barron, 1981) and the prevailing warm and humid climate must have affected the weathering pattern of the source rocks. An intense chemical weathering possibly destroyed most feldspars and labile constituents. Therefore the continental block provenance that provided detritus to the study area during the deposition of the Wadhwan sandstones was deeply weathered.

The formation of mature quartzose sands, such as those of the Wadhwan sandstones, have been ascribed to multicyclic reworking on cratons by several workers. However recent work has shown conclusively that quartzose sand is also being produced as first-cycle sediment from deeply weathered granite and gneissic bed rock exposed in tropical low lands of the modern Amazon basin (Franzinelli and Potter, 1983). The lack of second cycle grain of quartz suggest that recycling was perhaps not an important factor in the formation of quartz rich Wadhwan sandstones.

The development of first cycle quartz rich sand requires low relief in the provenance to allow prolonged weathering. This is demonstrated by quartz-poor nature of both fluvial and littoral Holocene sands derived from drainage basins in tropical highlands with high relief (Ruxton, 1970). Thus, even where the climatic potential for intense weathering exist, quartz rich sands will not be produced unless the relief is low. A low relief must have marked the continental block provenance prior to rifting, from where the Wadhwan sandstones were derived.

A large majority of the Wadhwan sandstones are texturally submature, this is, they contain under 5% clay but detrital grains are poorly sorted and not well rounded. This indicates that the Wadhwan sandstones were mostly deposited in environments rather protected from persistence wave and current action. This seems quite likely as the Wadhwan Formation represents localised deposition in estuaries and embayments (Casshyap and Aslam, 1992). The waves and currents had sufficient strength to winnow away the mud, but were not strong enough to bring about sorting and rounding of the detrital grains. The detritus was also enriched in quartz by destruction of 'labile' grains during long residence time at the sediment water interface.

The detrital grains of the Wadhwan sandstones are in the sand-size range and are believed to be transported from a distance of a few hundred kilometers, considering the location of the Aravalli highlands with respect to the study area. This distance of transportation is not sufficient to bring about rounding and sorting of detrital grains within the sand size range exhibited by the Wadhwan sandstones.

It is now a well established fact that the lower Cretaceous sedimentary rocks of Saurashtra were deposited in faulted troughs (Biswas, 1982). A recent study of these sediments, specially their facies, helped in constructing their tectono-sedimentary model (Casshyap and Aslam, 1992). The Lower Cretaceous sedimentary rocks including the Wadhwan Formation of Saurashtra basin were deposited in a failed rift. The development and infilling of the Lower Cretaceous Saurashtra failed rift was concomittent with the pericratonic rifting and opening of the Arabian sea to the west.

Fault-bounded basement uplifts along incipient rift belts within continental blocks shed arkosic sands mainly into adjacent linear troughs (Dickinson, 1985; Dickinson and Suczek, 1979). These authors have demonstrated that in such a tectonic setting, a spectrum of lithic poor quartzo-feldspathic sands forms a roughly linear array on Qt-F-L and Qm-F-Lt plots linking these arkosic sands with the craton derived quartzose sands that plot near the Qt and Qm poles. However the Qm-F-Lt plot of Wadhwan sandstones (Fig. 6B) shows that the points are mostly located on the Qm-Lt leg of the diagram and lie in the transition zone between the fields of continental block provenances and recycled orogen provenances. The basement uplifts may shed sands having affinity with detritus derived from recycled orogens provided erosion has been insufficient to remove cover rocks from basement (Mack, 1984). This may explain the false signatures of recycled orogen provenance in the case of the Wadhwan sandstones.

From the foregoing discussion, we can now construct a plate-tectonic model for the tectonic setting of the Lower Cretaceous Saurashtra basin during the deposition of the Wadhwan sandstones. An incipient rift developed within the Precambrian Aravalli continental block. The metasedimentary and granite rocks of the Aravalli craton were deeply weathered under the warm and humid climate during Lower Cretaceous. Thus most of the labile constituents of the source rocks were destroyed by weathering, and quartz rich detritus was shed into the Saurashtra rift. The sandstone was further enriched in the shallow marine depositional environment as a result of destruction of labile grains at the sediment water interface.

CONCLUSIONS

Analysis of the various factors influencing the detrital mineralogy of the Wadhwan sandstones and hence the provenance and petrofacies interpretation was carried out to arrive at a meaningful conclusion. The various factors examined included paleogeography, source rock composition, distance of transport, paleoclimate, depositional environments and diagenetic modifications.

The paleogeographic reconstruction of the Saurashtra rift suggests that the provenance of the sandstones was located towards northeast, in the Aravalli highlands, a few hundred kilometer from the study area. The Precambrian rocks of Delhi and Aravalli Supergroups identified as the provenance of the sandstones consist of mainly quartzites and phyllites which are intruded by granites. Detrital mineralogy of the Wadhwan sandstones matches the composition of the identified source rocks. The sandstones were mainly derived from metasedimentary rocks and granite-gneisses.

The Lower Cretaceous period was marked by warm and humid climate in the study area which was responsible for rigorous weathering of the Precambrian basement rocks in the provenance resulting in destruction of much of the feldspars and labile constituents. Paleoclimate was therefore a leading factor in the formation of highly quartzose sandstones of the Wadhwan Formation.

The sandstones are mainly texturally submature because they were deposited in rather protected environments of estuaries and embayments. The compositional maturity of the sandstones was increased by destruction of labile grains which remained at the sediment water interface for longer durations.

Diagenetic processes such as dissolution, replacement and compaction have brought about little modification of the original detrital constituents. Dissolution of feldspars has created about 2.0 percent of secondary porosity. The replacement of quartz grain by iron oxide and carbonate cement is only partial and localized. The grain to grain contacts of the sandstones indicate very little compaction.

The plate-tectonic setting and provenance of the sandstones were interpreted with the help of Dickinson's (1985) method of recognizing detrital modes and plotting them on Qt-F-L and Qm-F-Lt triangular diagrams. The detrital modes recognized and their average percentages are: Qm (91.6%); Qp (7.1%); K-feldspar (0.19%) and Ls (1.0%). The petrofacies analysis of the sandstones suggest continental block provenances with source on stable craton which has been recognized as the Aravalli craton. The continental block provenance that supplied detritus to the Saurashtra rift was deeply weathered. A low relief marked the continental block provenance permitting detritus a long residence time in soil. The fault-bounded basement uplifts along incipient rift belts within continental block are known to shed arkosic sands into adjacent linear troughs, but quartz-rich detritus was deposited into the Saurashtra rift because of warm and humid climate, low relief and long residence time in soil. The false signature of recycled orogen provenance in the case of Wadhwan sandstones may be attributed to insufficient erosion that failed to remove cover rocks from the basement.

ACKNOWLEDGEMENTS

This present study ia a modified version of a part of the M.Phil work of A.Z. Khan, supervised by K. Akhtar. The authors are grateful to Prof. S.N. Bhalla, Chairman, Department of Geology who provided facilities for research work.

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Manuscript received 7 July 1995