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Research Paper

Tectono-provenance and climatic setup for Maastrichtian Upper Sandstone (Lameta Formation) in Sagar sub-basin

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ABSTRACT
Infra-trappean siliciclastic unit of Lameta Formation in Sagar sub- basin were analysed for their petrographic attributes to determine the detrital components, systematic classification and precise description of rocks, provenance, tectonic history and climatic setup. The studied Sandstone unit are exposed as discrete patches below the Deccan lava flow at Shahpur (Railway line section), Magron and Gopalpura (Panchamnagar canal section) villages in Sagar district of Madhya Pradesh. Twenty seven representative uncontaminated Upper Sandstone samples were collected systematically and put into modal analysis under the polarizing microscope by Gazzi-Dickinson point count method. Detailed petrographic study indicate that the Upper Sandstone of Lameta Formation are fine to medium grained, sub-angular to sub-rounded, poorly to moderately sorted with fair amount of matrix. Modal analysis of detrital mineral components shows the presence of monocrystalline non-undulatory quartz grains over undulatory, polycrystalline and recrystallized quartz with insignificant amount of feldspar and rock fragments. Overall studies demonstrate that Upper Sandstone unit classified as quartz wacke to lithic wacke. Qt-F-L and Qm-F-Lt plots of detrital components indicate that sediments are mostly derived from the mixed source setting i.e. cratonic interior and recycled orogen setting. This unit is also characterized by the development of palaeosols due to the prolonged exposure for surface weathering and climate change.

***Keywords:* Lameta Formation, Upper sandstone, Tectono-provenance, Paleoclimate**

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I. Introduction

Siliciclastic sedimentary rocks are frequently employed to determine the pre-depositional historical events including provenance, tectonic setting and climatic setup of an area. Provenance study includes the distance and direction of transport, grain size and setting of the source region, climate and relief in the source area and the specific type of source rocks (Pettijohn et al., 1987). Certain parameters are generally taken into account to trace the tectono-provenance including the detrital mineralogy, heavy minerals along with the palaeocurrent analysis. Established provenance models of sedimentary rocks have been utilized to infer the mineralogical and chemical composition of sandstones (Ingersoll and Suczek, 1979; Dickinson and Suczek, 1979; Dickinson et al., 1983; Ghosh et al., 2016). Petrographic study helps in establishing relationship between composition of sandstone and tectonic setting apart from source rocks by incorporating detrital framework modes (Dickinson, 1970; Uddin & Lundberg, 1998). The petrographic data can be further incorporated to reconstruct the paleogeography, depositional systems and to describe the crust which is no longer exposed. Petrofacies can be defined as sandstone having similar composition in terms of detrital parameters such as Qt–F–L, Qm–F–Lt and Qm–P–K percentages and the ratio of different grain types (Dickinson and

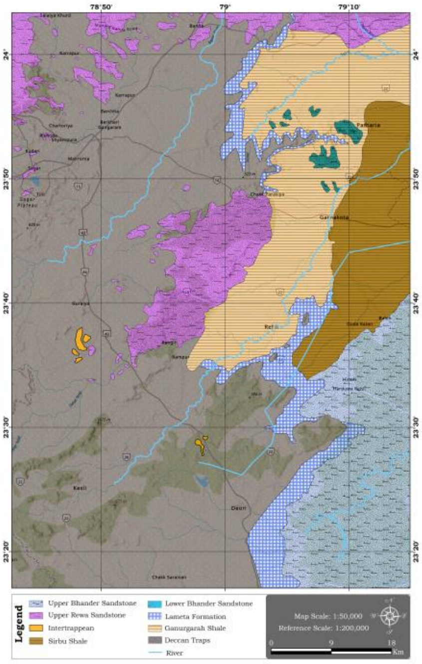

Figure 1: *Geological map of Lameta Formation in Sagar sub-basin, Madhya Pradesh (modified after K. Rajrajan, 1978).*

Rich, 1972). Sandstone petrofacies of various ages on a regional scale have been useful in interpreting geotectonic evolution of a sedimentary province (Dickinson et al., 1983; Cox & Lowe, 1995). The main hypothesis put forth for provenance investigation of sandstone is that every tectonic setting has its own unique rock type (Dickinson and Suczek, 1979; Dickinson, 1985), despite the fact that some mineralogical constituent can be influenced modifications. Maastrichtian infratrappean sediments in Upper Narmada valley are known for their significant variation in lithofacies and gives a wide range of depositional environment for their various depocenter in Central and Western India (Matley, 1921; Chanda, 1967; Singh, 1981; Brookfield and Sahni, 1987; Sahni and Khosla, 1994; Tandon et al., 1995, 1998; Tandon and Andrews, 2001; Shukla and Srivastava, 2008; Saha et al., 2010; Srivastava et al., 2015; Khosla, 2017). In Sagar sub-basin, scattered occurrence of these infratrappean sediments represented by a sequence of calcareous and arenaceous lithounits (Figure 1) are referred as Lameta Formation (Rajrajan K. 1978; Lunkad 1990; Tandon et al., 1995; Mankar and Srivastava, 2019). Underlying rocks are the Proterozoic sedimentary sequences of Vindhyan Supergroup which creates the accommodation space for the deposition of Lameta sediments, whereas in other depocenters Precambrian Gneiss and Upper Gondwana rocks forms the Basement complexes. In the present study tectono-provenance and paleoclimate of Lameta Sandstone have been established and no detailed work has been conducted previously on the analyses of detrital framework mineralogy of Upper sandstone of Lameta formation in Sagar sub-basin.

Table 1: *Lithostratigraphic division of Lameta Formation in Sagar sub-basin (modified by Singh G. et al., 2024 after K. Rajarajan, 1978).*

Age	Stratigraphic unit	Lithostratigraphy/Lithology
Late Cretaceous to Eocene	Deccan Traps	Basalt with Intertrappean sediments
Late Cretaceous (Maastrichtian)	**Lameta Formation**	**Upper Sandstone** **Upper Limestone** **Motteled Nodular Bed** **Lower Limestone**
-------------- Unconformity------------------		
Meso-Neo Proterozoic	Vindhyan Supergroup	Sandstones, Shale and Limestone
---------------Unconformity---------------------		
Palaeo-Proterozoic	Bijawar Group	
-----------------Non-conformity-------------------		
Archean	Bundelkhand Granite and Gneisses with Supracrustals enclaves	Granite, Gneiss, Schist, BIF and intrusives

II. General geology

Lameta Formation is considered as a significant stratigraphic unit chronicles the series of geological process occurred during Late Cretaceous period. It imprints the records of well-preserved dinosaur fossils, climate change and the great Deccan volcanic event (Sahni and Khosla, 1994). Lameta sediments developed along the Narmada river in a sporadic manner occupied some parts of East, West and Central India (Brookfield and Sahni, 1987; Tandon et al., 1990, 1995; Khosla and Sahni, 2000; Tandon and Andrews, 2001; Khosla, 2019). Geographically, six sedimentary basins were identified for the Lameta sedimentation (Mohabey, 1996a; Srivastava and Mankar, 2015a) and the categorization of different basin occurs locally based on their varying geographical position, lithological setup and paleontological characteristics. Sagar sub-basin is one of the depocenter for Lameta sedimentation where a thick sedimentary succession of carbonate and siliciclastic rocks deposited as isolated outcrops. Sagar district is situated along the southern periphery of Bundelkhand craton where the Maastrichtian infra-trappean sediments were developed over the Proterozoic sedimentary rocks of Vindhyan Supergroup. Infra-trappean sediments of this basin occurs as a massive strata of variable thickness ranges from a meter to several meters, eventually in Jhiraghat section thickness get to 75 meters (Lunkad, 1990). Stratigraphically, four lithounits of Lameta Formation have been recognized in the Sagar sub-basin are classified as Lower Limestone, Mottled Nodular bed, Upper Limestone and Upper sandstone. However, Outcrops of Upper Limestone unit is exposed only at Jhiraghat section in the south-eastern part of Sagar district and Green sandstone is not identified in the study area. A ferruginous, fine to medium grained, lensoidal unit of Upper Sandstone fringes the Deccan traps in the sections exposed at Shahpur (Figure 2), Magron and Gopalpura villages

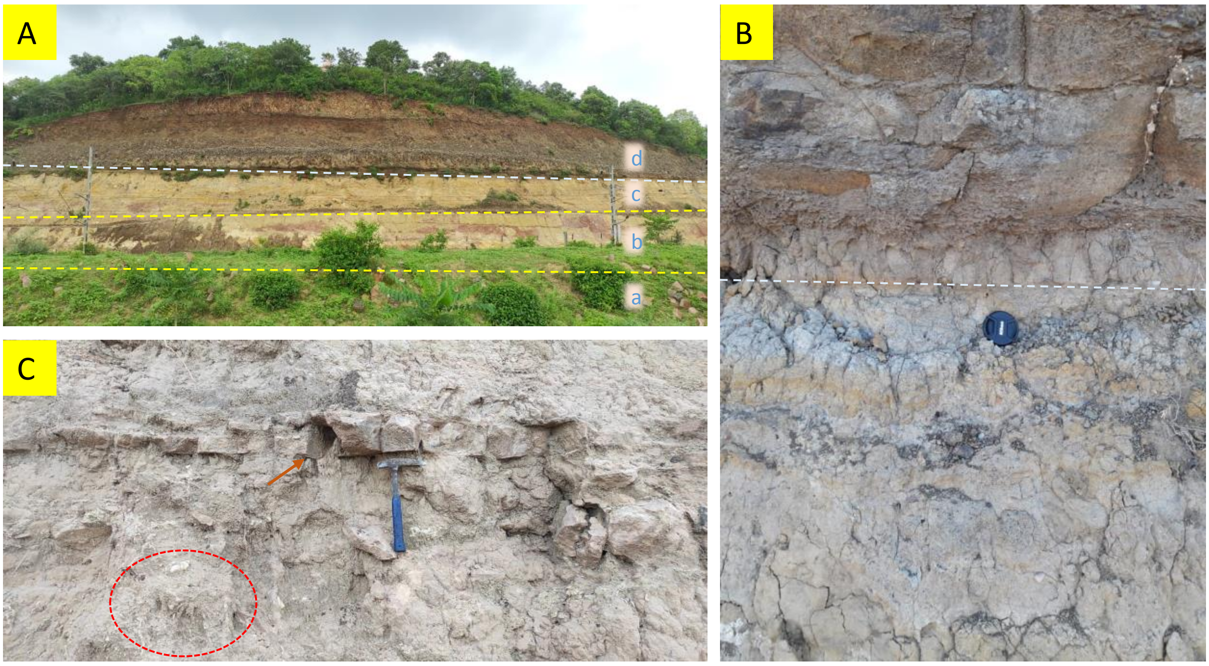

Figure 2: *Field photographs of Lameta Formation showing:* ***A)*** *Different lithounits of Lameta Formation marked by bottom to top (a-c), Lower Limestone (a), Mottled Nodular Bed (b), and Upper Sandstone (c) overlain by Deccan Trap (d) exposed along Shahpur railway cutting line, Sagar district;* ***B)*** *Contact between Upper Sandstone of Lameta Formation (bottom) and Deccan Trap (top) separated by white dotted line; and* ***C)*** *buff to pink colour massive Upper Sandstone unit indicates the bedding plane (red arrow), pedogenic modification and presence of root fossils (red dotted circle). Measurement of hammer (33cm).*

III. Methodology

The present study inquires the detrital mineralogy of Upper Sandstone of Lameta Formation exposed in Sagar sub-basin to unravel the tectono-provenance and climatic setup of the area. More than thirty five samples from two well defined exposures (Shahpur railway cutting, Magron and Gopalpura villages) were collected, out of which twenty seven best representative samples were further cut into standard petrographic sections. For quantitative analysis about 300-400 points per thin section were counted for determining the modal composition and other petrographic characters of the rock using Gazzi-Dickinson method (Gazzi, 1966; Dickinson, 1970; Ingersoll et al., 1984). The volume percent of different constituent grains i.e. quartz (Q), feldspar (F) and rock fragments (R) were calculated. For petrofacies analysis, counts for operational categories i.e. monocrystalline quartz (Qm), polycrystalline quartz (Qp), total quartzose grains (Qt), total feldspar content including the both plagioclase and K-feldspar (F), plagioclase feldspar (P), potassium feldspar (K), Lt and total unstable lithic fragments (L) as defined by Dickinson (1985) for a classic method for petrofacies analysis were performed and recalculated to 100 percent.

Table 2: *Percentage of framework mode of the Upper Sandstones of Lameta Formation, Sagar inland basin. Qt=Total quartz, F= Total feldspar, L= Unstable lithic fragments, Qm= Monocrystalline quartz, Lt= Total lithic fragments, Qp= Polycrystalline quartz, P= plagioclase, K= Orthoclase and microcline (Recalculated values).*

Sample No.	Qt	F	L	Qm	F	Lt	Qm	P	K
G2A	96.64	0	3.35	92.61	0	7.39	100	0	0
G2B	96.24	0	3.76	93.45	0	6.55	100	0	0
G3	96.58	0.45	2.96	94.31	0.45	5.24	99.52	0.29	0.19
G4	98.21	0.34	1.46	94.56	0.34	5.1	99.64	0.13	0.23
G5A	97.38	0.83	1.79	95.97	0.83	3.19	99.14	0.86	0
G5B	96.68	1.11	2.21	95	1.11	3.89	98.84	1.16	0
MA1	96.25	0.4	3.35	93.35	0.4	6.24	99.57	0.13	0.3
MA2	97.45	0	2.55	93.22	0	6.78	100	0	0
MA3	97.59	0	2.41	94.79	0	5.21	100	0	0
MA4	96.70	0.26	3.05	91.74	0.26	8	99.72	0.16	0.12
MA5	95.65	0.37	3.99	93	0.37	6.63	99.61	0	0.39
SHU1	95.47	2.05	2.55	89.45	2.05	8.5	97.76	0	2.24
SHU2	96.23	1.86	1.99	89.8	1.86	8.35	97.97	0.25	1.77
SHU3	98.38	0.23	1.39	94.11	0.23	5.65	99.75	0	0.25
SHU4	90.46	1.96	7.57	83.56	1.96	14.48	97.7	0	2.3

SHU5	98.95	0.54	0.53	90.59	0.54	8.87	99.4	0.3	0.3
SHU6	98.54	0.64	0.83	91.51	0.64	7.85	99.3	0.46	0.23
SHU7	98.67	0.97	0.38	94.37	0.97	4.66	98.98	0.41	0.61
SHU8	98.63	0.79	0.59	94.34	0.79	4.87	99.17	0.43	0.4
US1	100	0	0	97.01	0	2.99	100	0	0
US2	99.74	0	0.26	97.33	0	2.67	100	0	0
US3	97.87	1.26	0.88	95.29	1.26	3.45	98.69	0	1.31
US4	97.62	1.75	0.68	93.98	1.75	4.28	98.18	0.44	1.38
US5	99.49	0.51	0	94.56	0.51	4.93	99.46	0.54	0
US6	99.79	0	0.2	96.14	0	3.86	100	0	0
US7	98.06	1.42	0.55	96.32	1.42	2.27	98.55	0	1.45
US8	99.04	0.49	0.48	94.66	0.49	4.85	99.49	0	0.51
US9	99.77	0	0.23	95.14	0	4.86	100	0	0
Average	97.57	0.65	1.78	93.58	0.65	5.77	99.30	0.20	0.50
Minimum	90.46	0	0	83.56	0	2.27	97.7	0	0
Maximum	100	2.05	7.57	97.33	2.05	14.48	100	1.16	2.3

IV. Result and Discussion

4.1 Petrographic observations

Siliciclastic unit of Lameta Formation has been examined for their detrital framework mineralogy, matrix, cement and other diagenetic parameters. Petrographic studies of Upper Sandstone shows the presence of detrital quartz grains as main constituting material followed by the subordinate amount of rock fragments, feldspar, chert, mica and opaque minerals. Shape and size distribution of grains indicates the sandstone are mostly fine to medium grained, subangular to subrounded and poorly to moderately sorted. Intergranular spaces are filled by mostly siliceous cement (Figure 3D) together with ferruginous, siliceous and argillaceous matrix (around 18-20%). However, proportion of detrital matrix not exceeding this value in the sandstone samples. Textural attributes suggests the sub-mature to mature nature of sandstone. Quantitative measurements of framework grains shows the abundance of non-undulatory quartz ranging from 57.94% to 86.44% (averaging 72.16%) and undulatory monocrystalline quartz ranging from 5.08% to 33.18% (averaging 18.73%), polycrystalline quartz ranging from 0.83% to 7.96% (averaging 3.78%). Lithic fragments are the second most abundant grains in the sandstone includes detrital grains of chert, sandstone, shale and quartzite, with the value 0% to 7.4% (averaging 1.77%). Feldspar grains shows the presence of both fine grained, subangular to subrounded weathered K-feldspar (averaging 1.98%) and plagioclase feldspar (averaging 1.11%). Mica flakes are rarely seen except for some samples (averaging 0.05%).

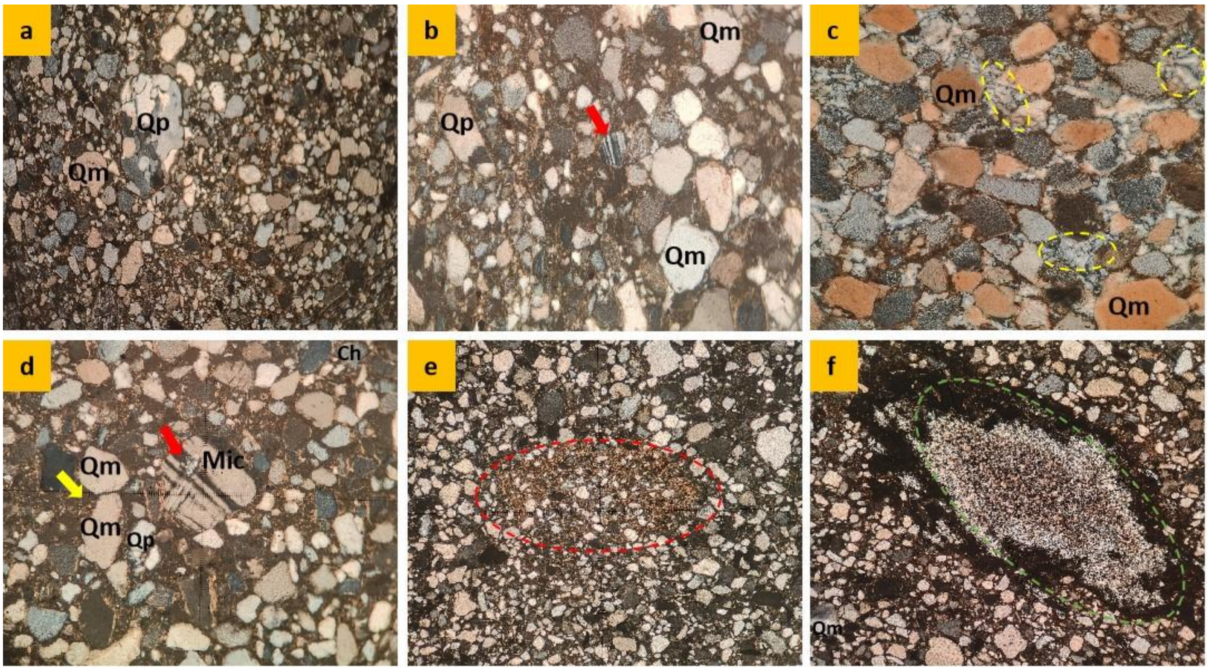

Figure 3: *Photomicrographs of Upper Sandstone of Lameta Formation under cross-polarized light (5x) showing:* ***a)*** *monocrystalline quartz grain with undulose extinction (Qm) and polycrystalline quartz grain displaying bimodal size distribution of sub-crystals with sutured intercrystalline boundaries (Qp);* ***b)*** *Unaltered medium grained plagioclase feldspar in quartz rich sandstone (red arrow);* ***c)*** *precipitation of silica cement (chalcedony) in intergranular spaces as shown by yellow dotted circle;* ***d)*** *detrital microcline (Mic),*

monocrystalline quartz (Qm), polycrystalline quartz (Qp) and chert (Ch) grains embedded in ferruginous argillaceous matrix (yellow arrow), note the alteration of feldspar grain by silica cement (red arrow); ***e)*** *argillaceous rock fragment (red dotted circle) surrounded by Qm-Qp quartz grains; and* ***f)*** *pore space filled by secondary silica (microcrystalline quartz) as indicated by green dotted circle.*

4.2 Sandstone classification

Textural and mineralogical parameters together are taken into account for the classification of sandstone (Dott's, 1964). Framework minerals including quartz, feldspar and rock fragments in addition to fine grained detrital minerals (<30µm) formed during diagenetic modifications or introduced by other process are also used to categorize the sandstone. Dott's (1964) classification provides great insights for the provenance studies and nomenclature of the rock based on the modal composition and matrix percentage. The Upper Sandstone unit exposed in the study area restricts in quartz wacke to lithic wacke field (Figure 4) based on Dott's (1964) scheme of classifications.

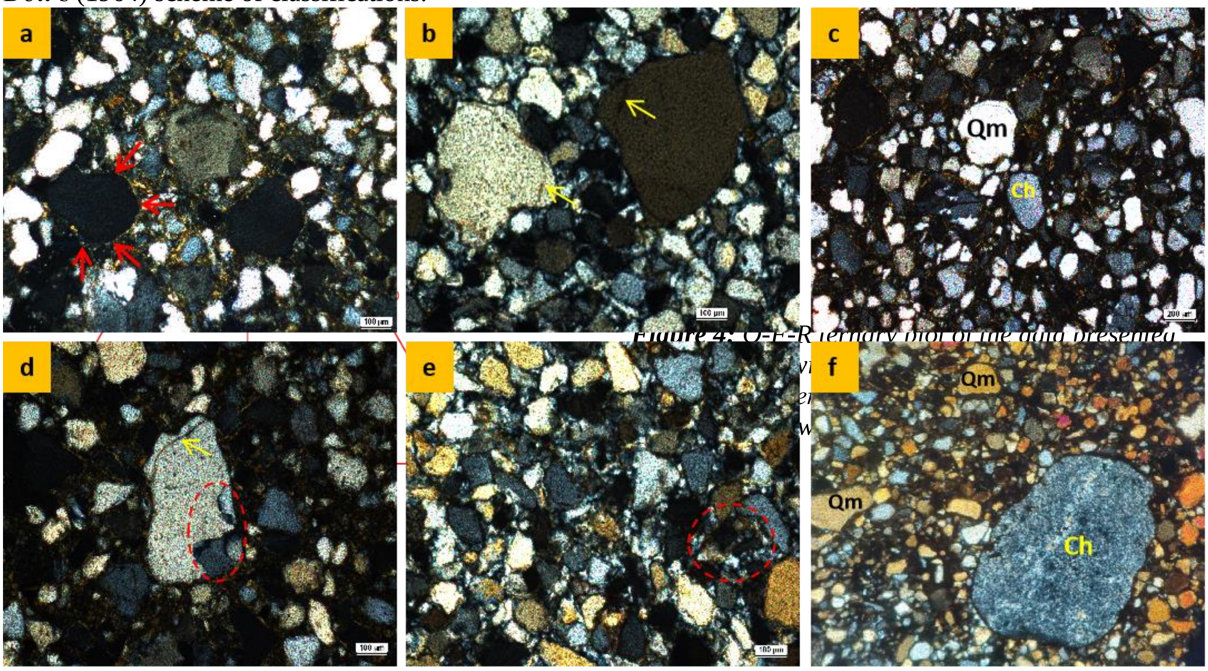

Figure 5: *Photomicrographs of Upper Sandstone of Lameta Formation under cross-polarized light exhibiting:* ***a)*** *pore lining clays (red arrows) enveloping detrital quartz grains;* ***b)*** *syntaxial silica overgrowth (yellow arrows);* ***c)*** *monocrystalline quartz (Qm) grains are fine to medium grained, subangular to subrounded, poorly to moderately sorted nature of sandstone with chert grain (Ch);* ***d)*** *dissolution along grain boundary (red dotted circle) and silica overgrowth (yellow arrow);* ***e)*** *quartz grain corroded by ferruginous cement (red dotted circle); and* ***f)*** *presence of subrounded to rounded chert grain (Ch) as lithic fragment surrounded by monocrystalline quartz grains (Qm).*

4.3 Provenance and Tectonic setting

Tectono-provenance studies of siliciclastic rocks predicted on the theory that various tectonic setting have their distinguishing rock type (Dickinson W. R., 1985). Framework mineralogy of the sandstone are the product of interplay between source rock composition, plate tectonic setting, climate and time (Pettijohn, 1987). Provenance studies mostly consider the detrital framework grains to discriminate the various tectonic setting because the nature of cement and proportion of matrix controlled by the diagenetic process (Dickinson, 1970). Petrographic attributes consists of framework grains i.e. Qt, Qm, Qp, K, P, L, Lt are quantified and normalized to produce petrofacies data using method provided by Ingersoll and Suczek (1979) and Dickinson (1985). Petrofacies data were plotted in standard triangular diagrams given by Dickinson and Suczek (1979) i.e. Qt-F-L, Qm-F-Lt and Qm-P-K to elucidate the provenance and tectonic history of Lameta sandstone. In Qt-F-L diagram, most of the samples of the Upper sandstone restricted to continental block with the source near craton interior provenance indicates the prominence of quartz grains (both monocrystalline and polycrystalline quartz) over feldspar and lithic fragments (Figure 6A). Monocrystalline quartz, feldspar and lithic fragments (including polycrystalline quartz) were plotted together in Qm-F-Lt diagram distributed in the continental block and the merger field between recycled orogen and continental block setting (Figure 6B). In ternary plot of Qm-P-K diagram, all the sandstone samples flock together near the Qm pole but marginally shifted towards Qm-K field (Figure 6C). The distribution of framework minerals in Q-F-L and Q-F-Lt triangular diagrams indicates that the detrital grains were derived from the granite and Gneissic rocks deposited in stable cratonic areas concerted with siliciclastic sedimentary layers. Overall detrital mineralogy and petrofacies investigation put forward that Upper sandstone sediments of Lameta Formation derived from the ancient Bundelkhand craton composed of granite and gneissic rocks and from their associated siliciclastic sedimentary sequences of Vindhyan Supergroup with absence of any volcanic detritus.

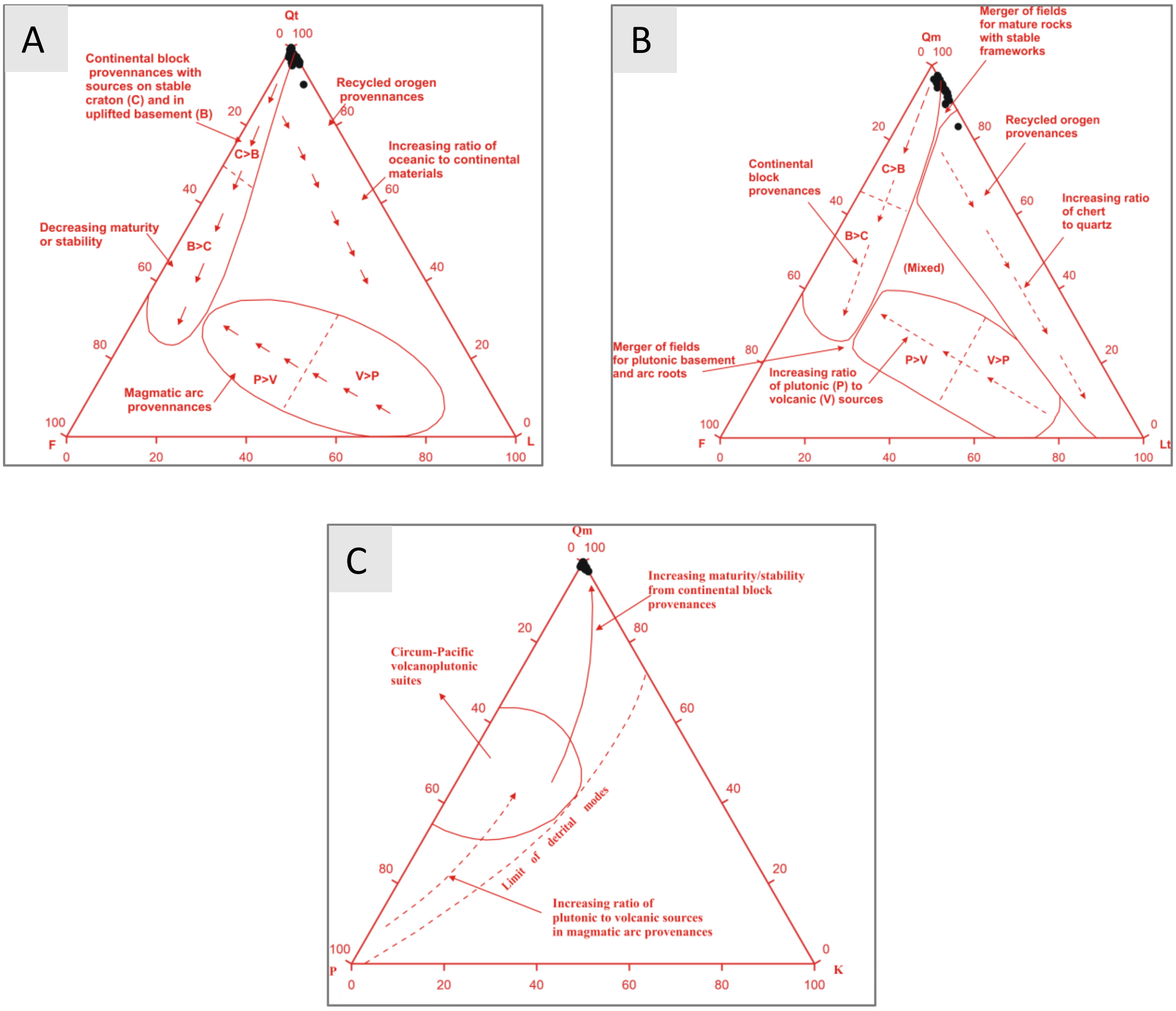

Figure 6: *Triangular **(A)** Qt-F-L, **(B)** Qm-F-Lt and **(C)** Qm-P-K plots showing mean framework modes for Upper Sandstone suites derived from different types of provenances after Dickinson and Suczek, 1979. (Data from Table: 2).*

4.4 Paleoclimate and Paleoweathering

Apart from provenance characters and tectonic setting of the source area, compositional maturity of clastic sedimentary rocks also controlled by the climate, weathering and transportation mechanism. Several authors have used detrital constituents of siliciclastic rocks to investigate the paleoclimate and paleoweathering process which influenced the mineralogical composition of sandstone (Dickinson and Suczek, 1979; Basu, 1985; Suttner and Dutta, 1986). The composition of sandstone and climate shows a close relationship (Suttner et al., 1981; Franzinelli & Potter, 1983; Mack, 1984; Stewart, 1991). The change in parent rock composition of sandstone resulted due to weathering, particularly chemical weathering, which breakdowns as well as modifies the primary composition of rock (Nesbitt & Young, 1982, Velbel & Saad, 1991). The present paper involves the petrofacies stu of Upper Sandstone to determine the ratio of total quartz to feldspar and lithic grains (Qt/F+R) and polycrystalline quartz to feldspar and lithic grains (Qp/F+R), plotted in log/log bivariate plot paleoclimate diagram (Suttner & Dutta, 1986) to reconstruct the climatic condition which affected the sediments of Upper Sandstone unit of Lameta Formation. The plots enables to differentiate between four climates, viz. arid, semi-arid, semi-humid and humid, depicting a humid environment for the area (Figure: 7A). The interpretation of humid climate also demonstrated by the Ansari (2008) in his study for the tectono-provenance and climate condition of Lameta sandstone of Jabalpur basin. Provenance and tectonic setting classification of sandstone

using modal composition and petrofacies analysis not always be consistent because detrital mineralogy is also affected by the weathering and climate condition of source area (Ingersoll R. V., 1984). Residence time of a sediment is a reflection of relief of an area. A low relief increases the residence time of sediments thereby destroying the original composition leaving quartz behind, which ultimately
makes the rock rich in quartz percentage. Presence of hot and humid climate enhances this process. The bivariate log/log plot of Weltje et al., 1994 shows samples mostly falls under field number 4, thereby suggesting sedimentation in low plain and tropical humid climate (Figure: 7B). The relatively high abundance of stable quartz grains and comparatively low abundance of Feldspar and lithic grains suggest the moderate to intense weathering and reworking of detritus in the source area.

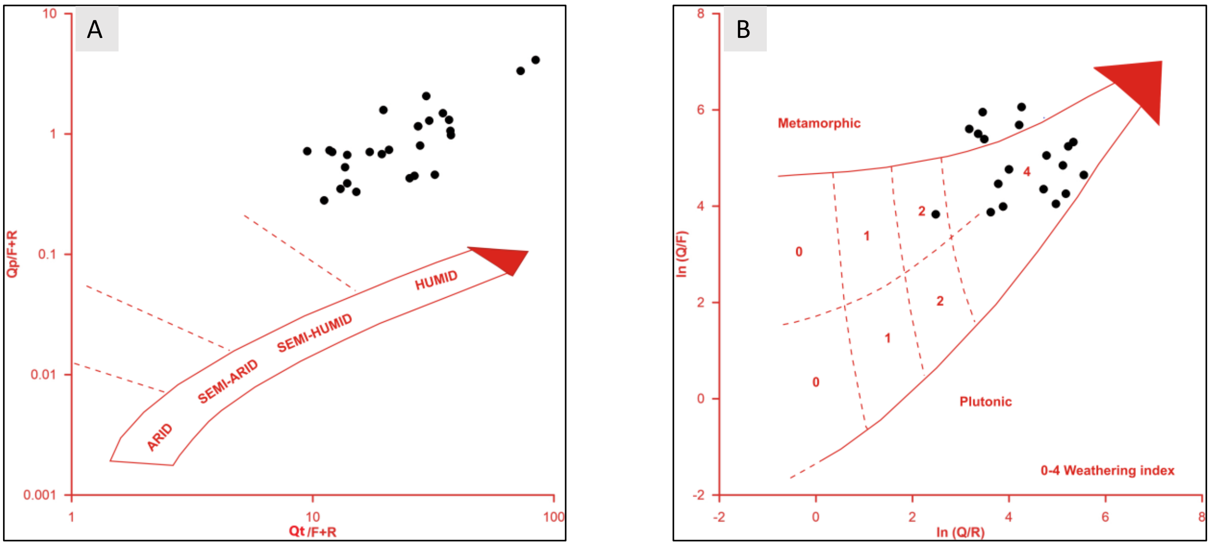

Figure 7: *showing* ***(A)*** *Bivariate log/log plot for Upper Sandstone (after Suttner and Dutta, 1986);* ***(B)*** *Log ratio plot (after Weltje et al., 1994). F: feldspar; Q: quartz; R: rock fragments. Field 1–4 refer to the semi-quantitative weathering indices declined on the basis of relief and climate as indicated in the Table 3.*

Table 3: *Semi-quantitative weathering index data*

Semi-quantitative weathering index (W= c*r) Weltje, 1994			Physiography (Relief) High (Mountain) 0	Moderate (Hill) 1	Low (Plains) 2
Climate (Precipitation)	Semi-arid and Mediterranean	0	0	0	0
	Temperate sub-humid	1	0	1	2
	Tropical humid	2	0	2	4

V. Conclusion

The Upper Sandstone are generally fine to medium grained, sub-angular to sub-rounded, poorly to moderately sorted with modest amount of detrital matrix (18-20%), indicated that the fluvial process may responsible to produce texturally immature to sub-mature sediments. According to Dott's (1964) sandstone classification, the siliciclastic unit of Lameta Formation classified as quartz wacke to lithic wacke. The standard Qt-F-L ternary diagram of provenance classification affirm the continental block setting with source near craton interior and recycled orogen setting for Upper Sandstone supplemented by Qm-F-Lt diagram, where sediments deposited in platform basin. The Upper sandstone samples plotted in the merger of continental block and recycled orogen field for mature rocks and stable framework exhibits majority of the sedimentary detritus are multicyclic sands of cratonic origin recycled through platform succession (Dickinson and Suczek, 1979. High quartz content and predominance of K-feldspar over plagioclase in Qm-P-K diagram shows intense weathering on craton with low relief and transport across continental surface (Dickinson & Suczek, 1979). It has been concluded that Upper Sandstone sediments of Lameta Formation are mostly derived from the granite and gneissic rocks of Bundelkhand craton and recycled through the associated platform sedimentary succession of Vindhyan Supergroup exposed in the study area with some influence of other sources. A large depositional gap between Proterozoic Vindhyan sedimentary rocks and Late Cretaceous Lameta Formation in Sagar sub-basin indicates the source sediments undergoes the longer reworking and recycling process. Weathering indices in conjunction with climate interpretation diagrams reveals that source rock sediments experienced significant chemical weathering under warm and tropical humid climate (Weltje et al., 1994) resulting in destruction of most of the feldspar grains.

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