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Tectonic setting of Kaladgi-Badami basin and its possible connection with adjacent Proterozoic basins, Karnataka, India

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ABSTRACT

Sedimentary rock types and basin geometries are interrelated with characteristic tectonic settings. In fact, sedimentation pattern at central stable cratonic areas are not same as that on continental margins. Kaladgi-Badami (KB) basinal feldspathic arenite (i.e., arkose) dominated rocks contain more plagioclase than potassium feldspar unlike the opposite scenario of Phanerozoic sandstones. Tectonic history of the KB basin has been interpreted since basin development, sedimentation through interrupting hiatus, tectonic reworking, redeposition at later developed depocenters and later exhumation, erosion, tectonism till Deccan volcanism and finally latest configuration. As per the International commission of Stratigraphy (ICS), principles of stratigraphic classification and usages of terminology of fundamental lithostratigraphic unit 'Formation' is reexamined in this paper. The definition of Formation as "smallest mappable rock unit with a definite lithologic characteristic that allow it to be distinguished from other such units" is improperly used because without mentioning a specific scale every unit is mappable or traceable. Therefore, the minimum mappable unit means the unit which can be at least visible in a scale in which entire basin can be seen. Based on this slight modification is proposed in the stratigraphy of KB basin. Geochronology based radiometric stratigraphy is best tool for determination of time sequence of geological events. However, it is always a matter of concern that dating methods and materials are often not suitable in sedimentary geology. In case of passive rifted sedimentary basins like Kaladgi, Badami and Bhima of the Dharwar Craton, there is negligible igneous events and indirect dating methods are mostly available. Detrital zircon dating can give maximum age or provenance age, which cannot be of much use. However, there are other indirect tools, which are already utilized by several workers earlier and based on the reviews and present observation and mapping compilation it is proposed that KB and Bhima basins used to be a single basin, and later tectonism followed by Deccan volcanism affected the present geographic continuity. Since the distance between westernmost Bhima basinal rocks and easternmost KB basinal rocks near Mudhebihal is nearly around 15km, it is logical to consider that these were geographically connected, because there is an intense faulting near to these basin margins.

KEY WORDS: Kaladgi-Badami basin, Bhima basin, Tectonic setting, stratigraphy, Karnataka.

INTRODUCTION

Cratonic basins are characterized by their typical shallow (up to a few km thick sediments at max) and bowl-shaped basins with continental granitoid-greenstone belts as basement rocks. The sedimentary units get thickened gradually toward the center of the basin (Prothero and Schwab, 2014). Kaladgi-Badami (KB) basin is one of the major Proterozoic basins in the Dharwar Craton (DC) (Fig 1). KB basin is a tectonically affected Proterozoic sediment depocenter with long geological history ranges from ~1.86 Ga (lower part i.e., Bagalkot Group) to ~0.8Ga (upper part i.e., Badami Group) (Joy et al., 2019). Basinal sedimentary rocks cover about 8,300 km^2 areas. Typical discontinuous patchy occurrences of sedimentary rocks are characteristic of this basin.

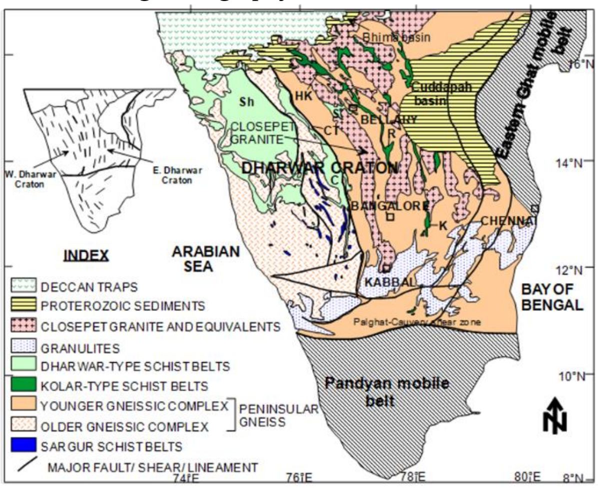


Fig 1. Geological map of Southern India shows the Dharwar Craton (DC) and adjacent units, Proterozoic basins and mobile belts (after GSI, 1994).

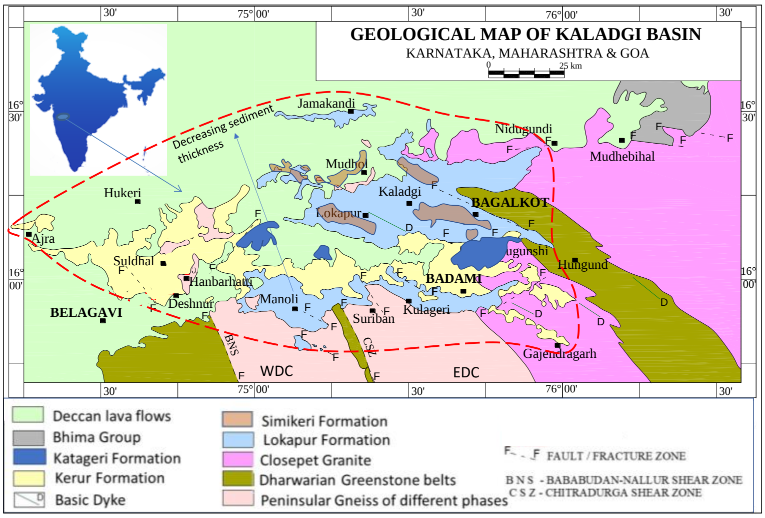


Fig 2. Geological map of Kaladgi-Badami basin (after Jaya Prakash et al., 1987).

The sedimentary patches are spreaded over a cumulative area of ~14000km^2 (i.e., ~175km along E-W and ~80km along N-S). In the southern part near Gajendragarh, Suriban and Manoli area, outliers of Kaladgi Supergroup are observed on basement (Fig 2). On the other hand, possibility of continuation of sediments below the Deccan Trap is very high at least up to Jamakandi area in the northern extreme, where inlier of Kaladgi Supergroup is found to be surrounded by Deccan trap. Similarly, in the western extreme near Ajra area inlier is present. The sub-trappean sediments were well confirmed by heliborne time domain electromagnetic data analysis (Sridhar et al., 2017). The easternmost extension is defined by the midway between Tugunshi and Hungund areas (Fig 2). The continuous geographic basin margin is affected by tectonism, differential weathering-erosion and Deccan volcanism. However, after connecting surface outcrops of sedimentary rocks from northern, southern, eastern and western extreme, it is possible to demarcate an approximate sub-elliptical outline of the basin. Most interestingly, this basin lies over both of the so called Eastern Dharwar Craton (EDC) and Western Dharwar Craton (WDC). The Suture Zone between EDC and WDC called Chitradurga Suture Zone (CSZ) passes below the basin. From the basic fundamental geology, term like “inter cratonic basin” is not so far introduced. Moreover, two cratons are usually separated by mobile belts in between. There is no such mobile belt between EDC and WDC. Therefore, as par the Goswami et al. (2023) EDC and WDC are not separate cratons but these are parts of same craton with slightly different geological development and evolution timing. Hence Kaladgi is intra Dharwar cratonic basin.

In this paper we review the entire tectonic history of the Kaladgi-Badami basin from relief difference creation and basin development through long lasting sedimentation and tectonic interaction to post diagenesis exhumation and volcanism. Therefore, as per geological time scale this review compiles major tectonic imprints of late Archaean to early Tertiary time frame.

GEOLOGY OF KALADGI-BADAMI BASIN

According to the latest stratigraphic column after Jaya Prakash et al. (1987), Kaladgi Supergroup is divided into older Bagalkot Group

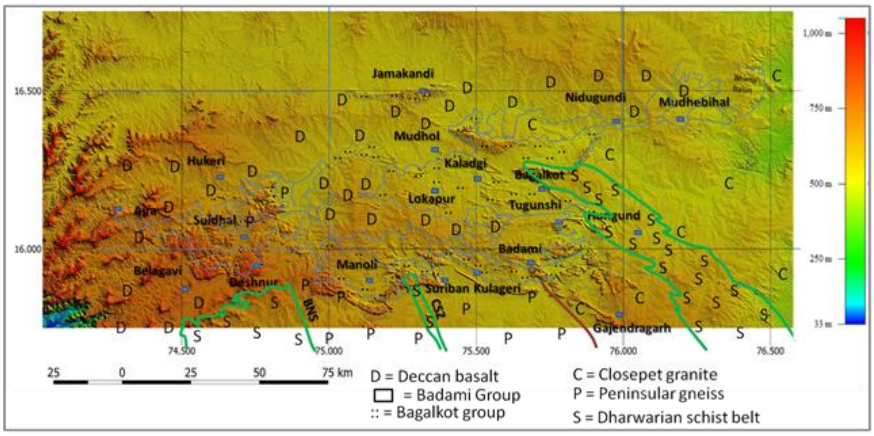
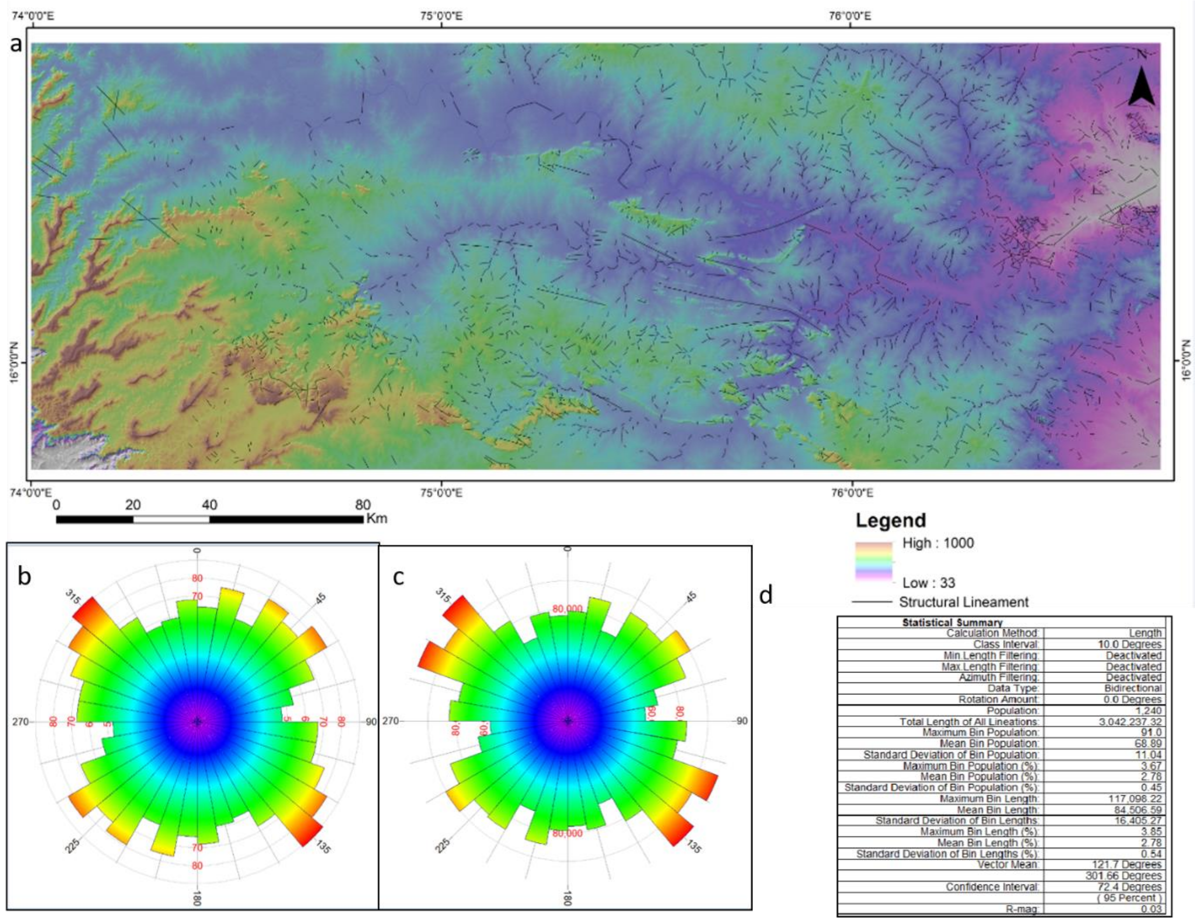


Fig 3. Digital Elevation Map (DEM) of Kaladgi-Badami basin. Litho-contacts are drawn as per the map in Fig. 2.

and younger Badami Group. Further, each of the Groups is subdivided into several Sub-group, Formation and Members (Table 1). Generally, Bagalkot Group (consists of quartzite, shale and limestone with stromatolitic dolomite and chert breccias) is highly deformed and often tightly folded especially along the mid-axial region of the basin like Lokapur, Kaladgi areas. Badami Group is not deformed in general and comprises mostly horizontal to gently dipping feldspathic conglomerate, arenite shale and minor limestone. The Digital elevation map (DEM) of KB basin (Fig. 3) is presented to visualize the range of elevation from ~ 40m to ~ 950m. However, the average elevation inside the basin is ~ 800m in the west and ~ 450m in the east. Thus, a gentle easterly slope is recognizable within the basin. Since the sub-horizontal undeformed Badami Group is topmost unit (mostly occur about ~ 650-680m RL i.e., elevation), it is not available in the eastern part where average RL is less than 650m. Thus, as per the principle of horizontality and lateral continuity of strata, Badami cannot be expected as such. Hence lower unit, i.e., Bagalkot Group occurs in the central and eastern part. Regional structural lineament plot over DEM and frequency as well as length based rose diagrams suggest that NW-SE trend is the most frequent as well as most continuous in terms of length (Fig 4a-d). This is due to the Krishna river system with its tributaries like Malaprabha, Ghatprabha, and Ilkal rivers.



Statistical Summary	
Calculation Method:	Length
Class Interval:	10.0 Degrees
Min.Length Filtering:	Deactivated
Max.Length Filtering:	Deactivated
Azimuth Filtering:	Deactivated
Data Type:	Bidirectional
Rotation Amount:	0.0 Degrees
Population:	1,240
Total Length of All Lineations:	3,042,237.32
Maximum Bin Population:	91.0
Mean Bin Population:	68.89
Standard Deviation of Bin Population:	11.04
Maximum Bin Population (%):	3.67
Mean Bin Population (%):	2.78
Standard Deviation of Bin Population (%):	0.45
Maximum Bin Length:	117,098.22
Mean Bin Length:	84,506.59
Standard Deviation of Bin Lengths:	16,405.27
Maximum Bin Length (%):	3.85
Mean Bin Length (%):	2.78
Standard Deviation of Bin Lengths (%):	0.54
Vector Mean:	121.7 Degrees
	301.66 Degrees
Confidence Interval:	72.4 Degrees
	(95 Percent)
R-mag:	0.03

Fig 4. a). Regional structural lineament plot over DEM. b). Frequency based rose diagram for lineaments. c). length based rose diagram suggest that NW-SE trend is the most frequent as well as most continuous in terms of length. d). parameters for rose diagram.

Despite having established stratigraphy (Jaya Prakash et al., 1987) with minute details up to member level, the fundamental unit (i.e., Formation) fails to represent presently defined Formations because they are not as distinct and large enough to be mappable in the surface or traceable in the sub-surface in the basinal scale. In fact, if the geological map of entire Kaladgi basin is observed it is found that in the basinal scale there are only four mappable units. However, at present these four units are given different lithostratigraphic status viz., Lokapur Sub-group, Simikeri Sub-group, Kerur and Katageri Formation. Although the entire stratigraphy is correctly established, the units are required to be reassigned especially in Lower Group. Lokapur, Simikeri should be kept under Formation. Any lithostratigraphic unit is mappable or traceable depending up on the scale. However, when fundamental lithostratigraphic unit (i.e., Formation) is defined it must represent the minimum mappable or traceable unit in a scale in which entire basin is covered. Thus, Kaladgi Supergroup comprises two groups viz., Bagalkot and Badami. Further, Bagalkot Group comprises Lokapur and Simikeri Formations. Badami Group is already properly assigned to comprise Kerur and Katageri Formations. The existing Formations like Ramdurg, Malaprabha, Yargatti, Yendigere, Muddapur, Yadhalli, Kundargi, Arlikatti and Hoskatti are actually Members, which comprises different marker beds of variable thickness (i.e., existing Members of Bagalkot Group are actually Beds). It is beyond any doubt that presently proposed revised stratigraphy (Table 2) is more

Table 1. Stratigraphy of Kaladgi-Badami basin (after Jaya Prakash et al., 1987)

	Group	Sub Group	Formation	Member	Thickness (m)
KALADGI SUPER GROUP	Badami Group	-	Katageri Formation	Konkankoppa Limestone	**85**
				Halkurki Shale	**67**
			Kerur Formation	Belikhindi Arenite	**39**
				Halgeri Shale	**3**
				Cave – Temple Arenite	**89**
				Kendur Conglomerate	**3**
	Angular Unconformity				
	Bagalkot Group	Simikeri Sub-group	Hoskatti Formation	MallapurIntrusives	**7**
				Dadanhatti Argillites	**695**
			Arlikatti Formation	Lakshanhatti Dolomites	**87**
				Kerkalmatti Haematite schist	**42**
				Niralkeri Chert Breccia	**39**
			Kundargi Formation	Govindkoppa Argillite	**80**
				Muchkundi Quartzite	**182**
				Bevinmatti Conglomerate	**15**
		Disconformity			
		Lokapur Sub-group	Yadhalli Formation	Argillite	**58**
			Muddapur Formation	Bamanbundi Dolomite	**402**
				Petlur Limestone	**121**
				Jalikatti Argillite	**43**
			Yendigeri Formation	Nagnur Dolomite	**93**
				Chikkashellikeri Limestone	**883**
				Hebbal Argillite	**166**
			Yaragatti Formation	Chitrabhanukot Dolomite	**218**
				Muttalgeri Argillite	**502**
				Mahakut Chert Breccia	**133**
			Ramadurg Formation	Manoli Argillite	**61**
				Saundatti Quartzite	**383**
				Salgundi Conglomerate	**31**
		Non-conformity			
		Granitoids, Gneisses and Metasedimentary rocks			

comprehensive, representative and coherent as per the definition. Due to the fluvio-marine transitional environment for sedimentation with cyclic transgression and regression events, simple lithostratigraphic correlation is not easy in this setting. The present problem with lithostratigraphic approach is due to the fact that the contacts between different lithofacies (lithostratigraphic unit) are diachronous, i.e., same litho-unit occur at different time at different parts of the basin. Hence strict lithological interpretation must be done with concept of sequence stratigraphy, which help in correlating coeval units, which may be of different lithology but formed at same time in different parts of the basin (Fig. 5).

Geological setting of KB basin is represented with a simple schematic model (Fig. 6) for better visualization. Basement complex comprises Tonalite Trondhjemite Granodiorite (TTG) i.e., Peninsular Gneissic Complex (PGC), Greenstone belt i.e., Hungund Schist Belt (HSB) and granite plutons i.e., Closepet granite (CG). Initially developed accommodation space was occupied by the Bagalkot Group of rocks, which got folded and tectonically affected by subsequent orogeny associated deformation events. During the later tectonics and non-deposition or hiatus period some dyke was intruded and then newly created accommodation space become depocenter of Badami Group above the angular unconformity plane. Later uplift, exhumation and faulting followed by Deccan volcanism gives present

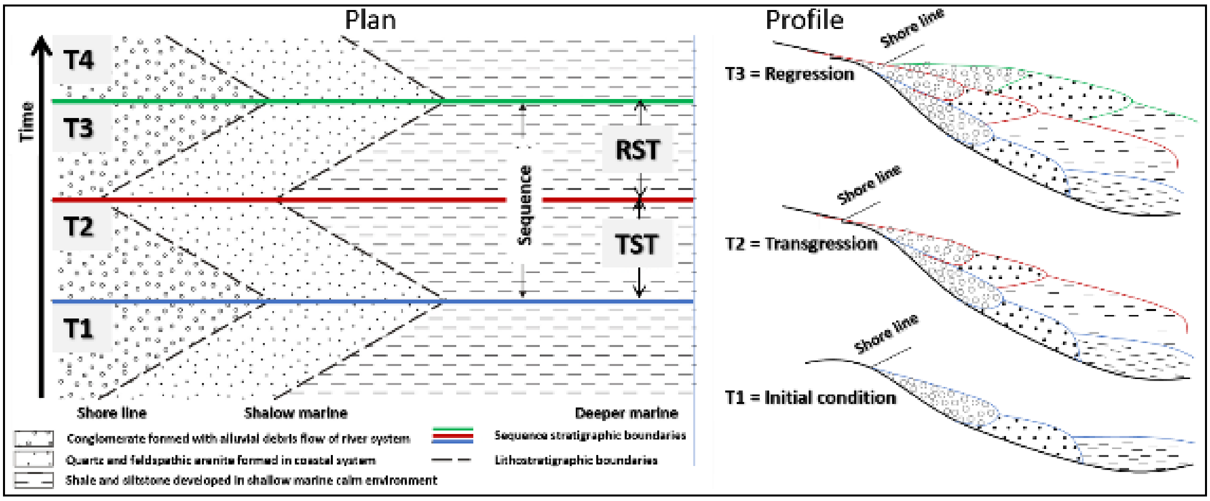


Fig 5. Diagram prepared to show the difference between sequence stratigraphy and lithostratigraphic concept. The dashed lines in the plan indicate lithocontacts without any time significance but the solid lines (blue, maroon and green) are sequence boundaries, which indicate a particular event at particular time. This can be understood from profile view of fluvio-marine (alluvial fan coast setting) environment of epeiric sea setting as observed in present area. During T1 profile across shoreline show progressive change in lithology from shallow to deeper part. After marine transgression during T2 followed by regression during T3, the depocenter of different lithounit changes. Therefore, simple lateral correlation of same lithounit cannot give any additional information, rather sequence boundaries (implying a particular episode, i.e, time line) are more meaningful. Hence, instead of lithology, it is better to use systems tract to describe a particular event. For example, the combined lithounit of T2 will be transgressive systems tract (TST) and similarly for T2 it will be regressive systems tract (RST). A complete cycle of regression and transgression form a sequence, which comprises several small episodes called systems tract e.g., transgressive systems tract (TST), high stand (HST) and low stand systems tract (LST) and falling stage systems tract (FSST).

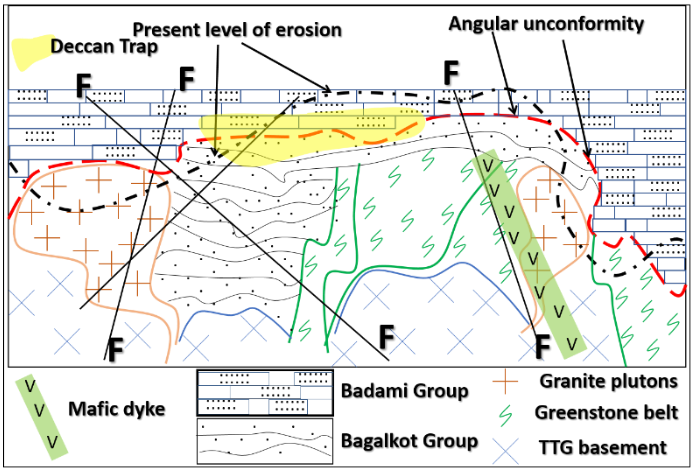


Fig 6. Comprehensive diagram section (not to scale) representative of geological disposition of different units.

geological configuration of the KB basin. Sedimentary rocks are dominated by feldspathic arenite to arkosic with plagioclase as more common than K-feldspar clasts. This is just like typical Precambrian arenites unlike Phanerozoic sandstones.

TECTONICS RELATED TO KB BASIN CREATION

According to Joy et al. (2019), 1,861 ± 4 Ma U–Pb baddeleyite age of dolerite dyke intruding the lowermost part of Kaladgi Supergroup indicate minimum age of the basin. This age is closely supporting the late Paleoproterozoic age (Sharma and Pandey, 2012) based on bio-stratigraphic marker stromatolites. Further, shales from Bagalkot Group in the lower stratigraphic part of basin indicated 1,800 ± 100 Ma of Rb–Sr isotopic ages with respect to chondritic Earth model (CHUR) (Padmakumari et al., 1998). Considering all these works it is safely predictable that the basin development is related to late Archaean Trans Hudsonian Orogeny (THO) during about 2Ga ago, which is related to development of a supercontinent called Columbia. This supercontinent is also known as Nuna or Hudsonland (Stauffer, 2006; Rogers and Santosh, 2002). During this time the amalgamation between south and north Indian cratonic blocks along the Central Indian Tectonic Zone (CITZ) causing northerly tilt of Dharwar cratonic block for about

1.9^0 angle (Goswami et al., 2023). This tilting event was also related to contemporaneous obduction of Dharwar cratonic block in the southern part along the Palghat Cauvery Suture Zone (PCSZ). Due to this block tilting southern part was uplifted and northern part were submerged to form depression in the form of proto basin. The deeper high-grade rocks were exhumed due to erosion in the southern part and the eroded materials were accommodated in the newly created KB basin. The Archaean basement of KB basin comprises Peninsular Gneissic Complex (PGC), Hungund Schist Belt (HSB) and Closepet granite (CG).

Post sedimentation deformation as well as volcanism imprints are directly visible from map and manifestations are already extensively studied by several authors (e.g., Awati and Kalaswad, 1978; Jadhav, 1987; Nair and Raju, 1987; Pillai and Kale, 2011; Mukherjee et al., 2016; Pillai et al., 2018). Detail studies on multistage deformation mechanism in basement along with the Bagalkot Group of sedimentary rocks by Mukherjee et al. (2016) give significant insights in this context and

Table 2. Revised Stratigraphy of KB basin (proposed in this work)

	Group	Formation	Member	Thickness (m)	Depositional environment
KALADGI SUPERGROUP	Badami Group	Katageri Formation	Konkankoppa Limestone	**85**	Dominantly fluvio-lacustrine deposit (**Jaya Prakash 2007; Mukhopadhyay et al. 2013**). Evidenced minor transgression-regression cycle
			Halkurki Shale	**67**	
		Kerur Formation	Belikhindi Arenite	**39**	
			Halgeri Shale	**3**	
			Cave – Temple Arenite	**89**	
			Kendur Conglomerate	**3**	
	Angular Unconformity				
	Bagalkot Group	Simikeri Formation	*Mallapur Intrusives* **Hoskatti Member** Dadanhatti Argillite beds	**7** **695**	Terrestrial fluvial fan deposits overlain by high-energy beach deposits grading upwards to tidal flats **(Kale and Phansalkar 1991; Jaya Prakash 2007; Mukhopadhyay et al. 2013**).
			Arlikatti Member Lakshanhatti Dolomite beds, Kerkalmatti Haematite schist, Niralkeri Chert Breccia	 **87** **42** **39**	
			Kundargi Member Govindkoppa Argillite beds, Muchkundi Quartzite beds, Bevinmatti Conglomerate beds	 **80** **182** **15**	
		Disconformity			
		Lokapur Formation	**Yadhalli Argillite**	**58**	Transgressive deposits with fluvial sediments at the base followed by beach and intertidal suite and grades upward in to cycles of alternating carbonate and muddy tidal flat deposits **(Kale and Phansalkar 1991; Kale et al. 1996; Bose et al. 2008).** Regression initiate at the top.
			Muddapur Member Bamanbundi Dolomite beds, Petlur Limestone beds, Jalikatti Argillite beds	 **402** **121** **43**	
			Yendigeri member Nagnur Dolomite beds Chikkashellikeri Limestone beds Hebbal Argillite beds	 **93** **883** **166**	
			Yaragatti Member Chitrabhanukot Dolomite beds Muttalgeri Argillite beds Mahakut Chert Breccia	 **218** **502** **133**	
			Ramadurg Member Manoli Argillite beds, Saundatti Quartzite beds, Salgundi Conglomerate beds	 **61** **383** **31**	
		Non-conformity			
		Granitoids, Gneisses and Metasedimentary rocks			

also indicated about the initiation of younger Badami sub-basin creation.

CONTEMPORANEOUS SEDIMENTATION AND TECTONICS

Between Bagalkot and the overlying Badami Group there is a hiatus of ~1Ga. Thus, extensional and contractional domains of continuous single event deformation (Mukherjee et al., 2016) took place after Bagalkot sedimentation is pre Badami. Southerly-directed gravity gliding of the Bagalkot Group over nonconformity was related to a tectonic uplift of the basement as a consequence of Grenville orogeny. This Mesoproterozoic orogeny is related to the creation of new sub-basin for accommodating newer Badami sediments. Moreover, this globally known Grenville orogeny is also related to assembly of continents to form Supercontinent called Rodinia (Tollo et al., 2004). This is also supported by the 1154±4Ma age from $^{40}Ar/^{39}Ar$ dating of an intrusive mafic dyke emplaced along the axial plane of the fold in Bagalkot Group (Pillai et al., 2018).

KB SEDIMENT DEPOSITIONAL ENVIRONMENT

Average total thickness of Badami and Bagalkot Groups are ~286m and ~4241m respectively. Hence cumulative thickness is approximately about 4.55km. However, from the sub-surface exploratory drilling data of Atomic Minerals Directorate for Exploration and Research, India it is found that Badami Group comprises >400m sediment thickness with substantial lithofacies variation (Varshanay et al., 2022). The cyclic transgressive and regressive nature of sedimentation was explained to be near-shore, shallow marine condition with individual marker litho horizons indicative of fluvial, lagoonal, beach and littoral-tidal flat environments (Jaya Prakash et al., 1987; Kale and Phansalkar, 1991; Sathyanarayana, 1994; Kale et al., 1996; Bose et al., 2008; Dey et al., 2009; Dey, 2015).

BAGALKOT DEPOSITIONAL ENVIRONMENT

Present observation supports the view of (Bose et al., 2008) and based on distinguishable lithological attributes in this fluvio-marine set up sequence stratigraphic approach is essential with characterization of facies association with suitable scale. Sedimentation starts with a coarsening-upward fan succession in a low-stand systems tract (LST) which corresponds to approximate bottom part of Ramdurg Member. This followed by the fining-upward transgressive systems tract (TST) equivalent to the upper Ramdurg to upper Muddapur Member. There were minor fluctuating events within major systems tracts. After TST, high-stand systems tract (HST) is evidenced by Yadahalli Member. Subsequently, there was a regressive event lead to creation of apparent disconformity (i.e., sub aerial unconformity with correlative conformity) defined as falling stage systems tract (FSST). Next cycle again starts with another LST with conglomerate horizon in the bottom part of Kundargi member of Simikeri Formation. Here, LST and FSST are also called as normal and forced regression, respectively. This LST was again followed by TST (~ Arlikatti Member) and HST (~Hoskatti Member). After this HST basin completely filled up and further accommodation space could not be created. Thus, a break in sedimentation with prolonged non-deposition and erosion occur along with intrusive and tectonic events after diagenesis. As such there is no evidence of syn sedimentary tectonism during Bagalkot Group sedimentation. Detail facies studies are not made in this context as there are already numerous works done by sedimentologists of the country. Moreover, availability of subsurface drill cores would have given more insights. Since fresh cores of Badami Group are available the Badami Group has been studied in more details.

BADAMI DEPOSITIONAL ENVIRONMENT

The Kerur Formation occupies much larger areas than the overlying Katageri Formation. Dominance of SW directed palaeocurrent implies a braided fluvial system at the lowermost Kerur Formation and Katageri Formation is interpreted to be of fluvio-lacustrine origin (Jaya Prakash, 2007; Mukhopadhyay et al., 2013).

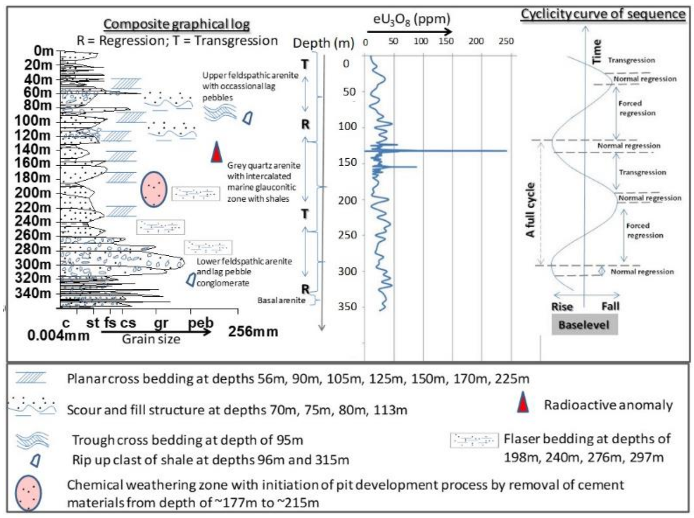


Fig 7. Composite litholog based on subsurface drill core suggests the lithofacies variation and changes in sequence with depth with uranium content variation.

Systematic sedimentary facies analysis is carried out from borehole core studies. Logging of vertical borehole cores for about 360m from entire Kerur Formation up to the basement unconformity contact suggests broadly 4 major lithofacies (e.g., 1. upper feldspathic arenite with lag pebble conglomerate, 2. grey quartz arenite, 3. lower feldspathic arenite with lag pebble conglomerate and 4. Basal arenite). These facies categorization is made based on distinguishable lithological attributes with sequence stratigraphic approach at uniform scale (Fig. 7). The basal sequence of coarse matrix supported fluvial conglomerate and feldspathic arenite starts above a thin shale indicate a regressive event, when the river enters much inside the shallow epeiric sea. However, for better and detailed understanding subdivision into sub-facies are also useful to describe the systems tract.
Following basis are standardized in the present study:

SCALE OF OBSERVATION:

It is very important to consider a practical and optimum useful scale in defining particular facies. Because microfacies are not at all relevant in studying about 360m depth ranges, presently macroscopic observations are taken into consideration. Thus, a thin shale lamina (~1mm or less thick) within consistent arenite (~100m) is not considered as separate facies in macroscale but that may be considered as separate facies in microscopic scale (if detailed study is performed). Thus, only selective portions can be studied for detailed facies analysis at microscale. For radioactive intervals especially for uranium exploration such detailed analysis may be taken up exclusively. Present context is not relevant to uranium related studies. For representing about 360m thick sedimentary column in a single sheet resolution cannot be less than 1m, which restricts depiction of thin unit (<1m) as separate unit/facies.

COLOUR, COMPOSITION AND FREQUENCY OF LITHO-UNITS:

These properties are given most importance in characterizing macro facies. There are certain zones where frequency of shale laminations is higher and often depending up on the composition and Eh-pH condition variation in colour is differentiable (such as greenish grey, purple, black, brick red etc). Grain size variation (ranging from clay to pebble) is well represented in this graphical log, in which entire spectrum from 0.004mm to 256mm is kept to easily demarcate the rock types visually at a glance.

PRIMARY SEDIMENTARY STRUCTURES:

This may not be always useful as fundamental criteria of facies classification from litho-core. However, primary sedimentary structures may often give useful information on depositional environments if accurate identification is made. For detailed analysis in understanding the depositional condition structures give valuable insights. For example, cross bedded sandstone may be differentiated from planar bedded sandstone. Shale can show typical tool marks or scour and fill structures at the top, cross bedded sandstone may be sub-divided into trough, hummocky, heringbone and planar tabular cross bedded facies. Presently we have studied only those structures clearly interpretable from core along with their significance. The studied litho-log represents a complete cycle and a partial cycle of sequence (Fig. 7), which starts with a regression when river went much inside the Epeiric Sea. Thus, thin marine shale is immediately overlain by conglomerate, which are not well sorted but matrix supported, sub-angular with moderate to low order sphericity. This implies about low transportation by debris flow from nearby highlands through small river channels into the inland sea. Presence of such conglomerates at different portions of the log suggest about its diachronous nature with variable timing and places of deposition as per the relative advancement and/or retreat of palaeo-shore line. Unlike present day rivers these rivers were of restricted length and such alluvial fan coast were common in Precambrian terrain along with shallow epeiric sea. After the regression transgression were initiated with sea level rise and marine encroachment and landward retreat of river mouth to give rise arenite facies with feldspar rich followed by feldspar poor quartz rich arenite and then heterolithic units of frequent shale bands. These rock types are implying a progressive transgression with characteristic sedimentary structures like wave ripples and associated cross stratifications of various types like tabular and trough. After this transgression another regression phase is identified from facies assemblage and significant structures. Thus, a complete sequence stratigraphic cycle is possible to visualize from a regression followed by transgression and again regression. After the regressive stage another incomplete transgression stage is preserved. This new sequence starts possibly with Belikhindi unit of feldspathic arenite in the log and cycle would have been completed after logging Katageri Formation. However, Katageri Formation is exposed at different areas (Fig. 2).

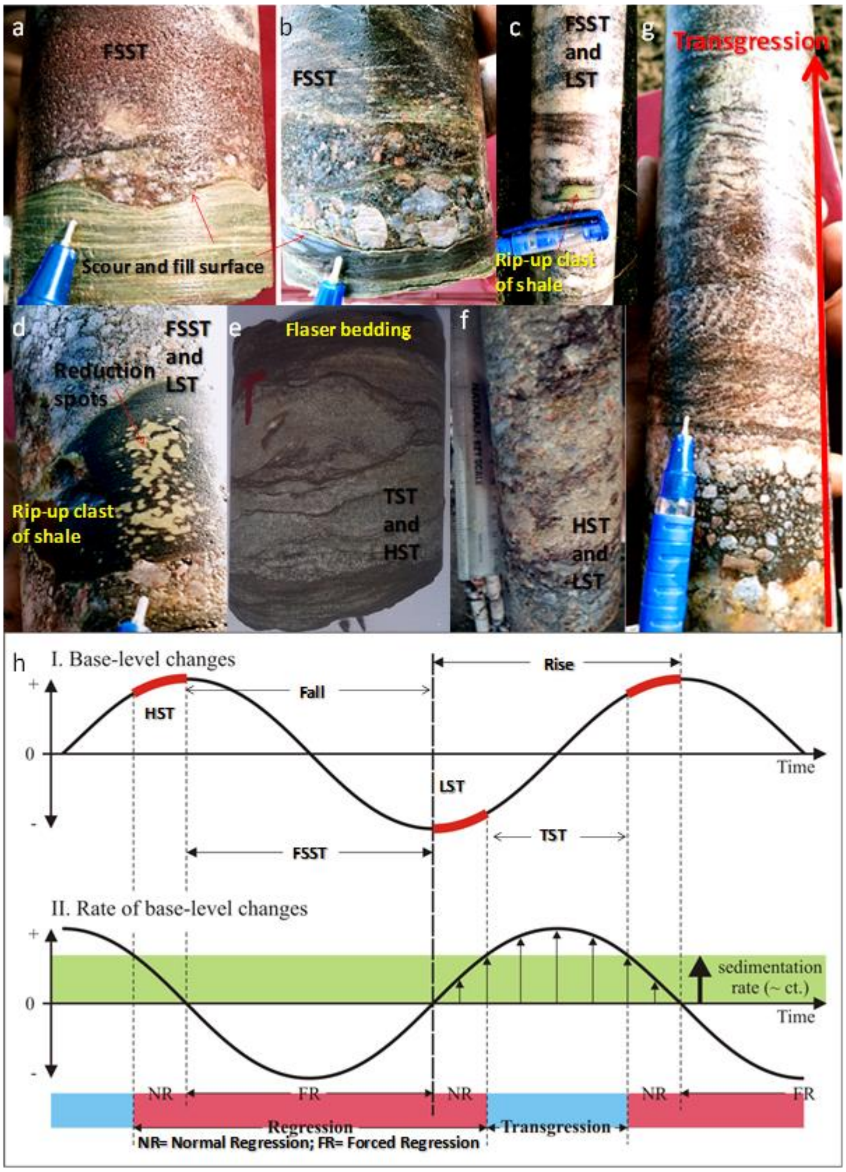


Fig 8. a-b. Scouring of shale bed top and later infilling of scoured portions by coarse grains. c-d. rip up shale clasts implying the transported chips of shale during scouring process of forced regression (FSST) and later settlement as fill structures along the LST. e. flaser bedding indicates marine transgression with thin shale laminae within sandstone (TST to HST). f. feldspathic arenite implying rapid terrestrial input with low transportation during normal regression when rate of sedimentation is higher than base level rise, i.e., either the post transgression HST or LST stage after FSST. g. transgressive facies association with fining upward sequence. h. standard sequence stratigraphic curves to substantiate the transgression - regression cycles.

The implications of sedimentary structures and grain size variation are significant in recognizing the systems tract. Presence of scour and fill structures, rip-up clasts of shale, matrix supported lag pebble conglomerate indicate regression stage and flaser bedding, quartz arenite and frequent shale indicate transgression event. Further details are discussed below for understanding the systems tracts with specific events, corresponding lithofacies and structures.

The initial marine sediments are overlain by forced regressive facies of conglomerate with typical rip-up clasts of shale, which were removed by erosive river current flow during regression and subsequently preserved within lag conglomerate. Such clayey sediments are highly cohesive and during sub-aerial exposure the dried-up chips often form flat tabular clasts of clayey sediment, which can be ripped up when scouring of such shale bed top take place by high velocity stream flow inside the regressive sea. Thus concave-upwards erosion surface of shale bed top implies excavation by aggrading stream. Further, during the waning stage of river flow intensity the scour gets filled by coarser sediments (Fig. 8a-d). Thus, the FSST and LST can be interpreted from such structures, which are produced during forced regression followed by normal regression. Transgressive facies are mostly characterized by quartz arenites with wave ripples (observed in outcrop but not in core), cross beds, flaser beds with overall fining upward grain size variation (Fig. 8e, g). However, increase in feldspar content in the arenite gives clue towards a significant event, i.e., normal regression, when the rate of sedimentation is more than the rate of creation of accommodation space, which is more prominently indicated from feldspar from nearby lands through minimum transportation along stream channels into the sea. Thus, the feldspathic arenite repeatedly occurs due to normal regression before and after transgression corresponds to LST and HST respectively (Fig. 8f, h). A brief overview of significant events with reference to marker surface, lithofacies association and condition of sea-level and/or river system is summarized in Table 3.

Table 3. The fingerprint features used as diagnostic criteria of significant stratigraphic surfaces (after Catuneanu, 2002)

Significant event marker surface	Nature of the plane	Facies		Depositional trend	
		Below	Above	Below	Above
Subaerial unconformity	Scoured or bypass	Not specific	Nonmarine	NR, FR	NR, T
Correlative conformity	Conformable	Coarsening upward marine	Coarsening upward marine	FR	NR
Basal surface of forced regression	Conformable or scoured	Coarsening upward marine	Coarsening upward marine	NR	FR
Regressive wave ravinement	Scoured	Coarsening upward shelf	Coarsening upward shore	NR, FR	FR, NR
Maximum regressive surface	Conformable	Coarsening upward	Fining upward	NR	T
Maximum flooding surface	Conformable or scoured	Fining upward	Coarsening upward	T	NR
Transgressive wave ravinement	Scoured	Coarsening upward	Fining upward	NR, T	T

TECTONIC IMPRINTS ON SEDIMENTATION

According to Gallagher and Lambeck (1989) subsidence of a basin can be reconstructed from the analysis of the accumulated sediments in a basin. Basically, strata get preserved in any basin due to tectonic subsidence of basin floor and such creation of accommodation spaces are syn-sedimentary phenomenon along with other processes like rise in absolute base level. From the analyses of aeromagnetic data basement structures was determined by Sridhar et al. (2018). According to Chaturvedi et al. (2012) there are complex N-S, WNW-ESE and NE-SW fault pattern noted along southern margin of the Kaladgi-Badami basin and the adjacent crystalline basement and also a distinct NE-SW structural zones in the eastern part of basin is interpreted to act as a facilitating factor in creating local depocenter for sediments. The heliborne geophysical data also gave insights on the fact that the entire basin is divided into several sub-basinal segments separated by fault-affected NE-SW and NW-SE oriented basement ridges. Further, sediment thickness was also estimated from the difference between digital elevation model and magnetic basement elevation grid. According to this study after Chaturvedi et al. (2012), average thickness of basin fill sediment is 400 m and at places about 800m thick pockets were also reported. In case of rift basin several fault segments are observed to act as depocenter (Leeder, 1995) and sedimentary fill deposits are wedge shaped with increased thickness nearby the active marginal parts. Exact basin configuration remains doubtful so far due to Deccan flood basalt coverings. However, attempt of mapping the sub-trappean sediments was taken by Sridhar et al. (2017) using heliborne time domain electromagnetic data. It was also observed from the sediment thickness map (Sridhar et al., 2018) that thickness reduce towards north and hence supports wedge like sediment body as typically expected in case of rift basin. Pillai et al. (2018) interpreted sediment accumulation curves (SAC) and explained that during the Bagalkot sedimentation basin floor subsidence rate was more than that during the Badami Group sedimentation. syn-sedimentary reactivation of basement faults is well explained from Bagalkot Group as a supportive tool of rifting (Kale et al., 1998; Kale and Pillai, 2011).

Badami Group also provides syn sedimentary normal faulting evidences in favour of rifting. Based on borehole data from Suldhal and adjacent areas (Figs. 1 and 9) sediment thickness is observed to be different across the fault which records the differences in the elevation of the depositional surface on the footwall and hanging wall sides. In fact, the Bababudan-Nallur Shear (BNS) zone passes below the sediment in this area.

PRESENT BASIN CONFIGURATION AND ARCHITECTURE

From the geological observations it is clear that sedimentation took place in passive rift setting in the Kaladgi-Badami basin. There is signature of depressed graben without igneous activity unlike active rift areas where presence of active volcanoes, elevated heat flows, high seismicity, thinner crust with elevated Moho beneath the rift zones are common (Hochstein, 2005; Kandie, 2015; Goswami et al., 2020).

There is unknown extension of sediments concealed below the vastly spreaded basaltic Deccan Trap flows. In fact, the present KB basin configuration is very much irregular because of

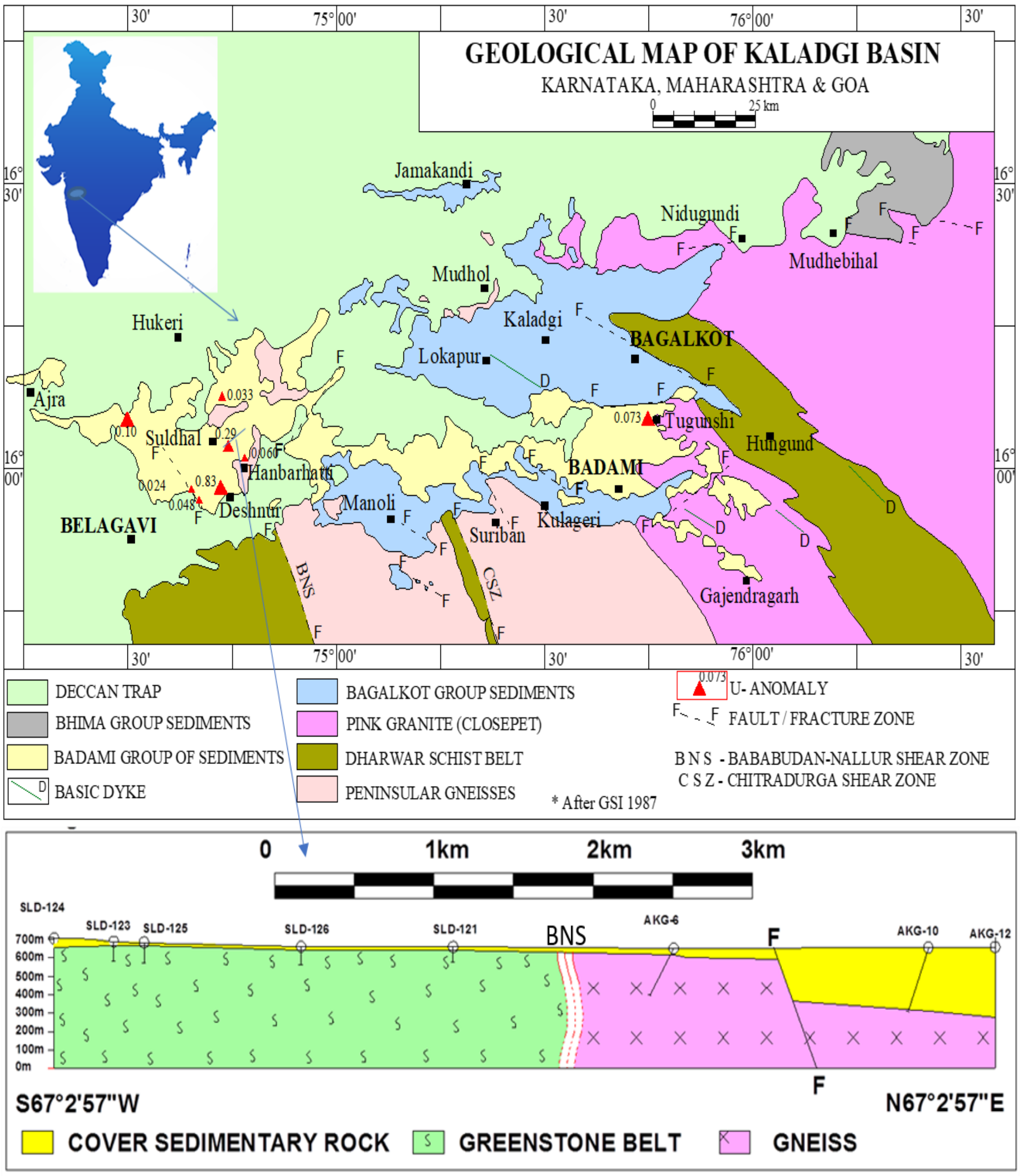


Fig 9. Transverse section along ~ENE-WSW based on sub-surface drilling data along the BNS contact between greenstone belt and gneiss

such extensive overlapping by the younger Deccan volcanism. As physiographically this southern part of Deccan plateau exhibits actual basin margin by forming typical rift shoulder with elevated topography (Goswami et al., 2016), later developed fault affected basement sediment contact should not be confused with actual basin margin. According to Jaya Prakash et al. (1987), sudden topographic rise of ~50m with reference to the surrounding granitoid-greenstone basement complex is noteworthy along the southern, eastern and western margins. Later developed depocenter for Badami Group of sediments was also created by subsequent reactivation of normal fault as a continuation of rifting after a prolonged time gap. Hence these younger rocks lie over the Kaladgi Group and also over the basement complex with distinct angular unconformity. The sedimentary rocks of KB basin are affected by several faults with different dimensions with trends varies among E-W, NE-SW and NW-SE. However, most widely visible fault set can be recognized as E-W trending Sirur-Katageri fault, Saundatti fault, B.N. Jalihal fault, Bilgi-Nidgundi fault and Bisnal-Mantur fault. Therefore, from the analysis of reported diastrophic features it is beyond doubt that Badami Group could not be affected by folding as such but extensively affected by faulting with dominant vertical displacements indicative of normal extension faulting. It can be confirmed that ductile folding event is older than the brittle faulting. Hence older Bagalkot rocks are affected by both folding and faulting. It is also understood from this structures that the entire system got exhumed gradually with time and shallow level deformation imprints could not affect the Badami sediments intensively and almost sub-horizontal to low dipping beds could be preserved.

DISCUSSION

PROBLEM WITH BASIN DIMENSION AND MARGIN DEMARCATION

The basement schist and gneiss of the sedimentary basinal rock indeed indicate shallow intra continental basin i.e., epeiric sea unlike normal marine basin of present-day sea floor with typical basaltic and gabbroic oceanic crust. For any basin of geological past the margin or deeper part is not easy to recognize at a glance because the geographical and geological basin margin is not same thing (Fig. 10). The actual geographic margin rarely remains intact but mostly eroded and removed after affected by tectonism and the preserved remnants of the sedimentary basin margin may not be actual margin. Therefore, depending upon the tectonic history, the Proterozoic basinal sedimentary rock map and contact relationships can give ideas on depth of sedimentation, which in turn give clues on sedimentation history. At places inside the basin only deeper basinal chemical sediments may be directly preserved above nonconformity on basement and at shallow level different clastic rocks may lie above basement. Therefore, even in undeformed basin also stratigraphic correlation must be made carefully after considering unconformity and correlative conformity. Transgressive and regressive events are also significant as already described. Field outcrop and subsurface borehole core lithology in Badami Group suggests clastic sediments dominated and shallow fluvio-marine transitional environment prevailed with transgressive systems tract above basement at apparent geographic basin margin. However, as per stratigraphic position of these horizontal beds this represent topmost part.

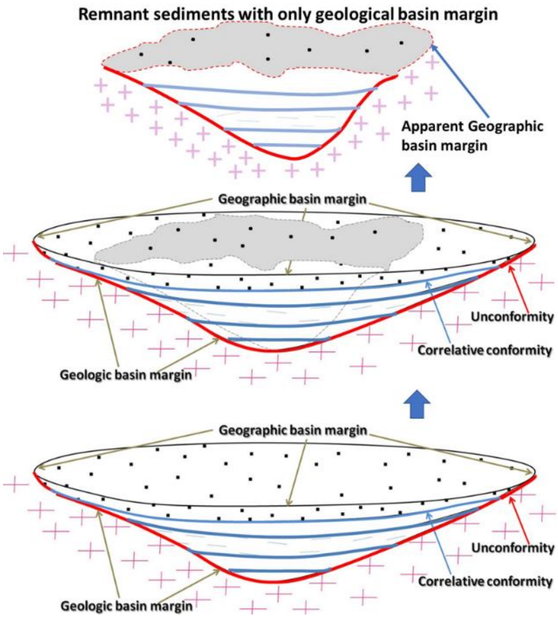


Fig 10. Progressive changes in basin margin with time. These continental basements imply shallow nature. Geographic (black surficial margin) and geologic basin margin (red sub-surface margin and crustal sedimentation above geologic margin indicates eventually preserve geologic margin only.

Now, the importance of scale and basin size come into the discussion because entire understanding is dependent up on the scale of observation. The first relevant question is what should be a minimum size of depression to qualify geologically as basin? Of course, very small depression sites with sedimentation cannot be preserved but there must be some quantification. It is also true that sediment thickness can give an idea on basin size because large basin size may have larger depth to accommodate more and more sediments. It is observed in general that sediment thickness is varying in between the maximum and minimum surface radius of basin (Fig. 11a). Thus, it is important to judiciously estimate the dimension of basin from sediment thickness. Although there may be exception and accuracy may vary, but definitely an isolated patch of ~1km thick sedimentary rock of 1 km^2 area cannot be a basin but it is expected to be a remnant part of earlier existing basin. Similarly, if there is very close proximity of two separately preserved sedimentary sequence and the terrain is intensely affected by faults it is naturally expected that the two sedimentary rock outcrops were part of same basin which got tectonically separated. In this context, time correlation and spatial correlation should be taken into consideration carefully. Depending up on the scale, for smaller area same litho-contacts can be correlated and can indicate same time but when broader area is studied then different litho-units can be deposited at different part of same basin at the same time. Thus, litho-contact tracing cannot give fruitful result of correlation (Fig. 11b). So, different lithology does not always mean different episode of deposition. In Figure 11b, a smaller part is enlarged to show the importance of scale in Figure 11c, in which lithostratigraphic correlation is well applicable. The carbonate dominated Bhima Group and clastic Badami Group are related with time correlatability, which is explained in details with sketches in Figure 5.

It can be seen from the combined map of the Kaladgi-Badami and Bhima basins that the distance between these two basins are only about

10-15 kms near Mudhebihal (Fig. 12). This clue gives enough scope of arguments that Kaladgi-Badami and Bhima basins were geographically connected before tectonism and these were part of a single basin. Therefore, principle of lateral continuity can be applied in correlating the sedimentary rocks between adjacent outcrops.

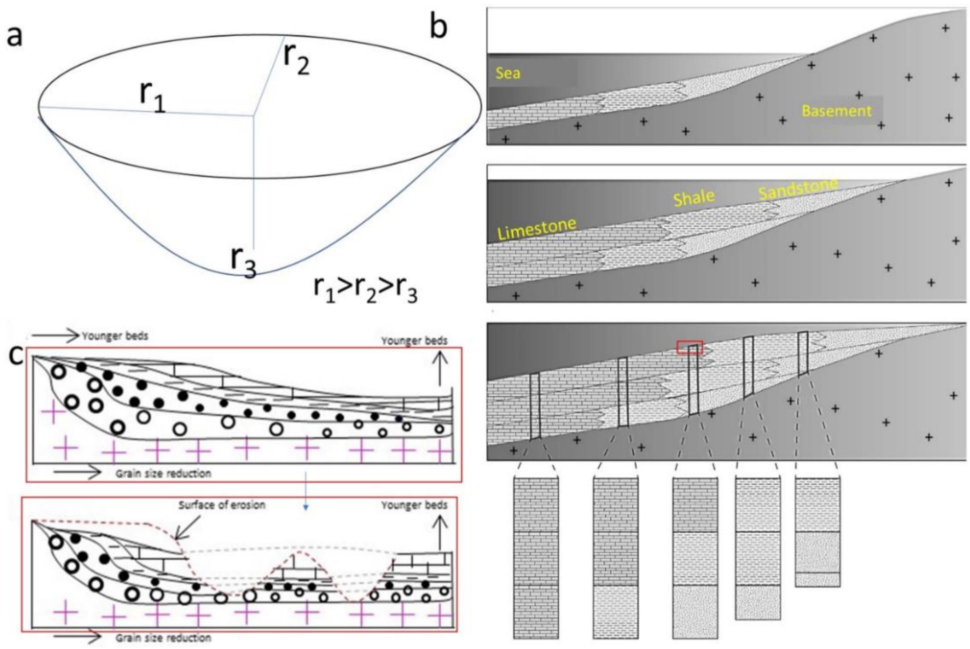


Fig 11.a. Proterozoic rift basin size and depth relation and broadly sub-elliptical geometry due to crustal tilting or stretching. b. lateral and vertical relations with changing sea level. Importance of scale of observation can be visualized in case of correlation of lithounits. c. for detail large scale over small area litho correlation is possible but for small scale over large are time correlation i.e., sequence boundaries are more important.

STRATIGRAPHIC CORRELATION BETWEEN KB BASIN AND BHIMA BASIN

Age data from the KB basin as well as Bhima basin are not sufficiently available. Based on chemo-stratigraphy and carbon isotope composition analysis Neoproterozoic age was proposed (Kumar et al., 1999; Nagarajan et al., 2008) for the Shahabad limestone of Bhima Group. Hence most widely accepted age is Neoproterozoic based on fossil evidences as well (Mishra et al., 1987; Maithy and Babu, 1996; Sharma and Shukla, 2012; Kale and Phansalkar, 1991; Jaya Prakash, 2007). However, according to another school of researchers (Augustine et al., 2015; Absar et al., 2016) Mesoproterozoic age is also suggested. Evidences based on suspected presence of limestone xenoliths of Bhima Group within 1090 Ma Siddanpalli Kimberlite (Dongre et al., 2008) and direct radiometric age of coffinite within the faulted and brecciated Shahbad limestone from Gogi uranium deposit (TIMS U–Pb age 1266 ± 76 Ma) proved that the age of Bhima Group is Mesoproterozoic (Pandey et al., 2008). Moreover, this hydrothermal uranium ore yielded a whole rock Pb-Pb isochron age of 1308 ± 49 Ma (Pandey et al., 2009). Therefore, more direct evidence supports Mesoproterozoic age of Bhima Group. Unfortunately, there is no such age dating available from Badami Group.

In fact, the correlatable Badami and Bhima sedimentation initiated as a consequence of assembly of Supercontinent Rodinia that was built up around 1260-900Ma ago and subsequently broken up by 750-633Ma (Hoffman, 1991; Kee et al., 2019). Badami is dominantly clastic unlike the carbonate rich Bhima Group. From the age correlation and geographic proximity as well as undeformed subhorizontal dip of bedding in both the depositional areas in general, it can be justified that these were deposited within same basin at separate depocentres. Bhima sediments represent relatively deeper or distal portion of the basin unlike the fluvial to marginal marine Badami Group. Subsequent faulting affected the preserved sediments to dislocate. As it is visible that Bhima basin does not have any natural/actual basin margin but everywhere tectonic/fault contact between basement and sediments is implying rigorous disturbances after sedimentation. Thereby the southern part of Bhima basin margin was totally eroded leaving behind remnants of uppermost part of arenite and shale (i.e., clastics) in the form of Rabanpalle Formation (Goswami et al., 2021). Dominant carbonates indicate shallow marine shelf like platformal environment where detritus supply got restricted and growth of stromatolites were common.

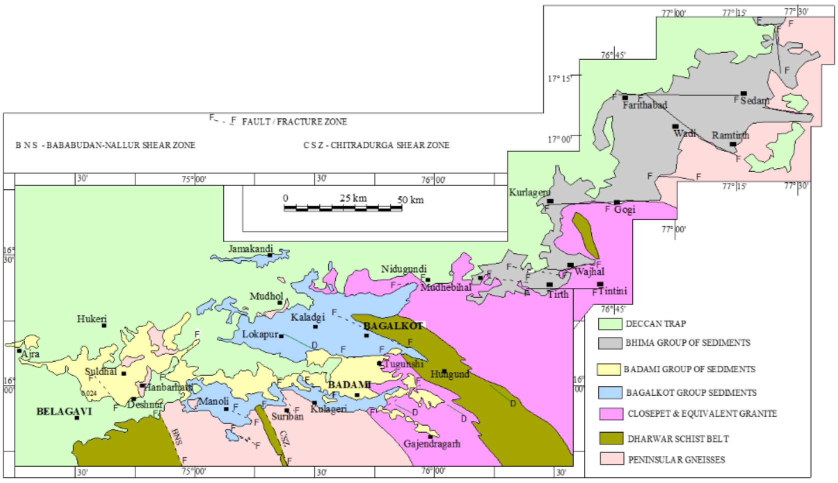


Fig 12. Combined map of KB and Bhima basin shows a broad geographic continuity and due to effects of tectonism and volcanism, present configuration is achieved.

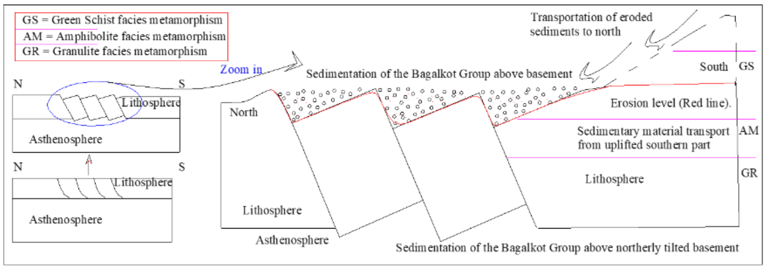


Fig 13. Northerly tilting of crustal block lead to basin creation at cratonic north and uplift with erosion along south. Exhumation lead to expose progressive deeper and higher metamorphic grade features towards south and eroded materials filled the basin in the north.

PROPOSED BASIN MODEL

Below Deccan Trap there may be Badami basinal limestone extension correlatable with the Bhima Group. However, based on the presently available data it is good enough to propose a new basin evolution model.

Initially developed block faulting due to northerly tilting of crustal block led to develop accommodation space for Bagalkot Group in proto Kaladgi basin. These normal fault arrays created passive rifting. The sediment supplied from uplifted southern basement erosion (Fig 13). Hence deeper higher-grade metamorphic rocks are exposed towards south. Along the present basin margin in the south of KB as well as Bhima basins low grade metamorphism is noted as lower greenschist facies. As we move south there is a systematic increase in metamorphic grade like upper greenschist facies followed by amphibolite facies and at very far granulite terrain also exposed along the southern extreme of Dharwar Craton. These observations are well known and thus raise the issue that where did the eroded sediment go! The answer can be explained from Figure 13. After basin filling and achieving temporary equilibrium, diagenesis of Kaladgi sediments was initiated and then Grenville orogeny affected the sediments with folding and then reactivation of faults along E-W trends. Several depocenters could be created due to this E-W fault system. Continued crustal tilting till achieving ~1.9^0 led to further sediment supply (Goswami et al., 2023) from the erosion of uplifted southern basement towards depressed northern basin. Shallow level fluvial through marginal marine to shelf environments could form to accommodate clastic and chemical sedimentation further. Systematic stages of progressive basin evolution are represented to visualize the impacts of tectonism followed by Deccan volcanism (Fig. 14).

After the diagenesis of sediments next deformation and faulting events affected sediment and E-W fault system with subsequent differential erosion again create omission of several parts of sedimentary rocks. Towards east deformation intensity increase is

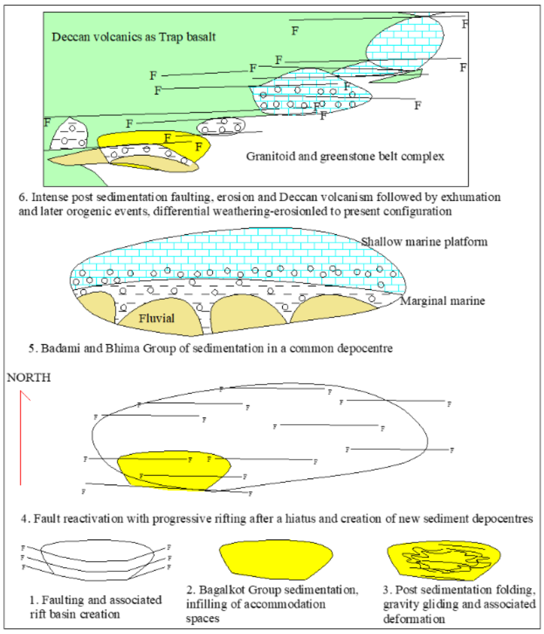


Fig 14. Progressive evolution model of KB-Bhima basin.

evidenced due to long lasting multi episodic Eastern Ghats Orogeny (EGO) and E-W compression was manifested in the form of E-W reactivated normal faults because of N-S maximum extension or minimum compression. Therefore, Bhima basinal rocks are more intensely deformed than Badami due to lesser distance from the site of main E-W compression regime of EGO.

At last profuse volcanism might have covered significant portion of the sediments in the NNW extension areas.

SCOPE OF FUTURE RESEARCH

Although the main aim of the paper is fulfilled by emphasizing few salient points regarding the stratigraphic reconstruction and basin correlation, the present work is not conclusive and there is further scope. Because, if the KB and Bhima is same basin then again Stratigraphic units of Bhima Group will have to be re-examined to fulfill the assignment criteria of Formation. Considering the KB and Bhima as a single basin all litho-units must be reassessed in terms of basin scale map. Finally, a combined comprehensive stratigraphic column will have to be prepared. In that combined Kaladgi-Badami-Bhima basin sub-basinal concepts must be introduced.

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