Implications of new $^{40}\text{Ar}/^{39}\text{Ar}$ age of Mallapur Intrusives on the chronology and evolution of the Kaladgi Basin, Dharwar Craton, India

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The Kaladgi Basin on the northern edge of the Dharwar craton has characters diverse from the other epicratonic Purana basins of Peninsular India. Sedimentological studies in the basin have established the presence of three cycles of flooding separated by an event of intra-basinal deformation accompanied by low grade incipient metamorphism. The overall structural configuration of the basin indicates its development by supracrustal extension accompanied by shearing in a trans-tensional regime during the Mesoproterozoic. This was followed by sagging that yielded Neoproterozoic sedimentation in a successor nested basin. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of an intrusive mafic dyke along the axial plane of a fold has yielded a plateau age of 1154 ± 4 Ma. This helps constraint the age of the various events during the evolution of this basin.

Keywords. Kaladgi Basin; geochronology; basin history; Purana basins; India.

1. Introduction

The Proterozoic history of Indian Peninsular Shield includes Mesoproterozoic Mobile Belts (MPMB: Radhakrishna and Naqvi 1986) and epicratonic, platform basins (Purana basins) that host Meso- and Neoproterozoic cycles of sediments that flank five Archean cratonic nuclei (Radhakrishna 1987; Kale and Phansalkar 1991; Ramakrishnan and Vaidyanadhan 2010; Sharma *et al.* 2014; Mazumder and Eriksson 2015). The Purana basins developed in an extensional tectonic regime, display structural contacts with the adjoining MPMB

that evolved in compressive tectonic regimes (Kale 1995). The Kaladgi and Bhima basins on the northern exposed edge of the Dharwar craton differ from the other Purana basins in that, they do not have any geographic proximity with MPMB.

The Purana basins display a paucity of associated contemporary igneous activity (Kale and Phansalkar 1991) that is normally expected during continental extension and subsidence of magnitudes of several thousands of meters (Condie 1982; Bott and Mithen 1983). Besides their significance in the evolutionary history of the basins, such associated igneous rocks provide the best source

of geochronological data of these unfossiliferous sediments. Although geochronological data of the ‘Purana’ sediments is sparse, they are generally accepted to have been deposited between 1.8 and 0.5 Ga, in independent basins that may or may not have opened concurrently (Kale 1991; Basu and Bickford 2015).

We present a basinal assessment of the evolution of the Kaladgi Basin, within the framework of new geochronological data of the only known mafic intrusive from the Kaladgi Basin. The implications of the age and evolution of the Kaladgi Basin are discussed in the context of contemporary events within the Indian Peninsular Shield and its position in supercontinental assemblies.

2. Kaladgi Basin

2.1 Geological setting

The Kaladgi Basin located on the northern parts of the Dharwar craton hosts ~4 km thick shallow marine platform sediments (Inset: figure 1). It hosts a Proterozoic succession formally entitled the Kaladgi Supergroup (Viswanathiah 1979; Jayaprakash *et al.* 1987) comprising the older Bagalkot and younger Badami Groups separated by a basin-wide erosional and angular unconformity. It is perhaps the only Purana basin that displays axial zone deformation and low grade metamorphism (Kale 1991; Jayaprakash 2007; Dey 2015). This basin has been recognized as being ‘difficult to categorize’ and may be a ‘fault-bounded basin related to far-field tectonism’ (Miall *et al.* 2015) or an intra-cratonic rift.

The thicker deformed Bagalkot Group (with an estimated stratigraphic thickness of more than 3600 m) is overlain by the comparatively undeformed, sub-horizontally disposed, 300 m thick Badami Group along the central parts of the basin (figure 1). The exposures of the Badami Group cover a WNW–ESE to E–W trending major shear zone (Shirur Shear) that is observed to have not only affected the Bagalkot Group exposed along it, but can also be traced eastward into the adjoining basement as a ductile shear zone attended by aplitic and pseudo-tachylitic veins and dykelets. It divides the Bagalkot Group exposures into the northern folded and deformed sector and the southern monoclinical sector with northward dips (figure 1).

More than 30 stratigraphic sections were measured across various parts of the basin to

record the succession of strata and their sedimentological characters. Appropriate thickness corrections were also applied for the structural features based on the un-folded cross-sections (see supplementary Data 1). Based on these, a composite litholog of the stratigraphic succession of the Kaladgi Supergroup has been reconstructed (figure 2). This also takes into account lateral facies changes recorded during our studies. They remained unrecognized by earlier workers resulting in the respective horizons being designated as additional members and adding to the number of stratigraphic units described in the basin (Jayaprakash *et al.* 1987; Jayaprakash 2007). The depositional environments enumerated in this figure are based on the primary sedimentary characters of the individual horizons and are consistent with those deciphered by earlier workers (summarized in Jayaprakash 2007; Bose *et al.* 2008; Kale and Patil Pillai 2011; Dey 2015).

2.2 Structural characters

The Bagalkot Group displays variable deformation in different sectors of the basin (see figure 1). Along the basin-fringes (along the Saundatti–Ramdurg–Badami tract in the south and the Jamkhandi–Bilgi sector in the north), gentle monoclinical folding and local deformation along faults has been recorded. These margins have suffered homogeneous strain-flattening, probably under the influence of gravity-related subsidence of the basin floor. Boundary-parallel normal faults (essentially trending E–W) that can be traced to the basement of the sediments, suggest a causal linkage between them and the growth of the basin.

In the central parts, particularly north of the Shirur Shear, the sediments display tight isoclinal (often doubly plunging and locally recumbent or overturned) folds around Yadwad, Lokapur and Bagalkot (Awati and Kalaswad 1978; Nair and Raju 1987; Mukherjee *et al.* 2016). The sub-vertical axial planes trend in the WNW–ESE direction; co-axial with a series of WNW–ESE trending shear zones/faults (see figure 1). The folds are transected by NNW–SSE to NE–SW trending transverse faults resulting in cross-folding; adding to the structural complexity of the deformation in the central sector of the basin. They are recognized to be shear folds, developed in a high stress/low temperature regime (Jadhav 1987) resulting from at least two phases of co-axial deformation in a WNW–ESE transpressional regime.

Figure 1. Geological map of the eastern part of the Kaladgi Basin (modified after GSI 1981, [Kale and Patil Pillai 2011](#)). Inset map shows the location of the Kaladgi Basin in peninsular India (EB and WB = Eastern and western blocks of the Dharwar craton respectively; EGB = Eastern Ghats Belt; PC = Phanerozoic cover; SGT = Southern Granulite Terrain). The correlations between various Precambrian sequences, the Dharwar craton and adjoining crustal blocks based on available age data is depicted in the time-chart on the right (from [Kale 2016](#)). The age of Mallapur Intrusives reported here are included in the chart.

Figure 2. Composite litholog of the Kaladgi Supergroup showing various components, their mutual relationships with one another, and their depositional settings. It is recognized that in any cross-section across any sector of the basin, horizons stacked one-above-the-other may occur adjoining each other as lateral facies variants from near-shore to off-shore facies as per Walther's Law. The relative sea-level curve is plotted on the basis of the subsidence analysis discussed in the text.

Cross-sections (see: supplementary figure S1 and Patil Pillai and Kale 2011: figure 4) were constructed across various sectors of the basin to unravel its structural complexity. They helped in documenting the inter-relations between various horizons in their pre-deformation state better. Figure 3 is a composite block-diagram created using such cross-sections that brings out the structural complexities of the Bagalkot Group exposed in the central parts of the Kaladgi Basin.

The cross-section of the Bagalkot Group shows closer affinities to a mobile/fold belt (analogous to a typical 'geosynclinal' cross-section) than to an extensional (half-rift) sedimentary basin. This axial deformation separates this basin from the other Purana basins that display deformation along their

margins (often representing structural contacts with the MPMB), while their central sectors are relatively undeformed (see, Kale 1991). Besides being arguably, one of the most pervasively deformed of the Purana sediments, the Bagalkot Group also displays development of incipient lower green-schist metamorphism (in some parts), slaty cleavages (in argillites), ductile folding (in stratified impure carbonates) and pseudo-mylonitic banding in quartzites in the proximity of faults and shear zones transecting the folded sediments.

The younger Badami Group whose exposures generally show very gentle rolling dips of magnitudes $<5^\circ$, on the other hand appears to have suffered almost no significant deformation. It is exposed with a sub-horizontal disposition, with

Figure 3. Block diagram depicting the structure of the Kaladgi Basin based on N-S cross-sections constructed across the basin. It portrays the structural complexities of the Bagalkot Group (with the Saundatti Formation shown in cream color and all other formations from this group depicted in blue). The rivers Krishna, Ghatprabha and Malprabha are shown as an easy reference with the geological map (figure 1). Selected examples of sediment accumulation curves (SACs) of the Bagalkot and Badami Groups (adapted from Patil Pillai 2004) are placed south to north for each graph. DI = Depositional Interface depth that takes into account the back-stripping effect and decompaction factors of successive horizons in the respective sections (see: supplementary Data 1 and table S1(a–d)).

some localized dislocations along faults (traceable to the faults from the Bagalkot Group and the Archean basement) that were apparently reactivated at the time of the deposition of the Badami Group.

2.3 Sedimentary and subsidence history

The sediments of the Kaladgi Supergroup have been examined from the perspective of their depositional environments for several decades. There appears to be a general consensus (Jayaprakash *et al.* 1987; Kale and Phansalkar 1991; Kale *et al.* 1996; Sambasiva Rao *et al.* 1999; Jayaprakash 2007; Bose *et al.* 2008; Dey *et al.* 2008, 2009; Dey 2015 and references therein) that the Bagalkot Group of sediments were deposited in a shallow shelf environment in an extensional setting. The individual horizons were deposited in a variety of co-existing environments during marine transgressions on a coastal system fed from the adjoining emergent cratonic segments of the

Dharwar craton. The younger Badami Group has a significant proportion of fluvial and fluvio-deltaic clastics. The shallow marine deposits from intertidal mudflats and subtidal carbonate flats occupy less than a third of the stratigraphic thickness of this Group.

Subsidence analysis of a basin is the reconstruction of the accumulation of sediments in a basin as a function of time (Gallagher and Lambeck 1989). Typical subsidence curves of sedimentary successions assume that the ‘net subsidence’ is the gradual lowering of the substrate on which the first sediments were deposited, leading to the accumulation of the succeeding pile of sediments (Sclater and Christie 1980; Bond and Kominz 1984; Allen and Allen 2013), commonly plotted using the ‘backstripping method’ that highlights the tectonic subsidence in a sedimentary basin. Subsidence curves provide a reliable method for understanding the nature of relative subsidence (which in turn is a function of the actual subsidence and/or the eustatic sea-level changes) of the basin

floor with respect to time. They have been ideally plotted using bore-hole data with an accurate time control on successive horizons. With the emergence of a fairly well-constrained eustatic sea-level curve during the Phanerozoic (Allen and Allen 2013), appropriate corrections of the same are now available that make it possible to model the nature of subsidence more accurately. Proterozoic sequences from the Purana basins are lacking in diagnostic fossils or other biological remains that may provide accurate biostratigraphic controls akin to Phanerozoic sequences. Dearth of interbedded rocks that could provide material for robust geochronological analyses adds to the uncertainties in their ages. For such sequences, where accurate age-controls for successive horizons are not available, sediment accumulation curves (SACs), based on Cant's (1989) equations provide a first order proxy for understanding the nature of basinal subsidence in Precambrian basins (Kale 1991).

The nature of relative subsidence in the Kaladgi basin was unraveled using a combination of the 30 stratigraphic sections and SACs for 17 measured sections. The stratigraphic sections and fault-corrected N–S cross-sections were plotted by Patil Pillai (2004). The principles, equations, methodology and data for representative five SACs (figure 3) are given in supplementary Data 1. SACs provide only a first-order approximation to the subsidence history, in absence of detailed chronological controls and with estimated ranges of compaction and backstripping. Consequently, no 'valuation' is taken on board when analyzing the SACs. It is evident that there is a significant variation in the nature of the subsidence of the basin floor in these two constituent groups from the Kaladgi Basin, only based on the gross geometry of their respective SACs. The relatively steep SACs of the Bagalkot Group suggest that the subsidence of the basin floor significantly more rapid than during the deposition of the Badami Group. Evidences of syn-sedimentary basement reactivation from the Bagalkot Group have been recorded earlier (Kale *et al.* 1998; Patil Pillai and Kale 2011; Kale and Patil Pillai 2011). Its subsidence was augmented by movements along the associated growth faults and shear zones. The Badami Group with flatter SACs appears to have been deposited on a slowly sagging basin floor in comparison. The fluvial influence recorded in the subhorizontal Badami Group sandstones substantiates this and suggests its origin as a nested sag (flanked by the folded hills of the Bagalkot sediments) along which a

continental fluvial system drained into a shallow marine platform.

2.4 Mallapur Intrusives formation

The occurrence of mafic dykes intrusive into the Kaladgi sequence (Foote 1876) found only passing reference in subsequent work, and they were clubbed with quartz veins, as Mallapur Intrusives by Jayaprakash *et al.* (1987) and Jayaprakash (2007). The very presence of such mafic intrusives in the Proterozoic sediments of the Kaladgi Group is significant, in light of the general paucity of igneous rocks in the Purana basins. We have sampled and dated the mafic body exposed in the Lokapur syncline (figure 4). Flattening of the pebbles in the conglomerate bands; preferred c-axis orientations and elongated recrystallisation of quartz grains in the quartzites; strong development of a pervasive slaty cleavage and local development of chloritic bands in argillites and in impure carbonates have been recorded from the sediments in the Lokapur syncline (Jadhav 1987; Jadhav and Phadke 1989). Intense cultivation and deep weathering have masked these exposures significantly. The mafic body occurs as a discordant intrusive into the sediments, parallel to the axial zone of the Lokapur syncline.

The intrusive mafic rock is greenish-grey coloured, with medium-grained crystalline texture. It is intensely jointed, with joints filled with secondary silica veins. It also displays weak foliation parallel to the slaty cleavages in the adjoining strata (figure 5b and c). It shows a holocrystalline, inequigranular, medium grained nature with a weak foliation (figure 6a). Textures ranging from glomeroporphyritic (with a fine grained matrix of plagioclase and pyroxenes), poikilitic (sub-ophitic), with phenocrysts displaying sutured borders appear to be inherent to the rock, composed essentially of plagioclase, pyroxenes with minor apatite, sphene and rutile, indicating its primary gabbroic nature. The clinopyroxenes display simple twinning, but the plagioclase display polysynthetic (albite-) twinning. The weak foliation is marked by parallel alignment of the sericitic and chloritic flakes. Chemical analyses of the whole-rock (table 1, figure 7 and supplementary Data 2) confirm that the rock belongs to the gabbro clan (in terms of its original composition).

Figure 4. (a) Geological map of the Lokapur Syncline (modified after [Jadhav 1987](#); [Patil Pillai 2004](#)). (b) N–S cross-section of Lokapur syncline (section line passing through Lokapur and location 2 in (a)) displaying the relation of the mafic body (black band with red stars at both ends) along the axial zone of the syncline. Faint grey lines mark the trace of bedding of the strata. The sense of movements of the associated shears is also depicted. The orientation of bedding is based on surface measurements extrapolated to depth. Note the vertical exaggeration of the section.

Some parts of this intrusive display a nearly unaltered, unfoliated igneous texture (akin to that of a coarse grained, holocrystalline dolerite/gabbro: figure 6a). Its exposures close to shear bands, axes of parasitic folding in the adjoining sediments, or where transected by transverse faults display a relatively more foliated texture. Albitization of the plagioclase (figure 6c), uralitization of the pyroxenes (figure 6d) to fibrous and flaky amphiboles, development of chlorite (often as bunched crystals aligned parallel to the foliation or as smaller crystals in the groundmass) and sericite (at the expense of plagioclase) evidence the incipient low grade metamorphism of the original mafic (gabbro/dolerite) rock at such positions. Strained quartz may have crystallized during the low-grade metamorphism. This low grade incipient metamorphism leads us to identify it as an ‘epidiorite’ in its present state. The term ‘meta-dolerite’ (if the term ‘dolerite’ is applied to the medium-grained textured rock based on its shallow emplacement and gabbroic composition) could be also used, but it would indicate a more pervasive alteration of the rock than is actually present in the Mallapur Intrusive.

This patchy imprint of the low-grade greenschist facies metamorphism is in conformity with the earlier observations of [Govinda Rajulu and Chandrasekhar Gowda \(1972\)](#), who recorded albitization of slates and of [Jayaprakash *et al.* \(1987\)](#), who recorded significant development of chloritic bands and slaty cleavages in the Jalikatti Phyllite and Arlikatti Argillite from the Bagalkot Group. This chlorite-grade metamorphism along the fold axes and shear zones indicates that this is not regional or basin-wide, but essentially local response to the concentration of stresses developed along such zones. The slaty cleavages and chloritization recorded in the shales and impure limestones hosting the meta-dolerite bear testimony of this shear-driven metamorphic imprint.

It is evident that since the intrusive is altered (at a lower green-schist grade) along with the host sediments; that its emplacement must have preceded the metamorphic event, but post-dated the folding since the fractures along fold-axes acted as conduits for its emplacement. It is perhaps for the first time that a detailed data on the Mallapur Intrusives is being compiled, given that earlier authors ([Foote 1876](#); [Jayaprakash *et al.*](#)

Figure 5. (a) Field photo of greenish-grey, medium-grained boulder of the mafic body showing spheroidal weathering. (b) Contact between the Mallapur Intrusive and the host Arlikatti Argillite exposed in a canal cutting at location 3 in figure 4. (c) Field photograph of the well cutting (at location 1 in figure 4a) of the mafic dyke displaying jointing (J1, J2) and weak foliation (F1) parallel to the slaty cleavage of the adjoining strata. Many of the steeply inclined joints are filled with secondary silica veins, some of which also show presence of chlorite in them.

1987) gave it only a cursory treatment. Besides its other implications, the epidiorite provides a good material enabling dating of this sequence for the first time.

3. Age

3.1 Previous work

A major limitation in the entire discourse on the Kaladgi Basin and its evolution is the lack of well-constrained ages. The only concrete geochronological data available is of the Peninsular Gneisses (>2600 Ma: see, compilations by Ramakrishnan and Vaidyanadhan 2010; Valdiya 2016) that form the Archean basement of the Kaladgi Basin. All other estimations of the age of this sequence have been indirect, based on correlations with strata from other Purana basins or on indirect inferences.

Based on stromatolite biostratigraphy and their correlation with the stromatolites from the Tadpatri Formation of the adjacent Cuddapah Basin, a Lower Riphean/Mesoproterozoic age (~1600 Ma) was assigned to the Kaladgi stromatolites (Viswanathiah and Sreedhara Murthy 1979; Jayaprakash *et al.* 1987; Sharma *et al.* 1998). Sharma *et al.* (1999) concluded that the stromatolites of the Lokapur and Simikeri Subgroups do not indicate a major temporal difference in the age and are all indicative of a Late Palaeoproterozoic to Early Mesoproterozoic age. Occurrence of ichnofossils *Palaeophycus tubularis* Hall and *Cochlichnus* led Kulkarni and Borkar (1997a, b) to assign a mid-Riphean/Mesoproterozoic (~1000 Ma) age to the Yadhali Argillites of Lokapur Subgroup and a Neoproterozoic (~800 Ma) age to the Cave Temple Arenites of the Badami Group, respectively.

Padmakumari *et al.* (1998) and Sambasiva Rao *et al.* (1999) gave model Rb–Sr isotopic age calculated with respect to CHUR for the shales from Bagalkot Group; and suggested that their deposition was younger than 1800 ± 100 Ma. Carbon and strontium isotopic composition of the carbonates from this basin, suggested a Post-Sturtian age (≤ 600 Ma) for Konkankoppa Limestone of Badami Group and a Mesoproterozoic age (between 1600 and 1000 Ma) for the carbonates of Bagalkot Group (Balesh Kumar *et al.* 1999). Basu and Bickford (2015; table 1) concluded that the Bagalkot Group was deposited between 1900 and 1800 Ma, while the Badami Group was deposited around 1700 Ma; an interpretation based on equivalences with the Papaghni and Chitravati Groups from the Cuddapah basin. Kale (2015) argued in favor of a much younger age of the Kaladgi Supergroup and pointed out lacunae in the assumptions supporting the older age.

Figure 6. BSE microphotograph showing (a) holocrystalline texture of the mafic dyke with glomeroporphyritic aggregates of plagioclase laths (Plg) with albite twinning and augitic pyroxene (Cpx) showing simple twinning. Also note the opaque iron oxides (Opq) and the partial alteration of plagioclase to sericite (Ser), (b) typical weakly foliated nature of the rock, (c) granophyric texture developed due to myrmekitic exsolution of albite from the plagioclase during the low grade metamorphism of the mafic rock, and (d) uralitization of pyroxenes (Cpx) yielding fibrous hornblende (Hbl) and actinolite needles (Act) resulting from the low grade metamorphism of the mafic rock.

3.2 $^{40}\text{Ar}/^{39}\text{Ar}$ dating

On this backdrop, the geochronology of the Mallapur Intrusive Formation (intrusive into the Simikeri Subgroup and hence post-dating it; but pre-dating the low grade metamorphism) provides the first direct evidence of age of the Bagalkot Group.

Two fresh whole rock samples of the mafic dyke (KB-1A and KB-1B: parts of sample D1) collected from the Mallapur Formation were dated by $^{40}\text{Ar}/^{39}\text{Ar}$ chronology method at the IIT Bombay – DST National Facility. Fractions of 120–180 μm size, powdered rock samples were packed in aluminum foil and irradiated for 12 hr

at the USGS Denver Research reactor along with high-purity CaF_2 and K_2SO_4 salts and the 523.1 ± 2.6 Ma Minnesota hornblende (MMhb-1) monitor (Renne *et al.* 1998). The irradiated samples were repacked in aluminum foil and argon was extracted in a series of steps up to 1400°C in an electrically heated ultra-high vacuum furnace. After purification, the argon released in each step was measured with a Thermo-Fisher ARGUS VI mass spectrometer. Interference correction factors for Ca- and K-produced argon were 0.000268 for $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$, 0.001186 for $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ and 0.000576 for $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$. The irradiation parameter J for the samples is 0.002618 ± 0.000013 . The program 22 ISOPLOT

Table 1. Major oxide and trace element (limited) compositions of the samples from Mallapur Intrusives.

Major oxides	Wt%			Trace elements	In PPM		
	D1	K1	D5		D1	K1	D5
SiO ₂	49.32	50.98	47.80	Ba	932.55	326.09	347.13
TiO ₂	2.38	2.21	2.54	Cr	6.21	124.24	88.93
Al ₂ O ₃	12.06	12.30	13.50	Ni	0.00	71.71	87.2
Fe ₂ O ₃	2.93	2.79	2.93	Cu	50.77	ND	ND
FeO	11.72	11.16	11.73	Sc	ND	39.87	33.69
MnO	0.21	0.20	0.22	Sr	227.16	202.29	182.49
MgO	3.27	4.41	4.31	Y	55.30	52.05	58.74
CaO	7.96	9.32	8.98	Zn	220.68	180.57	251.99
Na ₂ O	2.37	2.35	2.57	V	119.04	304.64	304.64
K ₂ O	0.35	1.18	1.23	Zr	283.30	224.29	214.94
P ₂ O ₅	0.37	0.31	0.47	Nb	59.53	ND	ND
Total	92.93	97.21	96.29	Hf	6.92	ND	ND
LOI	5.44	1.53	1.04	Ta	43.77	ND	ND
				Th	9.59	ND	ND
				U	28.79	ND	ND

D1 is a sample that is relatively more altered by low grade incipient metamorphism than the other two samples.

Figure 7. Classification of the intrusive body based on chemical analysis (table 1) of three samples from the Mallapur Intrusive in the Lokapur syncline. The fields for the TAS plots in the left are after Middlemost (1985), while those on right are after Wilson (1989), modified after Cox *et al.* (1979). The normative mineral composition, other indices and the XRD mineralogy of the samples are given in supplementary Data 2).

v. 3.75 (Ludwig) was used to plot the $^{40}\text{Ar}/^{39}\text{Ar}$ step heating data.

The age spectra for the two samples KB-1A and KB-1B are shown in figure 8. The intermediate to high temperature steps for both the samples exhibit excellent plateau. Sample KB1-A gives a plateau age of 1155 ± 6 Ma (2σ), comprising 53.9 % of total ^{39}Ar released; an isochron age of 1155 ± 7 Ma (2σ) and inverse isochron age of 1155 ± 5 Ma (2σ). The sample KB1-B gives a plateau age of 1154 ± 6 Ma (2σ), comprising 53.9% of total ^{39}Ar released, an isochron age of 1154 ± 7 Ma (2σ) and

inverse isochron age of 1154 ± 5 Ma (2σ). For both the samples all the three ages are statistically concordant and trapped argon composition shows atmospheric value of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio. This plateau indicates consistency at higher temperatures and negates any possibility of an imprint of lower temperature alteration suffered by the rock (McDougall and Harrison 1999). For the resolution of ages available by this method, it is not possible to distinguish between age of crystallization and age of emplacement for Precambrian shallow crustal intrusive rocks. Therefore, the plateau age for both

Figure 8. The age spectra of the two samples from Mallapur Intrusives Formation of the Kaladgi Basin. The ascending staircase patterns for the low temperature steps may be the results of low degree of incipient metamorphism these samples have undergone.

the samples, statistically indistinguishable at 2σ level, can be considered the emplacement age of this body.

3.3 Implications on age of Kaladgi Supergroup

The weighted mean plateau age of these two samples, $1154 \pm 4\text{Ma}$ (table 2) therefore is the emplacement age of the mafic intrusion. The

emplacement of this dyke along the axial plane of the folding; and its low-grade metamorphic alterations (conforming to that recorded in the host sediments) suggest that its emplacement was coeval or immediately after the peak deformation of the Bagalkot Group, enabling a hitherto unavailable chronological framework for it. Its sedimentation and commencement of deformation must have preceded the age of emplacement of the mafic body.

Table 2. The summary of the $^{40}\text{Ar}/^{39}\text{Ar}$ age data of the two samples of the mafic dyke is given below (detail parameters of this analysis are given in supplementary Data 3).

Sl. no.	Sample ID	Plateau age (Ma)	Isochron age (Ma)	Intercept	Inverse isochron age (Ma)	J value
1	KB-1A	1155 ± 6.0 52.4% of ^{39}Ar	1155 ± 7	294 ± 41	1155 ± 5	0.0025961 ± 0.000013
2	KB-1B	1154 ± 6 53.9% of ^{39}Ar	1154 ± 7	297 ± 23	1154 ± 5	0.0025961 ± 0.000013

Similarly, it also provides a more reliable lower age limit for the Badami Group that was deposited after the complete deformation (with attendant localized incipient metamorphism) of the older Bagalkot sediments and their eventual emergence as a source of sediments.

The presence of the stromatolitic assemblage equivalent to those in the Papaghni Group from the Cuddapah basin (Sharma *et al.* 1998), and the carbon–oxygen isotopic systematics (Balesh Kumar *et al.* 1999) provided a lower age limit of ~ 1600 Ma for this Group. Interpreting backwards from age of 1154 ± 4 Ma for the Mallapur Intrusives, it may be suggested that the intra-basinal reorganization attended by syn-sedimentary tectonism (as demonstrated by Kale *et al.* 1998) have preceded the intrusive event by not more than 100 m.y., leading to the disconformity between the Simikeri and Lokapur Subgroups. The presence of wide spread carbonate flats (manifested as the Petlur Formation) preceding this disconformity across the basin is indicative of the peak-transgression in the basin. Taking into account the net thickness of sediments of Bagalkot Group (13,717 m decompacted thickness: supplementary Data 1) it is unlikely that its sedimentation spanned more than a few tens of millions of years by modern analogy. Therefore, we estimate by extremely liberal estimates (of the slowest accumulation rate of sedimentation) that the initiation of sedimentation of the Bagalkot Group may have occurred at around 1300 ± 50 Ma. This places the age of sedimentation 200 million years later than the ages suggested by stromatolitic and ichnofossil assemblages or by the erstwhile correlation of the Bagalkot Group with the Papaghni Group.

At the same time, absence of such an intrusive in the overlying Badami Group substantiates that this Group must be younger than 1100 Ma. The postulation of the 1700 Ma age of the Badami Group (table 1 of Basu and Bickford 2015), therefore, cannot be tenable and must be revised. That the Badami sedimentation started

significantly after the deformed strata of the Bagalkot Group was exposed to the agents of erosion is borne out by the erosional and angular unconformity between the two Groups in the Kaladgi Basin. We therefore estimate that the Badami sedimentation cannot be older than 1000 Ma. The inferred age-ranges of deposition and hiatal break in the Kaladgi Basin by Kale and Phansalkar (1991) and that postulated by Kale (2016) are validated and refined by this data.

4. Discussion

4.1 Evolution of the Kaladgi Basin

The shallow marine sediments of the Kaladgi Basin testify to the fact that the initiation of sedimentation in it occurred due to marine encroachment in a vacuity created in this part of the Dharwar craton that evolved and deepened with time, attended by crustal extension and faulting. The syn-sedimentary deformation structures and the trends of fault and shear provide clues to the creation and growth of this vacuity on the Archaean Basement Complex. Occurrence of seismites, tectonogenic origin of chert breccias, intrinsic facies and deformation patterns in the Bagalkot Group within the northern sector, and the relatively less deformed southern and western sectors provide substantial evidence that the basin evolved as a complex polyhistory basin controlled by NW–SE and E–W trending basement penetrating shears and faults. The E–W Shirur Shear present in the eastern sector of the basin appears to have played a substantial role in the differential evolution of the various sectors within the basin.

Whether the Simikeri Subgroup actually represents a separate marine transgression is ambiguous, given that these sediments occur only within the synclinal segments within the Lokapur Subgroup. The progressively increasing frequency of syn-sedimentary deformation towards the end of

sedimentation of the Lokapur Subgroup (Kale *et al.* 1998) suggests that there was an incremental tectonic influence on the deepening of the shear-controlled depressions, which hosted the Simikeri Subgroup. Nonetheless, there is no doubt that the Simikeri sediments manifest a rise and subsequent fall in relative sea-level as has been depicted in figure 2. After the cessation of deposition, the sediments of Bagalkot Group underwent burial and diagenetic changes, followed by deformation. Jadhav (1987) and Jayaprakash *et al.* (1987) have attributed this deformation to an event of N–S compressive tectonism. Mukherjee *et al.* (2015) considered this to be a product of gravity gliding of the cover sediments along a detachment developed at the basement unconformity. The exercise of ‘unfolding’ the sequence (Patil Pillai 2004) indicated the presence of a strike-slip regime associated with the deepening and deformation of the Bagalkot Group. Taken together with the deformational characters, it logically follows that the inception of the Kaladgi Basin was in an extensional (partly trans-tensional) regime and that the basin-floor subsidence was augmented by active basement tectonics. This was followed by a phase of compressive folding that is speculated to have been controlled by movements along E–W to WNW–ESE trending shear planes, yielding the asymmetric, tight isoclinal folding of the Bagalkot Group. The structural characters recorded in the sediments as well as the basement penetrating shear zones (e.g., Shirur and Idgal, see figure 1) indicate that not only the sedimentary cover, but also the basement were involved in the deformation.

The orientation of the epidiorite body (Mallapur Formation) and its parallelism to the axial plane of regional folding should be recognized within the framework of evidences, which suggest that multiphase, co-axial deformation of the Bagalkot Group has been controlled by the same crustal-scale (E–W to WNW–ESE) shear planes that also controlled the sedimentation and growth of the Kaladgi Basin. It is possible that the fractures resulting from the sustained deformation, tapped sub-crustal depths that yielded the gabbroic magma. The emplacement must have occurred ‘syntectonic’, in light of the fact that this rock has suffered the same low grade greenschist facies metamorphism as its host sediments.

This was followed by a major hiatus, during which the Bagalkot Group was subjected to uplift, isoclinal folding and erosion. The sedimentation of the succeeding Badami Group was initiated as

a sag flanked by high-lands in the northern part (conceivably comprising the uplifted folded hills of the Bagalkot Group) and the eroded Dharwarian basement complex in the south. It is likely that they occupied the valley in front of the high-lands yielding fan deposits across much of their basal segments, followed by meandering and braided channel deposits. The dominantly fluvial sedimentation of terrigenous siliciclastics gave way to shallow marine and marginal marine sediments that testify to the flooding by an ensuing sea-level rise. This indicates that the tectono-thermal contribution to the subsidence of the Badami sub-basin was negligible as compared to its preponderance in the Bagalkot sub-basin. The SACs (figure 3) of the Badami Group (with a flatter trajectory) also support this inference. The relative sea-level curve plotted based on sedimentological studies (figure 2), the hiatal break and the dating of the epidiorite (Mallapur Formation) thus provide a robust framework for the chronology of events in the Kaladgi Basin, summarized in table 3 than was estimated earlier.

The Kaladgi Basin has a cross-sectional geometry akin to a (? failed or arrested) geosynclinal belt in a supracrustal regime. It hosts evidence of significant extension and subsidence (unlike geosynclinal belts), besides displaying only localized, low grade incipient metamorphism. It is likely that future subsurface geophysical investigations will enable a more accurate demarcation of the fault and shear geometry in this basin and help refine this model. This basin is located at a distance from any known contemporary tectonic belt within the Indian Peninsular Shield. The age and inferred chronology of the Kaladgi basin is temporally consistent with the pulse of reorganization of the Nuna supercontinent and the emergence of the succeeding Rodinia supercontinent (Cawood and Hawkesworth 2014; Condie *et al.* 2015). The ‘far-field’ tectonic basin model inferred for this basin (Miall *et al.* 2015) is valid to a large extent in light of this.

4.2 Mafic events

Purana basins are characterized by a paucity of associated igneous activity (see, Radhakrishna 1987; Kale 1991; Kale *et al.* 1998; Kale and Phansalkar 1991; Meert *et al.* 2010 and references therein). The mafic volcanics associated with the older sequences in the Vindhyan and Cuddapah basins and the tuffaceous rocks from some of

Table 3. *Inferred sequence and chronology of events in the evolution of the Kaladgi Basin.*

Stratigraphic unit	Events within the basin	Tectono-thermal events and ages	Computed/estimated age and ages
Kaladgi Supergroup	Badami Group	Continental sedimentation with localised marine transgression	Extension <i>~900–800 Ma</i>
		Emergence and erosion of folded strata (+ basement)	<i>1100–900 Ma</i>
		Post depositional events	Low grade metamorphism and deformation <i>1150–1100 Ma</i>
		Mafic intrusion Folding and faulting	1154±4 Ma
	Bagalkot Group	Basin deepening with synsedimentary intra-basinal tectonics	Extension <i>~1200 Ma</i>
		Local intra-basinal reorganisation (?)	Intra-basinal tectonics with co-axial deformation <i>>1200 Ma</i>
		Peak transgression Basin inception	Extension and subsidence <i>≤ 1300±50 Ma</i> <i>~1400±50 Ma</i>

Note: The estimated ages (or durations) are given in italics to denote their inferred nature, while the date reported here is given in bold upright font to highlight its robust nature.

the basins being recognized now (against their earlier descriptions as ‘porcellanites/siliceous limestones’, e.g., Basu *et al.* 2008) are exceptions. This is a contrast to the fact that the host cratonic blocks for these basins have been recognized to have been affected by multiple events of mafic intrusive activity during the Proterozoic, perhaps linked with basin-forming/basin-closing events.

This is true also for the three Purana basins on the fringe of the Dharwar craton. While the igneous activity in the basal sequences of the Cuddapah Basin is well documented, there is a paucity of such syn-sedimentary activity from the Bhima and Kaladgi basins. The basement of all these basins are, however, known to have been hosts of several mafic dykes, informally referred to as the ‘Newer Dolerites’ (see Radhakrishna and Naqvi 1986; Ramakrishnan and Vaidyanadhan 2010). The Mallapur Intrusives from the Kaladgi Basin represent the rare exception of igneous rocks from the northern parts of the Dharwar craton that had remained poorly studied so far.

The Dharwar craton is recognized to have been affected by mafic dyke-swarms at $\sim 2.2 \pm 0.1$ Ga and $\sim 1.8 \pm 0.1$ Ga, besides a younger episode at around 1.15 Ga (Chalapathi Rao *et al.* 1999; Chaudhuri *et al.* 2002; French *et al.* 2008; Meert *et al.* 2011; Osborne *et al.* 2011; Kumar *et al.* 2012,

2015; Belica *et al.* 2014). These events have been represented in the chronological chart of figure 1. Ernst and Srivastava (2008) and Chalapathi Rao *et al.* (2013) have argued in favour of a widespread magmatic event between 1200 and 1100 Ma to have affected the entire Peninsular Shield of India. The components of this event are dominated by lamproites, lamprophyres and comparable compositions, besides localized manifestations of rhyolitic and felsic tuffaceous units in the Chattisgarh and Bastar basins (Pradhan *et al.* 2008; Basu *et al.* 2008; De Kock *et al.* 2015). The indicative locations of these Proterozoic igneous rocks from the Indian Peninsular Shield are depicted in figure 9 on the backdrop of the Indo–Madagascar–Antarctica segment of the Rodinia assembly.

The age of the Mallapur Intrusives determined in this study demonstrates its relevance and equivalence within the younger event of Late Mesoproterozoic age, but with a gabbroic composition. It shows that this event of igneous activity that has widespread distribution in the eastern parts of the Dharwar craton is also manifested in the western parts of the craton. This igneous event may also have representatives in the ‘Newer Dolerites’ recorded intruding the Archaean basement of the Kaladgi and Bhima Basins that await recognition. The Mallapur Intrusives Formation has the capacity to provide more information in the days to

Figure 9. Occurrence of igneous suites/dykes within the Indian Peninsular Shield including the Mallapur Intrusives studied here is depicted on the backdrop of the segment of the Rodinia assembly that includes Antarctica, Sri Lanka, India and Madagascar (after Tucker *et al.* 2014) and distribution with respect to the Purana basins in India and other contemporary Meso-Neoproterozoic basins in this assembly.

come both from the paleomagnetic and chronological aspects of the northwestern exposed edge of the Dharwar craton.

5. Conclusions

Although known to be present since the time of Foote (1876), very little information is available

about the mafic rocks intrusive into the Kaladgi sediments. This contribution is an attempt to plug that gap. This study shows that mafic dyke has intruded into the uppermost beds of the Bagalkot Group, representing the post-sedimentary igneous event dated to be 1154 ± 4 Ma by $^{40}\text{Ar}/^{39}\text{Ar}$ age dating method.

This in itself is significant, since igneous activity in craton-interior basin normally precedes or

is contemporary with the basal sediments. The location of the Kaladgi basin on the northern exposed tip of the West Dharwar craton, and its 'axial deformation' rather than margin-linked deformation observed in other Purana basins may provide indicators to explain such igneous associations. The metamorphic imprint on this dyke suggests craton-margin (rather than the previously believed craton-interior) processes.

This is the first ever report of a robust geochronological date from this basin and has provided an important line of evidence in understanding the evolutionary aspects of this supracrustal epicontinental basin and far-field tectonics within the realms of the Proterozoic supercontinental assembly. It provides a substantial framework for elucidating chronology of events punctuating the evolution of the Kaladgi Basin and shows the need to revise several earlier proposed correlations and models of its evolution.

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