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Research paper

Evolving provenance in the Proterozoic Pranhita-Godavari Basin, India

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ABSTRACT

The Pranhita-Godavari Basin in central eastern India is one of the Proterozoic "Purāna" basins of cratonic India. New geochronology demonstrates that it has a vast depositional history of repeated basin reactivation from the Palaeoproterozoic to the Mesozoic. U-Pb laser ablation inductively coupled plasma mass spectrometry dating of detrital zircons from two samples of the Somanpalli Group—a member of the oldest sedimentary cycle in the valley—constrains its depositional age to ~1620 Ma and demonstrates a tripartite age provenance with peaks at ~3500 Ma, ~2480 Ma and ~1620 Ma, with minor age peaks in the Eoarchaean (~3.8 Ga) and at ~2750 Ma. These ages are consistent with palaeocurrent data suggesting a southerly source from the Krishna Province and Enderby Land in East Antarctica. The similarity in the maximum depositional age with previously published authigenic glauconite ages suggest that the origin of the Pranhita-Godvari Graben originated as a rift that formed at a high angle to the coeval evolving late Meosproterozoic Krishna Province as Enderby Land collided with the Dharwar craton of India. In contrast, detrital zircons from the Cycle III Sullavai Group red sandstones yielded a maximum depositional age of 970 ± 20 Ma and had age peaks of ~2550 Ma, ~1600 Ma and then a number of Mesoproterozoic detrital zircons terminating in three analyses at ~970 Ma. The provenance of these is again consistent with a southerly source from the Eastern Ghats Orogen and Antarctica. Later cycles of deposition include the overlying Albaka/Usur Formations and finally the late Palaeozoic to Mesozoic Gondwana Supergroup.

1. Introduction

Cratonic India hosts large unmetamorphosed and only mildly deformed Proterozoic sedimentary successions, with minor pyroclastic and volcanic rocks. These basins include the Vidhyan, Chhattisgarh, Indravati, Cuddapah, Bhima, Khariar and Pranhita-Godavari basins and are collectively known as the Purāna basins (Fig. 1)(Holland, 1906). Traditionally, they have been interpreted as having formed contemporaneously (Chaudhuri et al., 1999), but recent U-Pb detrital zircon (Malone et al., 2008; Bickford et al., 2011a, b; Mukherjee et al., 2012; Chaudhuri et al., unpublished data), palaeomagnetic (Gregory et al., 2006; Malone et al., 2008; Gregory et al., 2009) and ^{40}Ar-^{39}Ar glauconite studies (Conrad et al., 2011) have shown that this is a considerable over-simplification. Work over the last decade has established that different Purāna basins opened at different times, but the upper age limits of major depositional sequences are largely unconstrained, impeding the evaluation of their global significance. The question of the upper age limit of Purāna sequences, and the possibility of their continuity into the late Neoproterozoic or into the Cambrian has been debated for a long time, though recently, U-Pb ages from tuffs sampled from the Chhattisgarh and Indravati basins has led to a new hypothesis suggesting closure of at least these Purāna basins at c. 1000 Ma (Bickford et al., 2011a; Mukherjee et al., 2012), coinciding with orogenesis in the Eastern Ghats (Korhonen et al., 2011) and the central Indian tectonic zone (Bhowmik et al., 2012).

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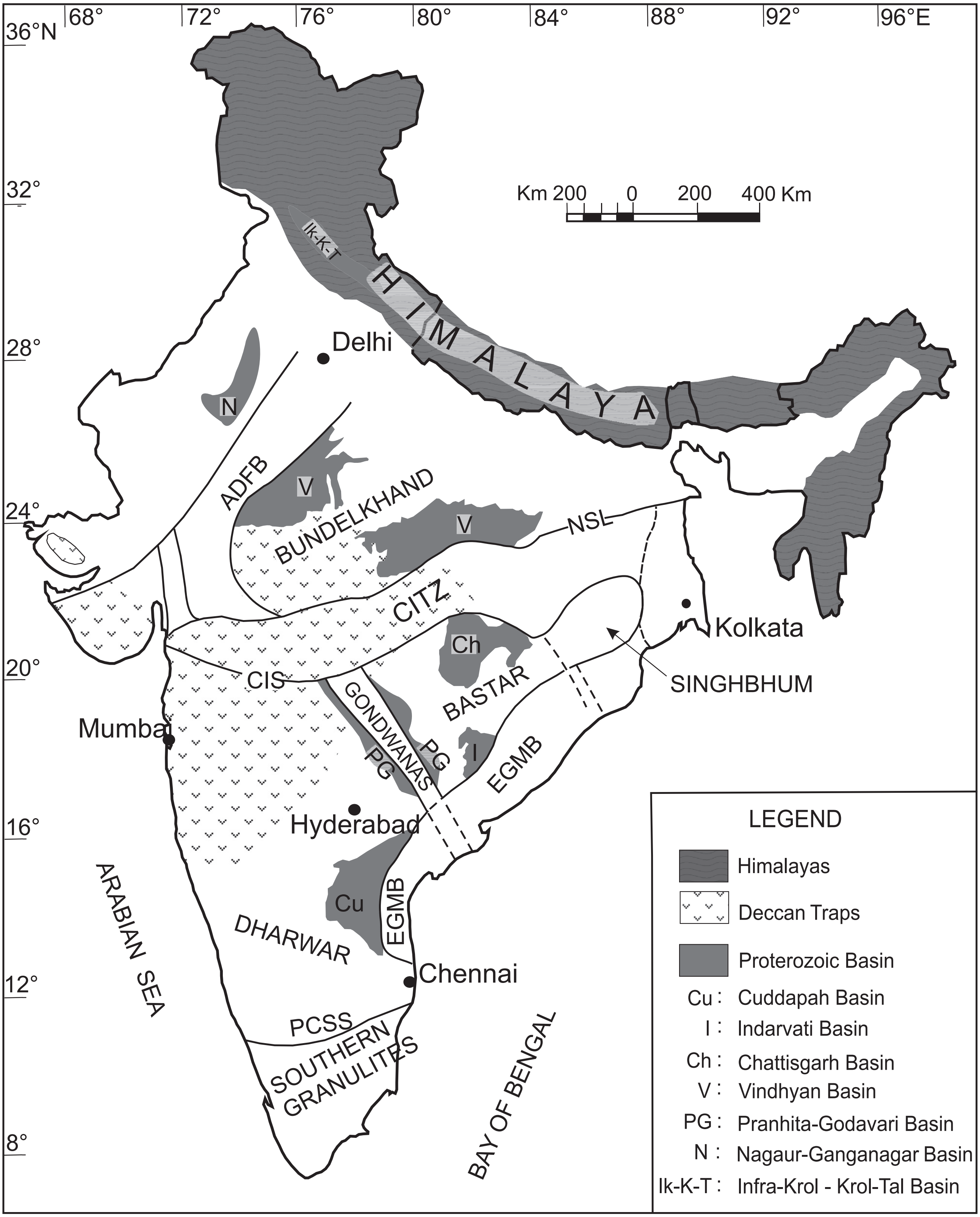

Figure 1. Map of India highlighting the main cratons, the Proterozoic orogens and the Proterozoic to early Palaeozoic so-called Purāna basins. ADFB – Aravalli–Delhi Fold Belt; NSL – Narmada–Son Lineament: CIS – Central Indian Suture; CITZ – Central Indian Tectonic Zone; EGMB – Eastern Ghats Mobile Belt; PCSS Palghat-Cauvery Shear System (modified from Vijaya Rao and Reddy, 2002).

2. Geological setting

The pre-Gondwana 'Purāna' basin of the Pranhita-Godavari Valley is preserved in, and may well have developed as, a major rift extending for about 450 km, from the Eastern Ghats Belt in the southeast to the Central Indian Tectonic Zone (CITZ) in the northwest (Fig. 1). Although previous workers had suggested that the Proterozoic sedimentary rocks in the basin were likely to be the preserved relics of a much larger basin (Ramakrishnan and Vaidyanathan, 2008), sedimentological studies by Chaudhuri et al. (2012) demonstrated that the rocks were deposited largely within the present rift boundaries. The rift developed along the NW–SE trending Karimnagar Orogenic Belt, which delineates a Neoarchaean granulite belt between the Dharwar and Bastar cratonic nuclei. The Pranhita-Godavari Valley preserves records of multiple Proterozoic rifts, as well as a Gondwana rift, opening and closing along the same zone where Purāna formations occur as several structural inliers within the younger Gondwana rift system. The Gondwana outcrops occur primarily as a linear belt along the axial part of the Valley, separating Purāna outcrops into two belts (Fig. 2). Both Purāna and Gondwana outcrop belts maintain similar depositional and structural trends (Chaudhuri et al., 2012), and Purāna formations can be lithostratigraphically correlated across the valley into several unconformity-bound sequences (Chaudhuri, 2003; Chaudhuri et al., 2012). The sequences, by turn, can be classified into at least three 1st or 2nd order depositional cycles (Fig. 3), each bounded by regional unconformities. The unconformity–bound cycles, representing major basin formation events, are stacked one above, generating a megasequence where basins are considered as genetic units rather than simply as a geographical unit (Whittaker et al., 1991). The cycles are characterized by very distinctive sets of lithologic attributes indicating deposition under highly variable modes and tempos of sediment generation, sediment supply and creation of accommodation space.

2.1. Cycle I

The Cycle I, or the basal cycle, comprises two smaller order unconformity–bound sequences, defined as groups, namely, the Mallampalli Group, which unconformably rests over crystalline basement, and the overlying Mulug Group. Equivalent Groups occur spatially separated on the east-side of the Valley, these are named the Devalmari and Somanpalli Groups (Figs. 2 and 3). The sedimentation age of the basal sandstone formation in these groups was constrained by $^{40}Ar/^{39}Ar$ dating of early authigenic glauconite grains by incremental heating technique on single grains (Conrad et al., 2011). Glauconites from Mallampalli sandstones yielded a plateau age of 1686 $\pm$ 6 Ma, whereas those from the Mulug and Somanpalli Groups yielded ages of 1565 $\pm$ 6 Ma and 1620 $\pm$ 6 Ma, respectively. The Mulug and Somanpalli Groups have been interpreted, on the basis of regional stratigraphic considerations, to have developed as two parallel belts within a protracted rift system. The former developed as a shallow tidal shelf deposit and the latter was deposited in a genetically related deep water slope and continental rise environment (Chaudhuri et al., 2012). Sedimentation in the shallow water–deep water couplet was terminated by contractional deformation (Ghosh and Saha, 2003), termed the Somanpalli orogenic belt by Chaudhuri et al. (2012). The age of basin inversion is not well constrained, but we consider that it coincides with the closure of Mulug–Somanpalli basin, and pre-dates deposition of the Penganga Group that overlies the Mulug Group above a major erosional unconformity.

The Mallampalli, Devalmari, Somanpalli and Mulug Groups are all characterized by mixed carbonate-siliciclastic assemblages, and the combined succession has been designated as the Pakhal Supergroup. The Pakhal Supergroup crops out primarily in the central and southwestern part of the Pranhita-Godavari Valley.

2.2. Cycle II

Cycle II comprises a major unconformity-bound sequence of mixed carbonate-siliciclastic rocks, designated the Penganga Group. The Penganga Group crops out mainly in the central and northern part of the Pranhita-Godavari Valley, and the basin had a northwesterly to northerly palaeoslope (Mukhopadhyay and Chaudhuri, 2003), contrasting with the underlying Pakhal Supergroup. The lower part of the Penganga succession comprises a thick fining-up succession of alluvial conglomerate-pebbly sandstone-coarse grained sandstone that grades upward into a succession of limestone and shale through a zone of quartz-arenite that was deposited in a tidal shelf environment. The outcrops of the carbonate-shale succession have been covered up by the Deccan volcanics (Fig. 2) in the northern part of the outcrop belt. However, it appears most likely that the outcrops extended further north–northwest beneath the volcanics, and connected down palaeoslope with open ocean situated along the present Central Indian Tectonic Zone.

The $^{40}Ar/^{39}Ar$ analysis of glauconites from a submarine-fan complex (Patranabis-Deb and Fukuoka, 1998) at the basal part of the carbonate assemblage did not yield any plateau age, but provided a provisional minimum age of c. 1200 Ma for initiation of carbonate sedimentation (Conrad et al., 2011), suggesting a much older age for opening of the Penganga Basin. The Penganga Group has been lithostratigraphically correlated with the combined succession of the c. 1400 to c. 1000 Ma Chandarpur and Raipur groups of the Chhattisgarh Basin (Mukhopadhyay et al., 2006; Conrad et al., 2011), which is consistent with the provisional glauconite age.

2.3. Cycle III

The red sandstones of the Sullavai Group, along with the Albaka and Usur groups, constitute Cycle III. Sullavai sandstones unconformably overlie different formations of the Penganga Group, the Mulug Group and the Mallampalli Group in different parts of the Pranhita-Godavari Valley, attesting to the variable degree of uplift of fault blocks and erosion during the sub-Sullavai hiatus, exceeding several thousand metres at places. The stratigraphic relationship attests to deposition of the Sullavai Group in fault controlled basins, representing a probable Neoproterozoic rift cycle. The Sullavai red beds comprise different types of feldspathic and sub-feldspathic sandstones and were deposited in extensive fluvial and erg environments (Chakraborty, 1991, 1999; Chakraborty and Chaudhuri, 1993).

The stratigraphic position of the combined succession of the Albaka Group and the unconformably overlying Usur Group could not be uniquely constrained though field mapping. The siliciclastic assemblage unconformably overlies the folded succession of the Somanpalli Group, and are here considered to either be lateral equivalents of, or stratigraphic younger than, the Sullavai Group. The Albaka and Usur successions comprise extensive quartz-arenites and shales deposited in tide- and storm-dominated inner shelf environments. Though the stratigraphic position of the Albaka and Usur groups is uncertain, along with the Sullavai Group, the sequences collectively constitute a siliciclastic depositional system that was fundamentally different from the system represented by the carbonate-dominated, mixed carbonate-siliciclastic Pakhal or Penganga successions of late Palaeoproterozoic and Mesoproterozoic age.

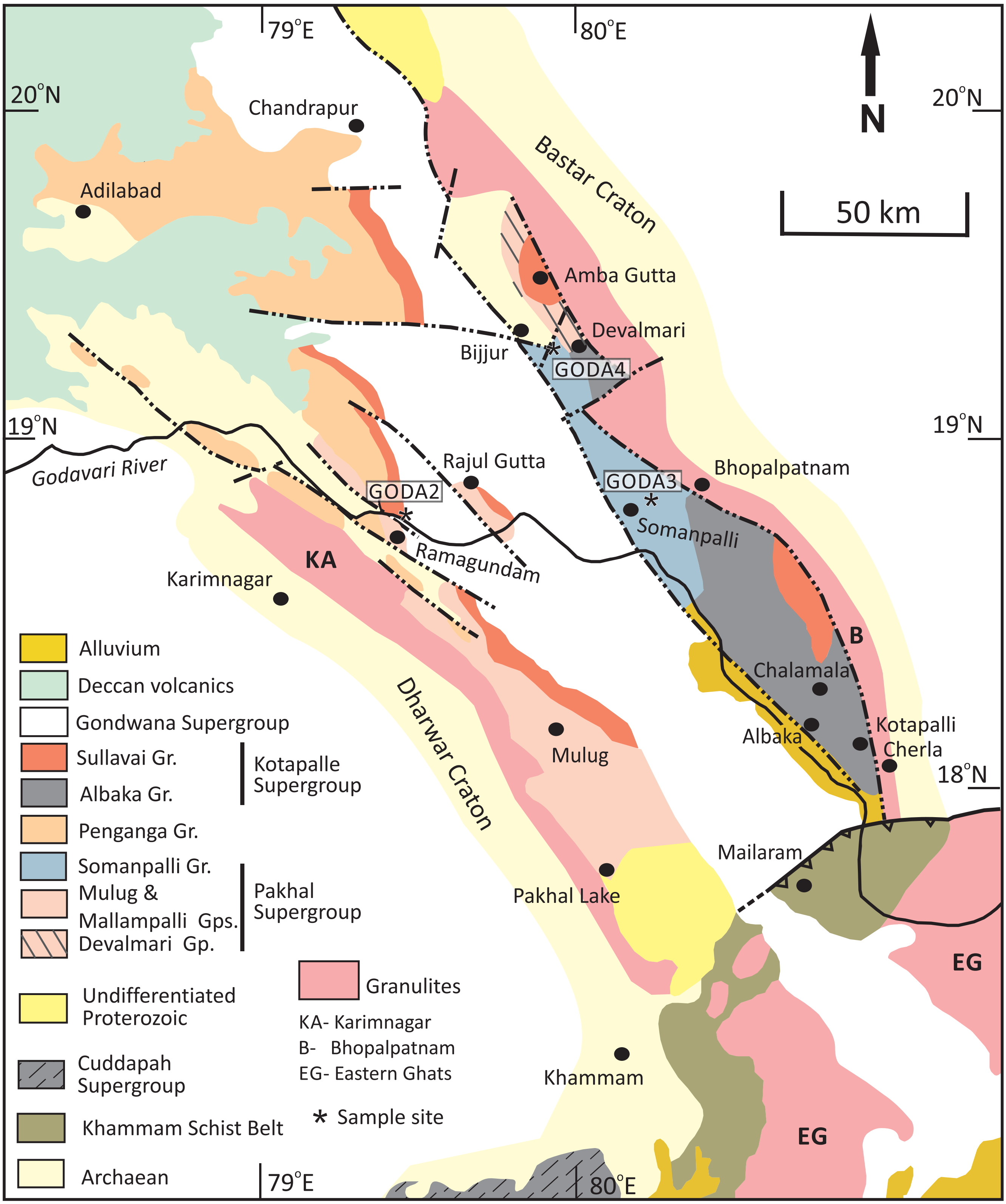

Figure 2. Generalized geological map of the Pranhita-Godavari Valley showing distribution of the Purāna sequences and of the Permian–Mesozoic Gondwana Supergroup. The basin occurs along the join of the Bastar and Dharwar cratons, and is bounded on the SW (west) and on the NE (east) by Karimnagar and Bhopalpatnam Granulite belts, respectively. Locations of the samples analysed for isotopic age of detrital zircon are shown.

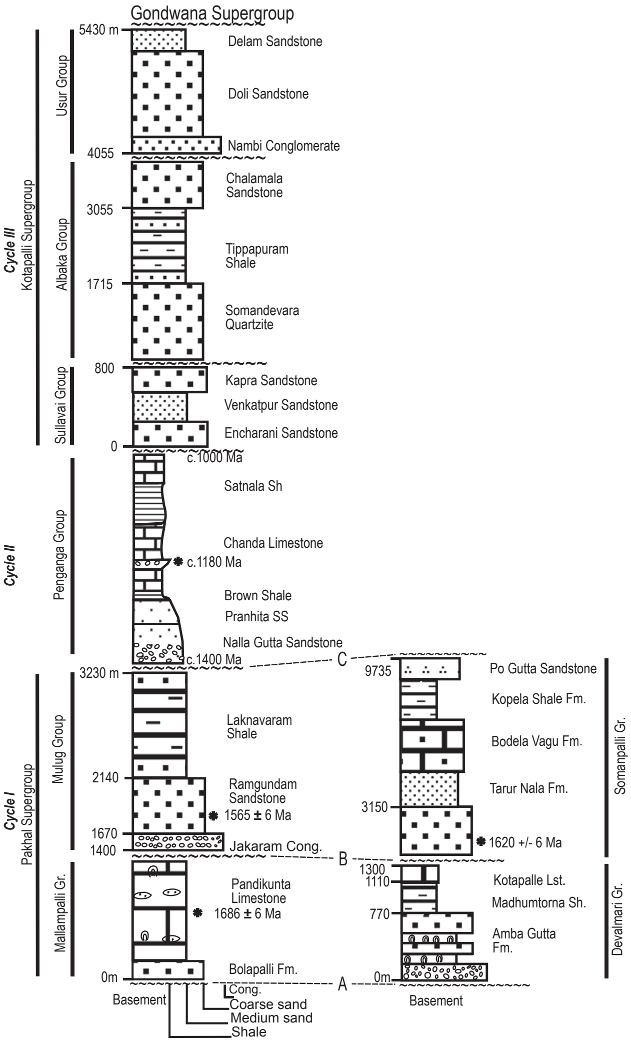

Figure 3. Composite stratigraphic column for the Purāna succession in the Pranhita-Godavari Valley. Different unconformity-bound sequences have been classified into three major cycles of sedimentation. The youngest Cycle consists of the Sullavai Albaka and Usur groups.

3. U/Pb laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS)

Samples were crushed and sieved to obtain the 79 − 400 μm fraction. This fraction was then panned and zircon separates were extracted using the methylene iodide heavy liquids. The magnetic minerals were removed using a hand magnet and the remaining zircon separates were hand−picked and mounted in epoxy resin discs. Care was taken not to overly bias the zircons during picking by selecting zircon grains of all sizes, colours and shapes. Prior to analysis, zircons mounts were carbon coated and cathodoluminescence (CL) imaged on a Phillips XL20 SEM with attached Gatan CL at Adelaide Microscopy (University of Adelaide). Zircon grains were imaged using ∼16 mm working distance and accelerating voltage of 12 kV.

Zircon grains were analysed on a New Wave 213 nm Nd-YAG laser coupled with the Agilent 7500cs Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at Adelaide Microscopy (University of Adelaide). A 30 μm spot size was used with a typical pit depth of 30−50 μm. The isotopic ratios were monitored and corrected for drift and within−run U-Pb fractionation by repeated analyses of GEMOC GJ-1 standard zircon (published thermal ionization mass spectrometry normalising ages of $^{207}Pb/^{206}Pb = 607.7 \pm 4.3$ Ma, $^{206}Pb/^{238}U = 600.7 \pm 1.1$ Ma and $^{207}Pb/^{235}U = 602.0 \pm 1.0$ Ma, Jackson et al., 2004). Over the course of analytical sessions, a total of 79 analyses of the GJ-1 external standard yielded a weighted average $^{207}Pb/^{206}Pb$ age of 609 ± 13 Ma (2σ, MSWD = 1.4) and $^{206}Pb/^{238}U = 601.6 \pm 2.0$ Ma (2σ, MSWD = 0.5). Analysis of the Plešovice zircon standard (TIMS $^{206}Pb/^{238}U$ age = 337.13 ± 0.37 Ma, 95% confidence limits, Sláma et al., 2008) was performed to check for validity of the applied method during the analysis of unknowns. A total of 46 analyses of the Plešovice internal standard yielded weighted average ages of $^{206}Pb/^{238}U = 341.1 \pm 1.7$ Ma (2σ, MSWD = 1.4), showing the general accuracy of the operating conditions.

4. Stratigraphic location of samples

Samples are discussed from oldest to youngest.

4.1. Somanpalli Group (Indravati) − GODA 03

Two samples of the Tarur Nala Formation of the Somanpalli Group were collected over 50 km apart from each other. The formation consists of a coarsening-up succession of black shale-mudstone-siltstone with a thin interval of mass flow ash-tuffs and greywackes. Sample GODA3 was collected from a channel-filling greywacke along the right bank of the Indravati River at N18°47′39″, E80°17′49″. The Somanpalli Group forms part of the Pakhal Supergroup, the first stratigraphic cycle in the Pranhita-Godavari Valley (Fig. 2).

4.2. Somanpalli Group (Biijur) − GODA 04

Sample GODA4 was also collected from a channel-filling greywacke from the Somanpalli Group. However, this sample was collected over 150 km away from sample GODA3 near the town of Biijur at N19°15′43″, E79°55′52″.

4.3. Sullavai Group − GODA 02

Sample GODA2 was from the stratigraphically overlying Sullavai Group that unconformably overlie different formations of the Penganga Group, the Mulug Group and the Mallampalli Group in different parts of the Pranhita-Godavari Valley (Fig. 2). The Sullavai Group forms Cycle III in the stratigraphy of the Pranhita-Godavari Valley, and, to date, there are no geochronological data on this Group.

Sample GODA2 was collected near the town of Ramagundam at N18°47′18″, E79°27′45″. The sample was collected from the Mancheral Quartzite Formation, at the base of the Sullavai Group. This formation is interpreted to represent alluvial plain to braided plain deposits. The sample was collected from the stratigraphically highest part of the formation.

5. Results

U/Pb LA-ICPMS results are presented in Table 1. U-Pb results are presented in Fig. 4a−d. Ages for individual analyses are quoted at the 1σ level, whereas averages and intercept ages are quoted at a 2σ level.

5.1. Somanpalli Group (Indravati) − GODA 03

Sixty analyses of sixty grains yielded forty two >90% concordant analyses (Figs. 4a and 5a). Of the near-concordant

Table 1
U-Pb isotopic data of zircons from the Somanpalli and Sullavai Groups.

Analysis	Isotope ratios					Concordancy	Ages (Ma)			
	$^{207}Pb/^{235}U$	1σ error	$^{206}Pb/^{238}U$	1σ error	rho		$^{207}Pb/^{206}Pb$	1σ error	$^{206}Pb/^{238}U$	1σ error
GODA-3 Somanpalli Group (Indravati)										
c1	24.02543	0.31589	0.51212	0.0068	0.990211	73	3663.3	15.33	2665.7	29.01
c2	31.14818	0.41482	0.69689	0.00934	0.993675	95	3589	15.69	3408.9	35.48
c3	8.02924	0.12929	0.2551	0.00376	0.915349	48	3040.5	20.93	1464.7	19.3
c4	10.44264	0.15898	0.46322	0.0064	0.907529	98	2491.5	21.39	2453.7	28.19
c5	26.16163	0.35826	0.65348	0.0089	0.994544	95	3418.9	16.53	3241.8	34.68
c6	28.07308	0.38526	0.68898	0.00941	0.99522	98	3446.2	16.49	3378.7	35.92
c7	10.97492	0.15046	0.48355	0.00657	0.99107	102	2502.9	17.74	2542.7	28.54
c8	8.51858	0.17323	0.41957	0.00633	0.741897	98	2313.6	32.2	2258.5	28.75
c9	3.96478	0.05888	0.28622	0.00393	0.924579	99	1632.1	22.25	1622.6	19.72
c10	3.07136	0.04251	0.2254	0.00308	0.987271	82	1601.6	19.74	1310.4	16.2
c11	19.17574	0.27139	0.54143	0.00754	0.983982	86	3227.2	17.42	2789.4	31.54
c12	37.56824	0.50651	0.74169	0.01021	0.979408	95	3780.3	15.17	3576.8	37.8
c13	8.56743	0.14383	0.37508	0.00561	0.890923	82	2515.1	23.08	2053.2	26.29
c14	20.30643	0.28924	0.53877	0.00769	0.997934	84	3325.4	16.4	2778.3	32.23
c15	29.51943	0.46516	0.71074	0.01038	0.926813	100	3476.2	20.8	3461.2	39.13
c16	9.56794	0.16075	0.4413	0.00637	0.859158	97	2425.9	24.46	2356.5	28.47
c17	12.78181	0.18017	0.47063	0.00663	0.99941	89	2800.7	17.11	2486.3	29.05
c18	28.59132	0.41963	0.68745	0.00983	0.974272	97	3478.3	17.82	3372.9	37.54
c19	29.06652	0.62702	0.67476	0.0119	0.817541	94	3535.5	30.29	3324.2	45.81
c20	29.30716	0.40573	0.70377	0.00976	0.998261	99	3480.2	16.47	3434.9	36.92
c21	10.72389	0.16767	0.45704	0.00664	0.929204	95	2559.3	21	2426.5	29.36
c22	11.86836	0.17372	0.47414	0.00685	0.987018	94	2667	18.05	2501.7	29.95
c23	26.17397	0.36512	0.61659	0.0087	0.988652	88	3510	15.76	3096.4	34.71
c24	8.36424	0.12925	0.40545	0.00584	0.932119	94	2341.3	20.89	2194.1	26.78
c25	10.47062	0.18004	0.46795	0.00696	0.864994	100	2479.9	24.35	2474.6	30.59
c26	3.84819	0.06676	0.28355	0.00409	0.831446	101	1594.8	27.38	1609.2	20.56
c27	20.53321	0.29376	0.53866	0.00782	0.985471	83	3343.1	15.85	2777.8	32.78
c28	10.67181	0.15807	0.47966	0.00674	0.94867	102	2470.1	19.7	2525.8	29.34
c29	10.79262	0.15392	0.46638	0.00654	0.983263	97	2536.5	18.04	2467.7	28.75
c30	25.2052	0.38481	0.64376	0.00956	0.972697	95	3386.1	17.32	3203.8	37.48
c31	3.82712	0.07444	0.28452	0.00432	0.780615	102	1578.3	31.38	1614.1	21.66
c32	13.06326	0.20058	0.49869	0.00727	0.94944	95	2742.3	19.61	2608.1	31.27
c33	3.90216	0.06119	0.28265	0.00401	0.904732	99	1626.7	23.38	1604.7	20.18
c34	30.5559	0.44586	0.72742	0.01063	0.998517	101	3493.5	16.14	3523.8	39.69
c35	26.65449	0.38015	0.66898	0.00961	0.992829	97	3412.1	16.05	3301.9	37.14
c36	29.00178	0.4216	0.66436	0.00969	0.99668	92	3553.5	16.23	3284.1	37.54
c38	26.99308	0.49194	0.65298	0.01024	0.860479	93	3470	25.27	3239.8	39.92
c39	3.88457	0.06064	0.2838	0.00408	0.92094	100	1610.3	22.72	1610.5	20.48
c40	21.70823	0.30765	0.59435	0.00846	0.995645	92	3275.9	16.04	3007	34.22
c41	28.4643	0.4126	0.76894	0.01099	0.985999	112	3297.1	16.82	3676.9	40.04
c42	27.59632	0.40362	0.6658	0.00962	0.987893	95	3473.2	16.77	3289.6	37.24
c43	9.98568	0.16749	0.44977	0.00667	0.884146	97	2466.1	23.23	2394.2	29.65
c44	10.21408	0.15633	0.46006	0.00666	0.945838	99	2466.1	19.87	2439.8	29.42
c45	3.88587	0.05777	0.28349	0.00407	0.965701	100	1612.8	20.58	1608.9	20.45
c46	9.97639	0.14691	0.45573	0.00655	0.976013	99	2442.2	18.44	2420.7	29.02
c47	14.20642	0.27577	0.51893	0.00827	0.820983	96	2813.5	27.49	2694.6	35.1
c48	29.50629	0.47616	0.70127	0.01058	0.934893	98	3496.3	19.96	3425.5	40.09
c49	17.84503	0.25299	0.5033	0.00717	0.995162	81	3229.4	16.17	2628	30.75
c50	17.3355	0.24777	0.52105	0.00746	0.998281	86	3128.6	16.49	2703.6	31.61
c51	26.57026	0.38264	0.65191	0.00939	0.999808	94	3448	16.26	3235.6	36.64
c52	33.71633	0.49715	0.74922	0.01088	0.984855	100	3600.7	16.95	3604.6	40.1
c54	29.4346	0.5135	0.70969	0.01125	0.90866	100	3474.1	22.38	3457.3	42.43
c55	10.36442	0.21695	0.47374	0.00792	0.798676	102	2441.5	30.94	2499.9	34.66
c56	10.99424	0.15727	0.34183	0.00475	0.97141	62	3077.7	17.75	1895.5	22.8
c57	21.52084	0.31622	0.57769	0.0082	0.966026	89	3308.5	17.74	2939.3	33.5
c58	7.24459	0.10738	0.28172	0.00394	0.943559	59	2713.4	19.38	1600	19.83
c59	4.92593	0.07668	0.26768	0.00386	0.926355	71	2145	21.28	1529	19.64
GODA-4 Somanpalli Group (Biijur)										
c1	32.51028	0.44076	0.41231	0.0057	0.980687	50	4438.2	14.66	2225.5	26.04
c2	4.65223	0.06558	0.1563	0.00219	0.993974	32	2950.7	17.62	936.2	12.23
c3	3.731	0.06124	0.27196	0.00394	0.882635	96	1616	25.95	1550.7	19.99
c4	31.03092	0.48089	0.74527	0.01135	0.982723	103	3481.9	19.8	3590.1	41.91
c5	26.55893	0.38536	0.68231	0.00989	0.998984	99	3377.7	17.63	3353.2	37.9
c6	16.78621	0.23674	0.43696	0.00622	0.990764	70	3357.6	16.68	2337	27.89
c7	24.04752	0.36976	0.62192	0.00939	0.981932	93	3368.2	19.62	3117.6	37.34
c8	4.03365	0.08585	0.27845	0.00451	0.761005	92	1719.4	36.63	1583.6	22.72
c9	10.78981	0.17585	0.48833	0.00738	0.927287	104	2462.5	23.09	2563.5	31.95
c10	20.80844	0.29454	0.40629	0.00586	0.981394	58	3801.6	16.06	2197.9	26.84
c11	12.83635	0.18493	0.4071	0.00589	0.995753	72	3047.9	17.44	2201.6	26.97
c12	22.46666	0.32837	0.52337	0.00771	0.992155	77	3532.9	17.31	2713.4	32.63
c13	28.38545	0.43878	0.70351	0.01097	0.991322	100	3432.8	16.72	3434	41.52
c14	11.27464	0.18284	0.46718	0.00711	0.938462	95	2608.7	22.2	2471.2	31.25

Table 1 (*continued*)

Analysis	Isotope ratios					Concordancy	Ages (Ma)			
	$^{207}Pb/^{235}U$	1σ error	$^{206}Pb/^{238}U$	1σ error	rho		$^{207}Pb/^{206}Pb$	1σ error	$^{206}Pb/^{238}U$	1σ error
c15	13.54869	0.20564	0.51545	0.00766	0.979111	97	2749.9	18.76	2679.8	32.58
c16	7.67399	0.12501	0.24111	0.00373	0.949664	45	3061.6	22.23	1392.5	19.39
c17	25.91503	0.38797	0.64164	0.00968	0.992345	93	3434.1	16.21	3195.4	38.01
c18	8.16028	0.12392	0.28543	0.00422	0.973591	56	2891.9	20.49	1618.6	21.18
c19	11.11052	0.16449	0.27982	0.00419	0.988712	47	3407.4	15.56	1590.5	21.12
c20	8.41135	0.12442	0.34336	0.00507	0.998237	72	2632.9	17.59	1902.8	24.31
c21	11.43437	0.20361	0.50353	0.00802	0.894463	105	2506.7	25.59	2628.9	34.4
c22	35.64645	0.53538	0.78729	0.01187	0.996162	104	3610.3	15.99	3743.4	42.82
c23	24.21476	0.36215	0.59353	0.00897	0.989597	87	3449.3	15.77	3003.7	36.28
c24	33.1939	0.51018	0.67446	0.01039	0.997713	89	3737.2	16.24	3323.1	39.99
c25	10.41069	0.17337	0.46701	0.00739	0.950219	100	2473.1	22.48	2470.5	32.46
c26	13.56717	0.206	0.34492	0.00539	0.971645	56	3390.3	15.65	1910.3	25.84
c27	8.70211	0.12664	0.39781	0.00597	0.969723	88	2441.3	16.8	2159	27.55
c28	6.2896	0.09126	0.20512	0.00307	0.969454	40	2997.7	16.05	1202.8	16.44
c29	31.12613	0.45496	0.72494	0.01097	0.965925	100	3527.9	16.14	3514.5	41
c30	10.43797	0.15442	0.4684	0.00706	0.981521	100	2472.3	17.67	2476.6	31.01
c31	29.95877	0.43521	0.72047	0.01085	0.964631	101	3477.9	15.56	3497.8	40.67
c32	30.84217	0.4423	0.44804	0.00645	0.99616	56	4239.2	15.6	2386.5	28.71
c33	9.89421	0.15392	0.46041	0.00712	0.99408	101	2412.5	19.99	2441.4	31.41
c34	16.18132	0.23644	0.43169	0.00622	0.986078	70	3317.5	17.08	2313.3	28.01
c35	29.66077	0.42995	0.70627	0.01067	0.959493	99	3492.8	15.69	3444.4	40.32
c36	16.00487	0.22775	0.41315	0.00616	0.954406	66	3367.8	15.16	2229.3	28.11
c49	21.83041	0.34622	0.58194	0.00935	0.98709	89	3317.2	17.31	2956.6	38.11
c50	13.91691	0.22947	0.5254	0.00832	0.960396	99	2759.7	21.33	2722	35.16
c51	26.99824	0.41195	0.63604	0.00998	0.97244	90	3510.1	15.53	3173.4	39.32
c52	20.82108	0.31579	0.43345	0.00675	0.973936	63	3701.8	15.22	2321.2	30.35
c53	7.4909	0.11021	0.29437	0.00443	0.977635	62	2693.6	16.4	1663.3	22.07
c54	19.41508	0.30097	0.45424	0.00716	0.983459	69	3521.6	16.17	2414.1	31.76
c55	25.24094	0.38009	0.57822	0.00847	0.972768	83	3557	17.98	2941.5	34.6
c56	21.48119	0.3148	0.49387	0.00732	0.988731	73	3549.6	16.97	2587.4	31.59
c57	41.32114	0.604	0.7824	0.01172	0.975811	97	3843.2	15.35	3725.8	42.39
c58	13.14144	0.19636	0.38161	0.00569	0.997889	65	3183.9	18.2	2083.8	26.55
c59	11.26762	0.17324	0.48728	0.00746	0.995736	101	2534.2	18.65	2558.9	32.32
c60	20.73576	0.32428	0.5503	0.00865	0.99491	85	3327	16.89	2826.4	35.95
GODA-2 Sullavai Group										
c1	3.78188	0.07628	0.27683	0.00417	0.746827	98	1607.7	33.16	1575.4	21.07
c2	1.66874	0.04937	0.16275	0.0026	0.53998	92	1052.1	56.91	972	14.4
c3	14.05869	0.2107	0.49314	0.00712	0.963363	90	2880.8	18.65	2584.2	30.75
c4	7.00423	0.11797	0.23618	0.00351	0.882374	46	2947.7	23.58	1366.8	18.3
c7	2.01403	0.06464	0.19346	0.0032	0.515375	105	1082.3	61.79	1140.1	17.29
c8	5.12309	0.1077	0.31279	0.00476	0.723886	91	1938.4	34.53	1754.4	23.36
c9	3.91106	0.22925	0.22483	0.00582	0.441625	64	2045.6	103.38	1307.3	30.63
c10	4.45709	0.08314	0.30434	0.00457	0.805005	99	1735.7	29.23	1712.8	22.57
c11	2.56596	0.05789	0.17199	0.00264	0.680373	58	1769.3	38.25	1023.1	14.51
c12	10.99549	0.18307	0.46287	0.00668	0.866792	95	2581.3	23.98	2452.2	29.43
c14	6.55692	0.10291	0.26909	0.00395	0.93528	59	2622.4	20.32	1536.2	20.09
c15	10.6016	0.17617	0.46698	0.00695	0.895625	99	2504.1	22.6	2470.3	30.56
c16	1.7928	0.2667	0.18407	0.00819	0.299095	115	948.5	285.24	1089.2	44.58
c17	7.7564	0.13789	0.39759	0.0061	0.863022	96	2245.7	25.09	2157.9	28.15
c23	5.56252	0.08737	0.26008	0.00383	0.937564	62	2403.1	20.49	1490.2	19.6
c24	1.59766	0.0368	0.16275	0.00252	0.672227	101	962.7	42.44	972	13.96
c26	3.93717	0.06541	0.28486	0.00417	0.881139	99	1630.1	24.67	1615.8	20.92
c27	11.30919	0.18242	0.48455	0.00718	0.918639	100	2552	21.17	2547.1	31.16
c29	3.9208	0.08259	0.28829	0.00428	0.704793	102	1601.3	35.66	1633	21.42
c30	10.95185	0.18146	0.45495	0.00676	0.896788	93	2603.9	22.18	2417.2	29.96
c31	11.37097	0.19625	0.49386	0.00743	0.871712	102	2529	23.77	2587.4	32.07
c32	11.76188	0.21674	0.49649	0.00765	0.836158	101	2577	26.14	2598.7	32.94
c33	11.26714	0.1912	0.48102	0.00719	0.880829	99	2559.8	23.24	2531.7	31.28
c34	4.27257	0.07537	0.14184	0.00213	0.851278	29	2971.8	24.63	855.1	12.01
c35	3.62141	0.06769	0.18398	0.00277	0.805494	48	2263.5	27.87	1088.7	15.1
c36	9.83326	0.15236	0.38452	0.0057	0.956715	78	2704.8	19.06	2097.4	26.54
c37	10.60831	0.22757	0.47113	0.00766	0.757913	100	2492.9	32.44	2488.5	33.55
c39	11.70832	0.18833	0.42256	0.00627	0.922474	80	2837.3	20.7	2272.1	28.4
c40	11.14465	0.22685	0.48127	0.00757	0.772742	100	2541.6	30.59	2532.8	32.93
c41	2.61041	0.0611	0.22808	0.00353	0.661234	104	1273.9	41.55	1324.4	18.55
c42	5.94814	0.10312	0.26836	0.00403	0.866215	62	2468.1	24.28	1532.5	20.47

analyses, a lone analysis provided a $^{207}Pb/^{206}Pb$ age of 3780 ± 15 Ma. Nineteen other analyses yielded Eoarchaean to Palaeoarchaean ages between 3680 Ma and 3200 Ma, with a probability distribution maximum at ca. 3480 Ma. A second age population of sixteen analyses lies between 2900 Ma and 2300 Ma, with a probability density distribution maximum of ca. 2470 Ma (Fig. 5a). The youngest six >90% concordant analyses yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 1613 ± 19 Ma (MSWD = 0.55). This age is interpreted as the maximum depositional age of this sandstone.

5.2. Somanpalli Group (Biijur) – GODA 04

Despite the distance between the two Somanpalli Group samples, the age-provenance of the two greywackes is similar. Seventy analyses were performed, but only twenty two were within 10% of concordance. One lone analysis yielded a $^{207}Pb/^{206}Pb$ age of 3843 ± 15 Ma, whilst another ten analyses produced $^{207}Pb/^{206}Pb$ Eoarchaean to Palaeoarchaean ages between 3650 Ma and 3300 Ma (Figs. 4b and 5b). These analyses clustered around a probability density distribution maximum of ca. 3500 Ma. Nine analyses yielded $^{207}Pb/^{206}Pb$ ages between 2800 Ma and 2350 Ma, with a maximum at ca. 2480 Ma (Fig. 5b). Two isolated >90% concordant analyses yielded $^{207}Pb/^{206}Pb$ ages of 1719 ± 37 Ma and 1616 ± 26 Ma. This latter age is interpreted as the maximum age of deposition, and is within error of that from sample GODA 03.

5.3. Sullavai Group – GODA 02

Sample GODA2 only yielded thirty analyses, of which twenty were within 10% of concordance. The oldest analysis provided a $^{207}Pb/^{206}Pb$ age of 2881 ± 19 Ma, whereas nine analyses yielded ages between 2600 Ma and 2450 Ma. A weighted mean of these analyses produced an age of 2547 ± 27 Ma (MSWD = 2). Six near-concordant analyses yielded $^{207}Pb/^{206}Pb$ ages between 2300 Ma and 1580 Ma. The youngest three of these yielded a weighted mean age of 1622 ± 29 Ma (MSWD = 0.14). Isolated analyses yielded $^{206}Pb/^{238}U$ ages of ca. 1320 Ma and ca. 1140 Ma (the $^{206}Pb/^{238}U$ age is quoted for analyses younger than 1600 Ma as with increasing youth, these ages are increasingly more precise than $^{207}Pb/^{206}Pb$ ages). The two youngest grains yielded near-identical $^{206}Pb/^{238}U$ ages of ca. 972 Ma. A weighted mean of these two yields an interpreted maximum depositional age of 972 ± 20 Ma.

6. Discussion

6.1. Constraints on the age of deposition of the Purāna sediments in the Pranhita-Godavari Valley

The two maximum depositional ages of the Somanpalli Group samples of 1613 ± 19 Ma and 1616 ± 26 Ma overlap in error with the 1620 ± 6 Ma age of authigenic glauconite from the same Group (Conrad et al., 2011). This suggests that the age of deposition of this Cycle 1 sequence is now well constrained to ∼1620 Ma, at the end of the Palaeoproterozoic.

The maximum depositional age of the Sullavai Group arenite of 972 ± 20 Ma, confirms the relative youth of the siliciclastic Cycle III in the Pranhita-Godavari Valley. This suggests that the Sullavai Group was deposited between this age and the Permian age of the

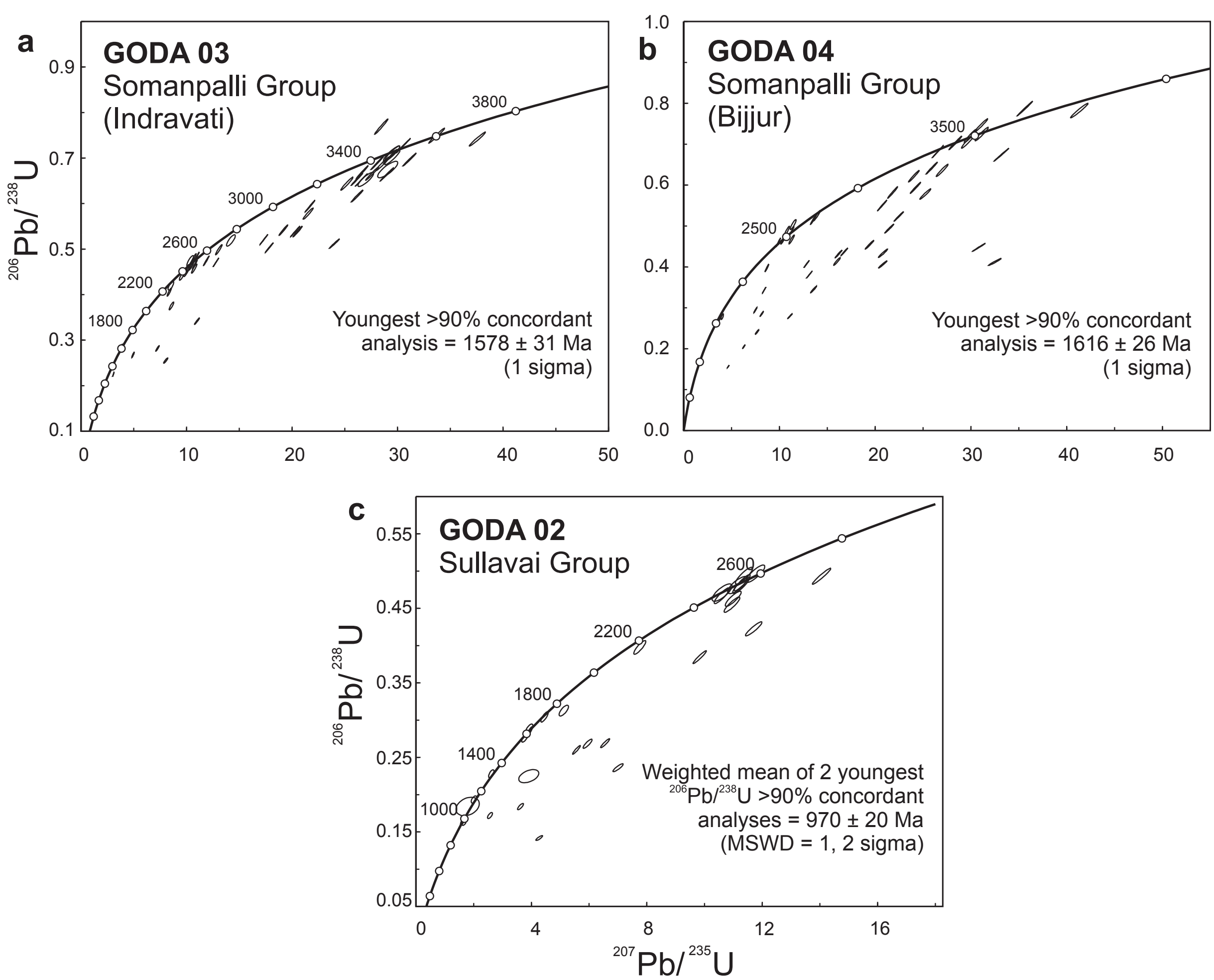

Figure 4. U-Pb LA-ICPMS zircon concordia plots. (a) Concordia plot for all detrital zircon U-Pb data from sample GODA 03 of the Somanpalli Group from the Indravati River. (b) U-Pb detrital zircon data from sample GODA 04 of the Somanpalli Group from near the town of Bijjur. (c) U-Pb detrital zircon data from sample GODA 02, an arenite from the Sullavai Group.

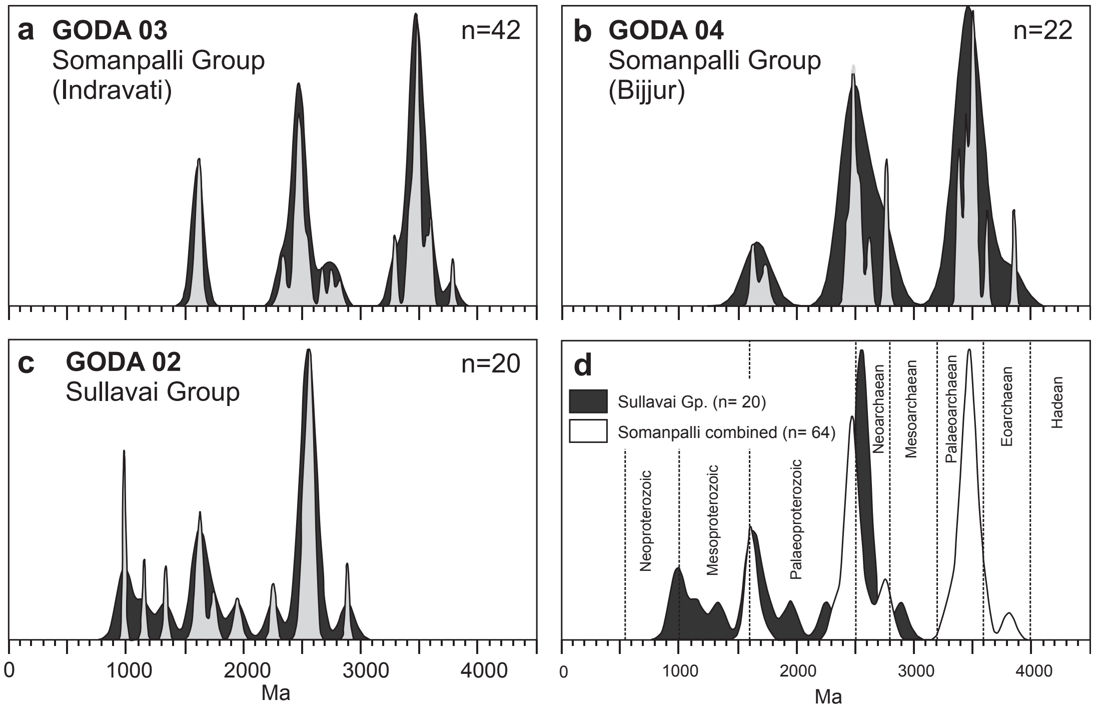

Figure 5. Greater than 90% concordant U-Pb LA-ICPMS zircon data plotted as probability density (light grey) and kernel density estimation (dark grey) plots (in a–c). (a) Sample GODA 03, Somanpalli Group from the Indravati River; (b) GODA 04, Somanpalli Group from Bijjur; (c) GODA 02, Sullavai Group arenite; (d) kernel density estimation plots of all the data, the Sullavai Group data and the combined Somanpalli Group (samples GODA 03 and 04). Plots constructed using software DENSITYPLOTTER (Vermeesch, 2012). Data older than 1400 Ma are plotted as $^{207}Pb/^{206}Pb$ ages, whilst those younger than 1400 Ma are plotted as $^{206}Pb/^{238}U$ ages.

basal Gondwana Supergroup. The overlying Albaka Group has been suggested to contain Cambrian detrital zircons (Chaudhuri et al., unpublished data), but this is yet to be fully published. Whether the Sullavai Group was deposited directly before the Albaka Group, or forms an older Neoproterozoic succession is unknown.

6.2. Provenance of the Pranhita-Godavari Valley Proterozoic-Palaeozoic sedimentary rocks

The distinct tripartite age peaks of the Somanpalli Group samples at ~3500 Ma, ~2480 Ma and ~1620 Ma suggests a source with similar-aged zircons exposed at the surface at ~1620 Ma (either as distinct rocks, or as recycled zircons from previous sedimentary cycles). The minor peaks at ~3800 Ma and ~2750 Ma are also quite distinctive. Presently, the Somanpalli Group crops out against the eastern Dharwar and Bastar cratons and the Karimnagar Orogenic Belt (Figs. 1 and 2). Veevers and Saeed (2009) studied detrital zircons from the Permian to Jurassic Gondwana Supergroup overlying the Purāna sequences in the Pranhita-Godavari Valley. Their study provides an interesting comparison to this one and allows us to examine the changing provenance of the region over 1.5 billion years of Earth history.

Veevers and Saeed (2009) suggested that the Permian–Jurassic of the Pranhita-Godavari Valley were sourced from a drainage system that originated in Antarctica in the region of the Gamburtsev Subglacial Mountains. A qualification to this was the presence of 2900–3470 Ma detritus in Triassic samples. They suggested that these originated in cratonic India – either the Dharwar Craton, or from the Karimnagar Orogenic Belt. Available data from the Karimnagar Orogenic Belt, however, does not support the presence of rocks of suitable antiquity (Santosh et al., 2004). The Western Dharwar Craton does contain rocks of suitable age, but the Eastern Dharwar Craton, the province adjacent to the Pranhita-Godavari Valley, does not (Jayananda et al., 2013). Small enclaves of Palaeoarchaean rocks have been found within the Bastar Craton (Ghosh, 2004) that may explain some of the ~3500 Ma detritus. Possible Indian Eoarchaean sources that might match the minor ~3800 Ma detritus are difficult to find. In the adjacent part of Antarctica, however, protoliths of up to ~3800 Ma have been recorded in the Napier Complex (Harley and Black, 1997) and the Ruker Terrane further south has granitoids and orthogneisses with protoliths of up to ~3500 Ma (Mikhalsky et al., 2001; Boger et al., 2008). Rare detrital zircons of up to ~3500 Ma are also seen in Triassic to Recent sediments and sedimentary rocks of this part of Antarctica (Veevers and Saeed, 2008, 2011). We therefore suggest that these characteristic ancient zircons provide a good fingerprint back to a source in Enderby Land, East Antarctica for the Somanpalli Group (Fig. 6).

Rocks and detritus between ~2750 Ma and ~2480 Ma are found in Enderby Land (Harley, 2003) and other proximal parts of Antarctica and form common detrital components in Antarctica and in the post-Permian of the Pranhita-Godavari Valley (Veevers and Saeed, 2008, 2009, 2011, 2013). In contrast, zircons of the third major age-source, ~1620 Ma, are common in orthogneisses and charnockites from the southern Eastern Ghats region – the Krishna Province (Henderson et al., 2014). The Somanpalli Group, therefore appears to be sourced consistently from the south, from rocks similar in age to those from the Napier Complex of Enderby Land and from the Krishna Province that stitched together the terranes in the latest Palaeoproterozoic (Fig. 6). Possible components from the adjacent late Archaean Indian cratons cannot be ruled out – and may represent part of the ~3500 Ma and ~2480 Ma peaks.

The Sullavai Group shares the latest Archaean/earliest Palaeoproterozoic age peak with the Somanpalli Group, although the age-maximum is slightly older in the Sullavai Group (2547 ± 27 Ma). The Sullavai Group age spectra also lack the >3.0 Ga zircons that are so well represented in the Somanpalli

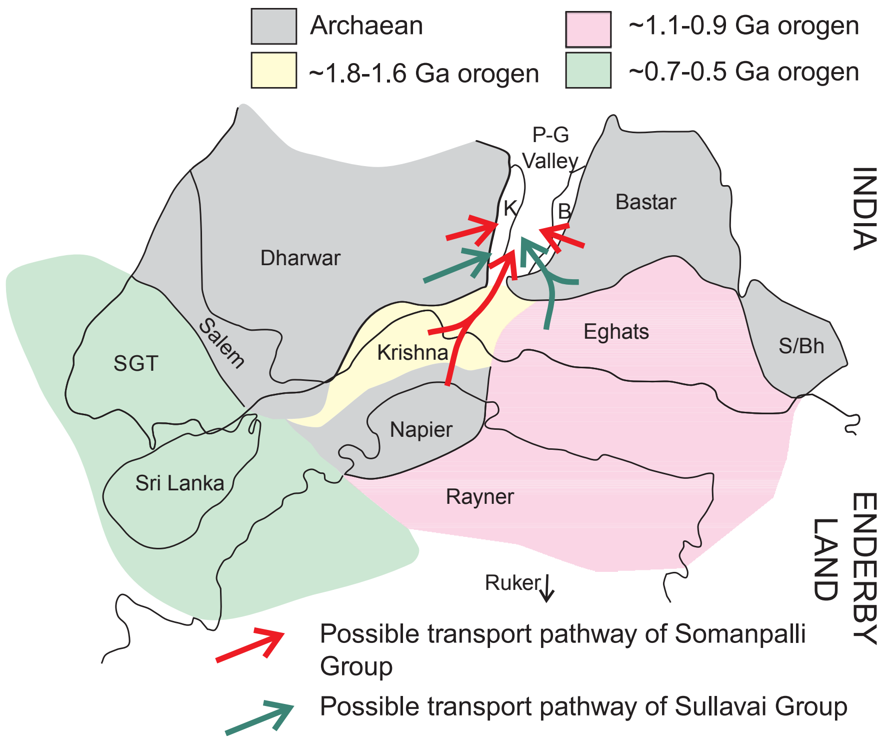

Figure 6. Reconstruction of SE India and Enderby land in Antarctica after the ~1580 Ma collision between the two along the Krishna Province of the southern Eastern Ghats (Henderson et al., 2014). Possible sediment transport pathways of the Somanpalli and Sullavai Groups are highlighted. After Veevers and Saeed (2009). Dharwar = Dharwar craton, Bastar = Bastar Craton, S/Bh = Singhbum Craton, Eghats = Eastern Ghats Orogen, Krishna = Krishna Province, Napier = Napier Complex, Rayner = Rayner Complex, Salem = Salem Block, SGT = Southern Granulite Terrane, K = Karimnagar Granulite Belt, Ruker = Ruker Terrane, B = Bhopalpatnam Granulite Belt, P-G Valley = Pranhita-Godavari Valley.

Group (Figs. 4 and 5), although, admittedly, the data are limited. The late Palaeoproterozoic zircon age peak is also seen in the Sullavai Group detritus, but unlike the Somanpalli Group, Mesoproterozoic zircons are also common and continue down to ~970 Ma. This early Neoproterozoic age for the youngest detrital zircons in the Sullavai Group is consistent with a source from the Eastern Ghats Orogen, where extensive high-grade metamorphism and voluminous charnockite magmatism occurred at this time (Korhonen et al., 2011).

7. Conclusions

The Somanpalli Group is sourced from rocks that are consistent with those found in the Enderby Land in East Antarctica, and from the Krishna Province. They were deposited on a northward dipping palaeoslope and were deposited at ~1620 Ma. The similarity in the maximum depositional age and the published glauconite age suggests that the Somanpalli Group was deposited in a foreland setting (similar to that suggested by Gupta, 2012)—in the foreland to the coeval Krishna Province—that involved the collision of Enderby Land with the Dharwar Craton (Henderson et al., 2014). The high angle of the Pranhita-Godavari Valley to the Krishna Province (Fig. 6), suggests that the basin may have formed as a rift valley in the orogenic foreland, similar to the Rhine Valley in the foreland of the Cenozoic Alps (Şengör et al., 1978).

The Neoproterozoic (to possibly Palaeozoic) Sullavai Group represents renewed deposition in the same basin, but this time demonstrates a different source region that contains the Eastern Ghats Orogen, to the northeast.

Modern detrital zircon geochronology is demonstrating the antiquity and history of pulsed subsidence in this part of India, demonstrating a billion-year scale of basin rejuvenation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2014.03.009.

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