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Article

Microbial community composition and function in groundwater systems of the Deccan Traps

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Abstract

Microbial diversity and functions within the Earth's deep subsurface remain pivotal in the Earth's major biogeochemical activities. Microbial communities of groundwater systems hosted by ~65-million-year-old Deccan basalts are investigated to delineate their characteristics, biogeochemical functions and environmental control. Quantitative PCR-based bacterial cell counts suggest 4.3×10^2–3.9×10^3 cells/mL. 16S rRNA gene sequence analysis shows considerable bacterial diversity and the existence of a core microbiome (16 amplicon sequence variants [ASVs] out of a total of 2020 ASVs) across the groundwater samples. Members of *Burkholderiaceae* and *Moraxellaceae* are predominant taxa within the groundwater. In comparison, the spring water and surface water microbiomes are significantly distinct. Non-metric multidimensional scaling highlights that the basaltic groundwater communities are influenced by local environmental parameters. Analysis of whole metagenomes indicates that the Calvin–Benson–Bassham cycle is a primary mode of carbon fixation in the subsurface water system of the Deccan traps. Metagenome-assembled genomes are affiliated to the genera *Limnohabitans* and *Methylotenera*, among others. Together with the presence of sulfate and nitrate in the groundwater environment, the presence of genes involved in dissimilatory nitrate and sulfate reduction indicates the prevalence of anaerobic/facultative anaerobic lifestyles among the microorganisms in this system. Amplicon and whole metagenome sequence-based analyses suggest the presence of microbial populations involved in local biogeochemical cycling. This study on the geomicrobiology of the water systems of Deccan traps elucidates microbial community composition and biogeochemical function in the igneous rock-hosted deep biosphere.

Keywords: groundwater; Deccan Traps; microbial community; metagenome-assembled genomes; chemoautotrophy; N and S cycling

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Introduction

Microbial diversity and function within the deep Earth subsurface remain pivotal in understanding the major biogeochemical activities of our planet. Despite significant research efforts on microbial life that resides beneath the Earth's surface, the deep biosphere continues to represent one of the "least understood environments till date" (Lopez-Fernandez *et al.*, 2018; McMahon and Parnell, 2014). Although a broad knowledge base on microbial diversity and their patterns of distribution is created through several continental and ocean drilling initiatives covering varied geological settings and ages, a number of fundamental questions on deep life remain poorly resolved. Major questions pertaining to the sustenance of life at greater depths concentrate on two major aspects: (1) who inhabits the deep subterranean environment, and what putative metabolisms support their sustenance in such an aphotic, oligotrophic, multi-extreme habitat, and (2) how do geochemical parameters (*i.e.* various electron acceptors, electron donors, etc.) influence microbial metabolisms and, thereby, shape the microbial community structure in deep environments (Amils *et al.*, 2023; Atencio *et al.*, 2023; Bell *et al.*, 2020; Bomberg *et al.*, 2015; Herzig *et al.*, 2024; Kadnikov *et al.*, 2020; Kieft, 2016; Lollar *et al.*, 2019; Momper *et al.*, 2023; Osburn *et al.*, 2014; Pedersen *et al.*, 2014; Purkamo *et al.*, 2015; Simkus *et al.*, 2016)? Deep subterranean habitats are diverse with respect to geochemical parameters and subsequent microbial colonisation; consequently, the answers to the questions are subjected to the habitat specifications (Amils *et al.*, 2023; Atencio *et al.*, 2023; Bell *et al.*, 2018, 2020; Hernsdorf *et al.*, 2017; Ijiri *et al.*, 2018; Ino *et al.*, 2016; Kadnikov *et al.*, 2020; Momper *et al.*, 2023).

Although different deep biosphere habitats manifest different features, these subterranean environments are typically characterised by oligotrophy, absence of sunlight and photosynthetically derived organic matter, where chemolithoautotrophic organisms are thought to be the primary producers (Pedersen, 2000). Previous studies suggest that geogenic and/or biogenic hydrogen (H_2) facilitates microbial metabolism within these energy-starved subsurface environments (Amils *et al.*, 2023; Hernsdorf *et al.*, 2017; Ijiri *et al.*,

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2018; Nealson *et al.*, 2005; Nyyssönen *et al.*, 2014; Stevens, 1997; Stevens and McKinley, 2000). Under the natural conditions that prevailed in the deep Earth crust, geogenic hydrogen may be produced through serpentinisation, radiolysis of water, degassing of magma-hosted systems, etc. or biologically via fermentation, anaerobic methane oxidation, etc. (Beaver and Neufeld, 2024; Gregory *et al.*, 2019; Nealson *et al.*, 2005). Along with hydrogen metabolism, the interplay of dynamic carbon, nitrogen and sulfur cycles with the involvement of diverse microbial groups make the overall system a complex paradigm (Hernsdorf *et al.*, 2017; Momper *et al.*, 2023). Complex processes such as autotrophic carbon fixation with hydrogen/sulfur oxidation (as a source of electrons/energy) coupled with nitrate reduction are reported to be one of the putative metabolisms plausible in anoxic deep biosphere (Lau *et al.*, 2016). Oxidation of methane and other reduced inorganic molecules, such as ammonia and nitrite, and reduction of sulfate or iron (Fe^{3+}) or manganese (Mn^{4+}) as terminal electron acceptors while assimilating carbon via auto/hetero/mixotrophic processes are also frequently observed in these environments (Casar *et al.*, 2021; Dutta *et al.*, 2018; Momper *et al.*, 2017; Purkamo *et al.*, 2013; Vaccarelli *et al.*, 2021). Interestingly, heterotrophy, fuelled by the metabolic intermediates or products of chemolithoautotrophic metabolism, is also detected in many such environments (Purkamo *et al.*, 2015; Sahu *et al.*, 2022). Deciphering the biogeochemical processes constituted by the complex networks of metabolic transformation by the resident microbial members of any particular deep subsurface environment is identified as one of the major approaches for understanding the different modes of sustenance of life, such as the energetic edge (Ino *et al.*, 2016; Wu *et al.*, 2016a).

A number of deep biosphere studies are conducted in the subterranean water systems across the continents (Hallbeck and Pedersen, 2008; Herzig *et al.*, 2024; Itävaara *et al.*, 2011; Momper *et al.*, 2017; Nyyssönen *et al.*, 2014; Purkamo *et al.*, 2016; Sahl *et al.*, 2008; Wu *et al.*, 2016a). One of the first studies that gave an overview of microbial diversity as well as its function from a genomic point of view was conducted in deep crystalline rock environments of the Fennoscandian shield (Nyyssönen *et al.*, 2014). Taxonomically and functionally diverse populations are observed among different deep subsurface horizons of the Fennoscandian shield, which vary in response to the prevailing lithology and hydrochemistry. Subsequent studies within other deep crystalline rock and groundwater environments gave an extensive overview of the microbial processes that govern the terrestrial subsurface environments (Amils *et al.*, 2023; Bell *et al.*, 2020; Momper *et al.*, 2017; Probst *et al.*, 2018; Wu *et al.*, 2016a). Many of these studies employed genome reconstruction from metagenomes to get better insights into individual genomes of microbes in a microbial community of deep terrestrial subsurface (Atencio *et al.*, 2023; Bell *et al.*, 2018, 2020; Coskun *et al.*, 2024; Hernsdorf *et al.*, 2017; Kadnikov *et al.*, 2020; Momper *et al.*, 2023; Thieringer *et al.*, 2023). Although past research has provided important information on microbial communities inhabiting various continental subsurface environments, the progressively hot and seismically active igneous province of deep continental biosphere within Deccan Traps is comparatively underexplored. Albeit limited, studies initiated by our laboratory (Dutta *et al.*, 2018, 2019a,b) have provided some insights into the endolithic microbial life and their genomic potential. Nevertheless, the nature and function of deep biosphere within the aquifers hosted by the Deccan Traps, and comparison of such microbial life to the rock-hosted one remains uncharacterised, unlike other subsurface environments.

The volcanic province of the deep subsurface of the Deccan Traps is considered to be an unusual extreme environment for life with progressive increase in temperature and lithostatic pressure (at a rate of ~15°C/km and ~26 MPa/km, respectively), low organic carbon (<50 mg TOC/kg) and the presence of multiple heavy metals (Dutta *et al.*, 2018; Goswami *et al.*, 2024; Roy and Rao, 2000; Shukla *et al.*, 2022). In the present study, microorganisms inhabiting the aquifers deep-seated within the one of the largest continental flood basalt, *i.e.* the Deccan Traps, and their interaction with surrounding rock matrix is investigated through a combination of geochemistry, metataxonomics, and metagenomics followed by genome reconstruction techniques. Aquifer-inhabiting planktonic and rock-inhabiting endolithic microorganisms have been investigated to identify the core microorganisms. The knowledge base developed through this study can be used for gathering further information on global subsurface microbial abundance, diversity, and metabolism.

The Deccan Traps in western India (also known as Deccan Volcanic Province) represent one of the largest continental flood-basalt provinces, with an approximate area of >0.5 million km^2 and a total thickness of >2 km near the eruptive centre (Bhaskar Rao *et al.*, 2017; Schoene *et al.*, 2015). The ~65-million-year-old Deccan basalts are underlain directly by granitic basement rocks of Precambrian age (~2700 Ma) with a thin intermediate, weathered zone. Apart from its geological importance, this volcanic province has gained considerable scientific attention owing to the well-known Reservoir Triggered Seismicity within the Koyna Seismogenic Zone (KSZ) (Roy, 2017). The KSZ has experienced recurrent seismic activity during the past five and half decades, starting soon after the impoundment of the Shivajisagar (Koyna) water reservoir on the Koyna River in 1962 (Gupta *et al.*, 2015). Geological mapping combined with geophysical and geochemical studies carried out in the past provide crucial information about the subsurface fault-fracture systems in this seismogenic zone (Goswami *et al.*, 2019, 2020, 2024). However, the characteristics of microbial life that exist in the deep biosphere of this igneous province remain unexplored, mostly due to difficulty in accessing the deep subsurface samples. Recent scientific drilling (up to several kilometres below the surface) enabled geomicrobiologists to explore deep life hosted by the igneous crust using the rock cores recovered. These studies conducted on the basaltic and granitic rocks provided evidence of bacterial and archaeal life within this extreme realm, including the characterisation of piezophilic bacteria and various chemolithotrophic bacterial populations thriving in the deep biosphere (Dutta *et al.*, 2018, 2019a,b; Mandal *et al.*, 2022; Saha *et al.*, 2024; Sahu *et al.*, 2022). In comparison with these, microbial life within the deep groundwater of this igneous province remained uncharted until the aquifer samples were available for geomicrobiological analysis post establishment of the deep boreholes. The present study was therefore conducted to investigate the microbial community structure and function of the groundwater systems of Deccan Traps, identify the local geochemical factors that probably control the microbial communities and ascertain if the groundwater system represents a distinct ecological niche as compared to the surface water system of this igneous province. Overall, the study aims to provide a better understanding of the nature and function of deep microbial life as guided by the physicochemical factors of the Deccan Traps.

Materials and methods

Sample collection

Water samples were collected from three groundwater sources (bore wells), one natural spring and two surface water sources (Koyna River and Koyna Reservoir) of the Koyna-Warna region

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Table 1. Hydrochemical characteristics of the water samples. "ND" denotes "not detected". GW, groundwater; GWS, groundwater seepage; SW, surface water

Sample details		KD [SW]	KR [SW]	PBW [GWS]	BW [GW]	BGRL [GW]	DBW [GW]
Location		17°24'34.4"N, 73°44'38.4"E	17°21'03.2"N, 73°52'43.8"E	17°18'15.9"N, 73°47'36.1"E	17°09'01.0"N, 73°40'03.5"E	17°17'52.0"N, 74°07'42.0"E	17°17'56.5"N, 73°44'18.6"E
Depth (m)		0	0	2	100	100	1027
Elements (mg/L)	Ca	12.8	11.0	21.2	29.3	32.1	10.0
	Fe	142.1	177.8	113.5	170.7	135.0	106.4
	K	16.0	15.7	9.3	14.3	15.5	16.0
	Mg	8.6	6.7	16.9	25.0	27.8	5.8
	Na	17.1	16.9	10.4	15.5	16.6	17.2
Carbon (mg/L)	TOC	2.8	2.2	2.5	2.1	1.9	2.2
	TIC	3.6	5.7	2.8	3.0	7.1	5.2
	TC	7.9	9.4	6.7	6.6	10.4	8.9
Organic acid (μg/L)	Acetate	0.05	0.03	0.04	0.02	0.01	0.05
	Succinate	0.09	0.05	0.08	0.05	0.02	0.10
	Pyruvate	0.00	0.00	0.00	0.00	0.00	0.00
	Citrate	0.00	0.00	0.00	0.00	0.00	0.00
	Oxalate	0.20	0.16	0.19	0.15	0.12	0.20
	Lactate	0.19	0.11	0.17	0.10	0.03	0.20
Anions (mg/L)	Cl^-	232.4	330.6	295.6	9.9	500.6	595.1
	SO_4^{2-}	156.6	312.7	140.6	0.0	209.3	266.3
	NO_3^-	24.0	36.0	21.0	0.0	50.6	61.0
	NO_2^-	2.4	1.6	0.6	3.1	1.3	4.6
	PO_4^{3-}	14.0	22.6	6.6	0.0	41.3	52.0
	HCO_3^-	49.2	2.2	52.0	4.8	10.9	13.6
Others	$\delta^{18}O$	–4.1	–4.7	–6.3	–4.0	–3.9	–2.5
	δ^2H	–44.0	–33.6	–45.2	–34.0	–34.6	–23.4
	pH	7.5	7.8	6.4	8.2	7.8	8.1
	DO (ppm)	5.0	3.1	3.5	1.7	4.7	4.3
	Conductivity (μS/cm)	352.0	403.0	285.0	220.0	325.0	296.0
No. of bacterial cells (per litre)		ND	547,000	3,930,000	ND	3,090,000	433,000
No. of archaeal cell count (per litre)		ND	ND	ND	ND	850	ND
dsrB copy number (per litre)		ND	148	1270	ND	3340	1080

(Fig. S1; Table 1). The sites used for water sampling were: (1) the Koyna pilot borehole KFD1 in Gothane, drilled at the centre of a 2 × 2 km seismic cluster in the northcentral part of the Koyna seismogenic zone, near the Donichawadi fault (sample obtained from a depth of 1027 m, referred to as DBW in this manuscript); (2) a tube well adjacent to the borehole KBH-5 in Phansavale, located in the vicinity of a seismic cluster in the southwestern fringes of the Koyna seismogenic zone, adjoining the western face of the Western Ghats escarpment (depth 100 m, referred to as BW in this manuscript); and (3) a groundwater well near Karad, about 40 km to the east of the Koyna seismogenic zone (depth 100 m, referred to as BGRL in this manuscript). For groundwater sampling, water from each of the wells was flushed out via continuous pumping (for 15–30 min) until the dissolved oxygen level reached a steady state (as monitored by a Thermo Orion multi-parameter probe). The spring water (referred to as PBW in this manuscript) was sampled from the water tank which received the slow-flowing water from the spring. For the surface water, multiple subsamples were collected from the Koyna River (referred to as KR in this manuscript) and Koyna Reservoir (referred to as KD in this manuscript). From each site, 2–4 L of water was collected in sterile containers and stored at 4°C for shipment. The samples were stored at 4°C in the laboratory until further analysis.

Hydrochemical analysis

Measurement of major elements was conducted using Inductively coupled plasma mass spectrometry (ICP-MS) (iCAP Q, Thermo Scientific). Cavity ring-down spectroscopy (L2130i Picarro) was used to measure stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δ^2H). Major anions (Cl^-, NO_2^-, SO_4^{2-}, NO_3^-, Br^- and PO_4^{3-}) were measured using a Dionex ICS 2100 (Thermo Scientific). Total organic

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carbon (TOC), total inorganic carbon (TIC), and total carbon (TC) were measured using an OI analytical TOC analyser. The alkalinity of the water samples was measured using U.S. Environmental Protection Agency (US EPA) method 310.2. Measurement of pH, dissolved oxygen (DO), and conductivity was done using highly sensitive probes (Orion) fitted with an Orion multimeter (Thermoelectron Corporation). For measurements of organic acids, a 20 µL sample was injected into the Ultimate High-Performance Liquid Chromatograph (Dionex® 3000 U-HPLC, Thermo Fisher Scientific). A C18 reverse-phase analytical column was used with a mobile phase of a binary mixture of solvents: (1) water (30%) and (2) acetonitrile (70%). The separation was performed at room temperature, and the flow rate was maintained at 1 mL/min. The compounds were monitored at wavelengths of 254, 265, 286 and 295 nm. The calibration curves consisted of five standard solutions ranging from 0.1 to 50 mg L^{-1}. Chromeleon 6.8 software was used for data acquisition and integration.

Extraction of DNA

For each sample, 1000 mL of water was filtered using a sterile 0.22 µm filter, and total DNA was extracted from the filters using a Metagenomic DNA Isolation kit (Epicentre) following the manufacturer's protocol. The quality of the extracted DNA and its concentration were measured using a NanoDrop 2000 spectrophotometer, followed by fluorometric quantitation using Qubit (Thermo Fisher Scientific).

Quantitative polymerase chain reaction

Quantification of the copy number of the structural (bacterial and archaeal specific 16S rRNA gene) and functional (*dsrB*) genes has been done through quantitative polymerase chain reaction (qPCR) following the methods reported by Dutta *et al.* (2018). Details of the qPCR primers used are provided in Table S1. All the reactions were set in triplicate. Bacterial 16S rRNA gene copy numbers were determined in each sample by comparing the amplification result to a standard dilution series ranging from 10^2 to 10^{10} of plasmid DNA containing the 16S rRNA gene of *Achromobacter* sp. MTCC 12117. Genes encoding archaeal 16S rRNA and *dsrB* were PCR amplified from the metagenome, cloned into a TA cloning vector, and plasmid DNAs for each gene targets with copy numbers 10^2 to 10^{10} were used as standards for quantitation purposes. Quantitative PCR has been performed in Quant Studio 5 with Power SYBR green PCR mastermix (Invitrogen), with a primer concentration of 5 pM. Melting curve analysis was run after each assay to check PCR specificity.

16S rRNA gene amplification and sequencing

Following the quality check, extracted DNA were subjected to amplification of the V4 region of the 16S rRNA gene using primers 515F/806R (Bates *et al.*, 2011) (Table S2). On purification of the PCR products, further sequencing was done on the Ion S5 platform (Thermo Fisher Scientific). Refer to Table S2 for a detailed procedure. The sequenced reads were submitted to the short read archive under BioProject ID PRJNA445925.

Amplicon data analysis and contamination removal

Raw data obtained from Ion S5 were analysed through the QIIME 2 amplicon-2024.10 (Bolyen *et al.*, 2019) bioinformatics pipeline. Default parameters were used with each module, unless specified otherwise. Along with the reads from the samples, a reagent control (SRA Accession: SRR35284829) was also included in the amplicon data analysis. This control sample was created by subjecting nuclease-free water to the same DNA extraction and amplicon sequencing procedure as the samples. All datasets were quality filtered, clustered, denoised and chimera filtered using DADA2 with the parameters "denoise-single --p-trunc-len 270 --p-trim-left 30 --p-pooling-method pseudo --p-min-fold-parent-over-abundance 2" (Callahan *et al.*, 2016). The ASVs obtained were assigned taxonomy using the "feature-classifier classify-sklearn" module with the naive Bayes classifier "GG-2024.09.backbone.v4.nb.sklearn-1.4.2" pre-trained on Greengenes2 2024.09 (which is in turn is based on GTDB r220) (Bokulich *et al.*, 2018; McDonald *et al.*, 2024; Pedregosa *et al.*, 2011). Based on recommendations by Sheik *et al.* (2018) and techniques used by Purkamo *et al.* (2020), contamination removal was performed by removing all ASVs unassigned to domains and those affiliated to Eukarya, mitochondria, chloroplast, *Streptococcaceae*, *Propionibacteriaceae*, *Lactobacillaceae*, *Escherichia-Shigella* and *Staphylococcaceae.* The reagent control was used to run "quality-control" modules with "decontam-identify" and "decontam-remove" parameters (Davis *et al.*, 2018). Finally, singletons (ASVs with a total of only one read across samples) were removed as suspected contaminants, and the retained ASVs were used for determining relative abundance and core ASVs. Diversity parameters were determined by rarifying all samples to 180,000 reads and then using the "diversity alpha" module.

Statistical analysis and phylogenetic tree construction

The relative abundance of core ASVs of the groundwater samples (BGRL, BW, DBW) was determined at the genus level and used to calculate Spearman's rs correlation with the geochemical characteristics of the respective samples. Euclidean distances between the correlations were used to plot the Unweighted Pair Group Method with Arithmetic mean (UPGMA) dendrogram. These statistical analyses were performed with PAST v4.12b (Hammer *et al.*, 2001). Non-metric multidimensional scaling (NMDS) based on the Bray–Curtis dissimilarity was conducted for the microbial communities at the family level. Families having greater than 1% average abundance across all the samples were considered for this analysis. The function envfit was used to fit environmental vectors to the ordination plot using the vegan package (Oksanen *et al.*, 2025) in R. NMDS analysis of microbial community structure was conducted using R and R Studio. Ten of the ASVs with the highest relative abundance (>2% on average) in groundwater samples were subjected to phylogenetic analysis. National Center for Biotechnology Information (NCBI) databases were queried with the blastn suite to find the closest matches for these ASVs from extreme environments. The ASVs were grouped by their order and aligned with ClustalX2 (Larkin *et al.*, 2007). A neighbour-joining tree was created from the alignment using MEGA 11, with the bootstrap method (n = 1000), Jukes–Cantor substitution model, gamma distribution (G = 1.00) rates among sites and pairwise deletion treatment (Tamura *et al.*, 2021). The phylogenetic tree was visualised with the ggtree v3.12.0 R package (Xu *et al.*, 2022).

Whole metagenome sequencing and analysis

Metagenomes of three water samples (two groundwater samples and one surface water sample) were considered for whole metagenome sequencing. Following metagenomic extraction, DNA was enzymatically digested and size selection was made using the E-Gel

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electrophoresis system (Invitrogen, Thermo Fisher Scientific). After size selection, DNA was ligated with Ion Xpress barcode adapters and pooled together for emulsion PCR using the Ion OneTouch™ 2 System (Thermo Fisher Scientific). The PCR product was sequenced using the Ion S5 platform. Quality checking of the trimmed paired-end reads was conducted using FastQC (version 0.11.7). Trimmed sequences were assembled using SPAdes assembler (Bankevich *et al.*, 2012) using default parameters. Quast 4.3 was used for evaluations of metagenomic assemblies and different assembly statistics (Gurevich *et al.*, 2013). Best k-mer was selected on the basis of longest contigs and N50 value for different samples and was annotated using the Genomes OnLine Database (GOLD) v.6 (Mukherjee *et al.*, 2017). Kyoto Encyclopedia of Genes and Genomes (KEGG)-based annotation was selected for further analysis. The annotated data are available under IMG GOLD Analysis Project IDs Ga0247434 (PBW), Ga0247435 (DBW), and Ga0247436 (BGRL). Heatmaps were created to compare metagenomic inventories of rock and water samples with respect to carbon, sulfur, and nitrogen cycles using the pheatmap package in R (Kolde and Kolde, 2015). The annotated data for rocks were based on the analysis reported by Dutta *et al.* (2018).

For reconstructing metagenome-assembled genomes, the single-end metagenome sequencing raw reads obtained were reverse complemented in silico with seqtk-v1.4 (r122) (H. Li, 2016). Read quality filtering, human contamination removal, assembly, binning, bin refinement and reassembly were performed with the MetaWRAP v1.3.2 pipeline and the tools therein using default settings unless specified otherwise (Uritskiy *et al.*, 2018). Filtered reads were concatenated for co-assembly with MEGAHIT v1.2.9 (D. Li *et al.*, 2015). Binning was performed in single-end, "universal" (bacteria and archaea) mode using MetaBAT 2 v2.12.1, MaxBin 2.0 v2.2.7, and CONCOCT v1.1.0 (Alneberg *et al.*, 2014; Kang *et al.*, 2019; Wu *et al.*, 2016b). Bin refinement was performed using MetaWRAP's bin_refinement module with a minimum completion threshold of 50% and maximum contamination of 10%. The resulting bins were used to determine relative abundance in terms of genome copies per million filtered reads using the quant_bins module, and then refined bins were reassembled using identical thresholds. The samples were clustered via the UPGMA (Unweighted Pair Group Method with Arithmetic mean) algorithm using the Bray–Curtis similarity index and a bootstrap of 1000, with the help of PAST v4.12b (Bray and Curtis, 1957; Hammer *et al.*, 2001). Completeness of the bins based on the presence of lineage-specific marker genes was calculated using CheckM v1.0.18, and quality was inferred based on standards delineated by Bowers *et al.* (2017; Parks *et al.*, 2015). Taxonomy assignment was performed using GTDB-Tk v2.4.0 (database r220) (Chaumeil *et al.*, 2020). Functional annotation was performed in metagenome mode using the eggNOG-mapper v2.1.12 with eggNOG DB v5.0.2, employing Prodigal v2.6.3 for gene prediction while searching via MMseqs2 v15.6f452, with default settings (Cantalapiedra *et al.*, 2021; Huerta-Cepas *et al.*, 2019; Hyatt *et al.*, 2010; Steinegger and Söding, 2017). DRAM 1.4.0 was used for functional annotation of Metagenome-assembled genomes (MAGs), assessment of pathway completeness, and categorising different microbial metabolisms (Shaffer *et al.*, 2020).

Results

Hydrochemical characteristics of water samples

The hydrochemical characteristics of the water samples were analysed to ascertain the local physicochemical conditions available to the inhabiting microbial communities (Table 1). Groundwater samples were found to be slightly alkaline in nature (pH 7.8–8.2), having low dissolved oxygen (1.7–4.7 mg L^{-1}) and organic carbon (1.9–2.2 mg L^{-1}). The inorganic carbon content of these samples, however, was relatively higher (3.0–7.1 mg L^{-1}), particularly compared to their surface water counterpart. Diverse concentrations of the anions (Cl^- 9.9–595.1 mg L^{-1}, NO_2^- 0.6–4.6 mg L^{-1}, NO_3^- 0–61 mg L^{-1} and PO_4^{3-} 0–52 mg L^{-1}) and elements (Ca 10–32.1 mg L^{-1}, Fe 106.4–177.8 mg L^{-1}, Mg 5.8–27.8 mg L^{-1}, K 9.3–16.0 mg L^{-1} and Na 10.4–17.2 mg L^{-1}) were detected. An overall greater concentration of anions and elements was detected in groundwater samples than in surface water. However, the concentration of Fe was found to be higher in surface water. Among the groundwater samples, DBW showed relatively higher concentrations of Cl^-, SO_4^{2-} and NO_3^-. The values of $\delta^{18}O$ and δ^2H in the samples showed variation but indicated their meteoric origin (Das *et al.*, 2020; Hosono *et al.*, 2020). The DBW sample showed the lowest values of $\delta^{18}O$ and δ^2H. Non-metric multidimensional scaling based on the geochemical characteristics of the samples showed distinct patterns of the partitioning of groundwater and surface water samples (Fig. S2). It was highlighted that the groundwater ecosystems of the Deccan Traps were mainly constrained by pH, total organic carbon (TOC), TIC, Mg, Ca, NO_3^-, Fe and SO_4^{2-}. Among the organic acids tested, oxalic and lactic acids were detected at relatively higher concentrations (oxalic acid 0.12–0.20 mg L^{-1} and lactic acid 0.03–0.20 mg L^{-1}), followed by acetic acid (0.01–0.05 mg L^{-1}) and succinic acid (0.02–0.10 mg L^{-1}). Principal coordinates analysis (PCoA) based on major hydrochemical parameters, along with organic acids detected in the samples, also showed the distinctive nature of groundwater compared to its surface water counterpart (Fig. S3).

Quantitative estimation of microbial cells and dissimilatory sulfite reductase gene

Quantitative PCR-based estimation of bacterial 16S rRNA and *dsrB* genes was possible in all but two samples (KD and BW). The estimated bacterial cell counts, as obtained through qPCR, showed 4.3×10^2–3.9×10^3 cells mL^{-1} (Table 1) (assuming an average of 4.2 16S rRNA gene copies/genome of bacteria; Stoddard *et al.*, 2015). The archaeal 16S rRNA gene was detected only in the BGRL, showing a presence of around 8.5×10^2 cells L^{-1}. Gene fragments of the *dsrB* gene were detected in the same four samples whose bacterial 16S rRNA gene copy number was estimated. Deep subsurface water samples (BGRL and DBW) yielded 1.08×10^3–3.34×10^3 copies L^{-1}, while the surface water sample KR showed a lower abundance of *dsrB* (1.48×10^2 copies L^{-1}).

16S rRNA gene sequence data and alpha diversity analysis

After quality filtering, totals of 939,455 and 691,998 reads were obtained from the groundwater and surface water samples, respectively. These quality-filtered reads were grouped into 2020 and 1596 ASVs for groundwater and surface water, respectively (Table S3). The average numbers of filtered reads and ASVs obtained per groundwater sample were 313,152 and 705, respectively, while 345,999 reads and 847 ASVs were obtained for surface water samples on average. Among the groundwater samples, the highest number of ASVs was obtained for BGRL (1466 ASVs). Most of the ASVs were affiliated to bacteria (>98.86% for all samples) and a small fraction (<1.14 % for all samples) was affiliated to archaea. The Shannon and the Simpson indices indicated that microbial communities of the groundwater were relatively less diverse and uneven compared to their surface water counterparts. Interestingly,

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only 16 of 2020 ASVs were shared among the three samples (Table S3). These shared ASVs, representing the core community of the groundwater, covered 4.69–36.95%, with the highest in the sample from the deepest sample (DBW, 1027 mbs).

Microbial community analysis

Taxonomic affiliation showed the presence of 61 bacterial and four archaeal phyla. Pseudomonadota was the most abundant phylum across the samples (Fig. 1a). Based on average abundance, Pseudomonadota accounted for 88.41–98.93% of the groundwater communities, whereas in the surface water it covered only 30.08% (KD) and 35.64% (KR). However, spring water (PBW) showed an abundance of Proteobacteria (65.69%) and Deinococcota (33.34%). The rest of the major populations were consisted of Actinomycetota, Deinococcota, Bacteroidota, Planctomycetota, Verrucomicrobiota, and Cyanobacteriota in the bacterial domain and Thermoproteota and Nanoarchaeota in the archaeal domain. On examining KD and KR, it was interesting to note that Actinomycetota, Bacteroidota, Planctomycetota and Verrucomicrobiota corresponded to significantly higher proportions in these surface water samples in addition to Pseudomonadota.

Among the most abundant families, *Burkholderiaceae*_A_595421 was detected as the predominant one across the three deep groundwater samples (13.93–58.65%), followed by PIVM01 (in class Gammaproteobacteria, 0–43.46%), *Moraxellaceae* (2.87–12.49%), and *Nevskiaceae* (0.02–26.51%) (Fig. 1b, Table S4). Among the other major taxa in groundwater samples, *Sphingomonadaceae*_486827, *Methylophilaceae* and *Pseudomonadaceae*, along with *Burkholderiaceae*_A_566089, *Minwuiaceae* and *Caulobacteraceae*, were detected in fewer groundwater samples. Surface water microbial communities (for samples KD and KR) were dominated by *Nanopelagicaceae* (12.69–21.75%), *Burkholderiaceae*_A_595421 (12.37–14.57%), *Pseudomonadaceae* (0.009–17.57%), UBA1268 (under order Pirellulales, 15.39–8.33%), *Chitinophagaceae* (5.21–7.68%), and *Cyanobiaceae* (1.86–10.56%). The spring water community was found to be quite interesting because it was mainly composed of members of only three families, each present in nearly equal proportions (*Burkholderiaceae*_A_595421 [36.15%], *Deinococcaceae* [33.34%], *Pseudomonadaceae* [28.56%]) and together covering 98.05%.

Among the taxa which could be identified at the genera level PIVM01, *Hydrocarboniphaga*, *Methylotenera*_A_557637, *Novosphingobium*, *Fluviicoccus*, *Pseudomonas*_E_648040, *Comamonas*_F_589250, *Sphingorhabdus*_C (*Nevskiaceae*), *Acinetobacter,* and *Limnobacter* were most prominent in the groundwater. *Cavicella*, *Pararheinheimera*, *Caulobacter*_487784 etc., were the other prominent genera present in these samples. In comparison to the groundwater, the surface water samples showed a characteristic abundance of unclassified *Nanopelagicus*, *Rhodoferax*_C, *Prosthecobacter*, *Aquirufa*_904070, *Caulobacter*_487784, *Priestia*_289346, *Limnohabitans*_A and *Parasediminibacterium. Deinococcus*_B, *Pseudomonas*_E_647464, and *Janthinobacterium*_571526 members were the major genus (covering 79.77% of the community) represented in the spring water community. Phylogenetic analysis of the predominant ASVs from the major orders showing high sequence identity and resemblance with organisms of similar taxonomic groups reported from deep subsurface, igneous crust or volcanic or other extreme environments corroborated their strong ecological, physiological and metabolic attributes (Fig. S4).

Non-metric multidimensional scaling was used to describe the distribution of different samples according to the relative abundance of microbial taxa in relation to geochemical parameters (Fig. 2a). The figure highlights the geochemical variability among the samples and demonstrates their relative control on the microbial community composition. A set of environmental parameters, especially pH, NO_2^-, PO_4^{3-}, Ca, K, and Mg, explained their control in shaping the groundwater community mostly through regulating the abundance of *Burkholderiaceae*_A_595421, *Nevskiaceae*, *Sphingomonadaceae*_486827, PIVM01 (in class Gammaproteobacteria), *Methylophiliaceae* and *Moraxellaceae.* Greater TOC, DO, HCO_3^-, and conductivity segregated the surface water samples and the spring water with major contributions from *Spirosomataceae*, *Verrucomicrobiaceae*, *Cyanobiaceae*, *Chitinophagaceae*, *Flavobacteriaceae,* and *Bacillaceae*_H_289398.

Analysis of the core community of the groundwater

Sixteen ASVs of the groundwater community constituted the core microbiome (shared ASVs across three groundwater samples) (Table S6). Identification of these compositional core members was considered to be imperative in terms of providing the foundation for understanding the unique contribution of dominant, rare and common taxonomic groups (Shade and Handelsman, 2012). Taxonomic analysis of the shared ASVs showed their affiliation with three classes and eight families. A maximum number of the core ASVs (11 of 16 ASVs) were affiliated with Gammaproteobacteria (major family, *Burkholderiaceae*, *Moraxellaceae*), followed by Alphaproteobacteria (four of 16 ASVs, *Sphingomonadaceae* and *Caulobacteraceae*) and Bacteroidia (one ASV in the core microbiome, *Chitinophagaceae*).

The distribution patterns of the core ASVs (at class level) correlated with the geochemical parameters, and they clustered in five groups mainly according to the geochemistry of the water samples (Fig. 2b). *Hydrocarboniphaga*, *Aquabacterium*_A_591266 and *Phenylobacterium* (members of Group 1) were positively correlated with TOC. In contrast, Limnobacter and *Sediminibacterium* (members of Group 5) were negatively correlated with TOC. Group 2 members (*Acinetobacter*, uncultured *Burkholderiaceae*_A_595421, *Sphingorhabdus*_C, *Cavicella* and *Ramlibacter*_588642) were positively correlated with pH, whereas Group 3 (*Caulobacter*_487784, *Novosphingobium* and u_*Moraxellaceae*) members were negatively correlated with pH. *Pseudomonas*_E_648040 (member of Group 4) was found to be positively correlated with SO_4^{2-}, Cl–, Na, K, HCO_3^-, PO_4^{3-} and NO_3^-. Members of Group 2 were negatively correlated with conductivity, total carbon, DO and TIC, whereas members of Group 3 were positively correlated with the same environmental variables.

Analysis of metagenome-assembled genomes

Whole metagenome data from two groundwater samples (BGRL and DBW) and the spring water (PBW) yielded six high-quality (>90% completeness and <5% contamination) and 10 medium-quality (>50% completeness and <10% contamination) bins (Table S7). Quality thresholds suggested by Bowers *et al.* (2017) were followed. These genomic bins were used for detailed annotation and analysis (Fig. 3; Table S8). The selected medium and high-quality draft bins showed affiliation to diverse bacterial taxa spanning the families *Alteromonadaceae* (genus *Pararheinheimera*), *Burkholderiaceae* (*Rhodoferax*, *Janthinobacterium*, *Undibacterium* and *Limnohabitans*), *Deinococcaceae* (*Deinococcus*), *Methylophilaceae* (*Methylotenera*), *Moraxellaceae* (*Acinetobacter*, *Fluviicoccus*, *Perlucidibaca* and JAJNDL01), *Nevskiaceae* (*Hydrocarboniphaga*), and *Sphingomonadaceae* (*Sphingorhabdus* and *Novosphingobium*). Among these, all but *Deinococcus* were

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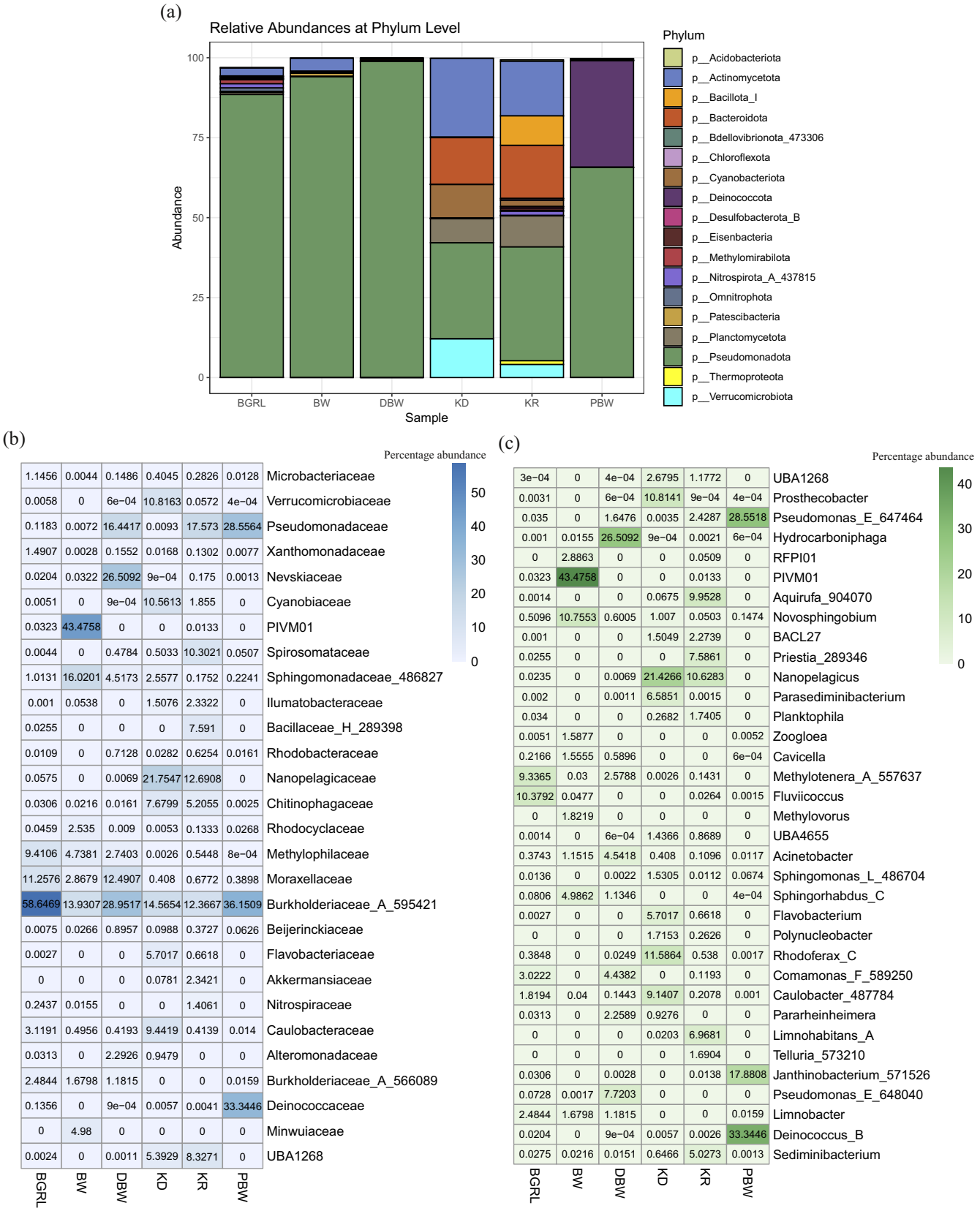


Figure 1. Microbial community composition of the water samples. (a) Relative abundance of major taxa (at Phylum level) present in the microbial communities. (b and c) Heat maps displaying the relative percentage abundance of major microbial families (b) and genera (c).

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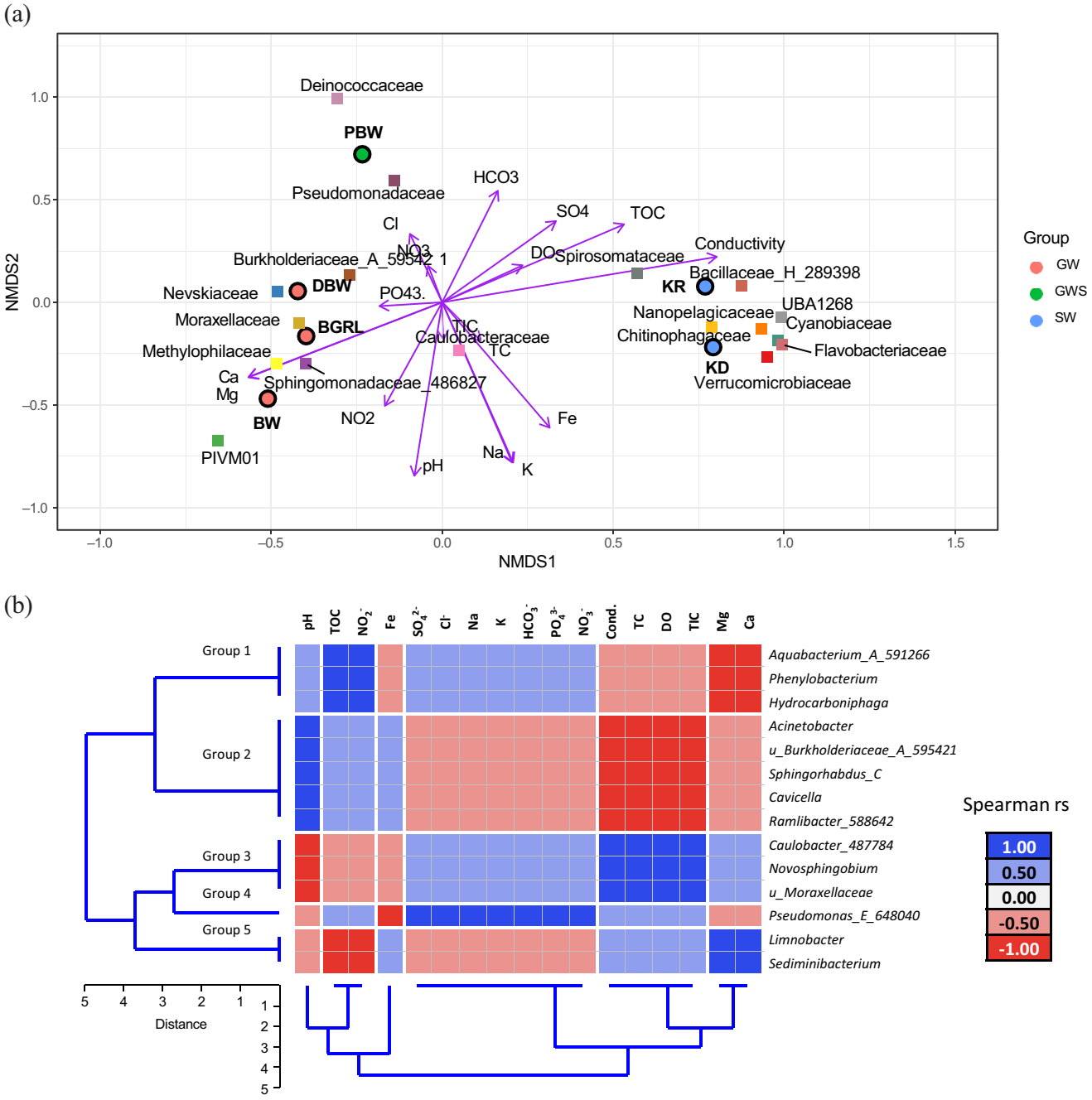


Figure 2. (a) Non-metric multidimensional scaling (NMDS) plot of major microbial families with geochemical parameters (stress: 2.740543×10^{-5}). In the NMDS plot, the circles represent samples, the squares represent families and the vector represents geochemical parameters. GW, groundwater; GWS, groundwater seepage; SW, surface water. (b) Heatmap of the Spearman correlations between core amplicon sequence variants (ASVs) with the geochemical parameters. Dendrogram displaying the unweighted pair group method with arithmetic mean (UPGMA)-based clustering of microbial classes and the geochemical parameters.

members of phylum Pseudomonadota (formerly Proteobacteria). Of the Pseudomonadota, 13 bins were of class Gammaproteobacteria and two were of Alphaproteobacteria.

Abundances of the bins across the samples were compared and it was found that all bins were present in all the samples, although their abundance varied considerably from <1 to 491 genome copies per million filtered reads, thus suggesting a ubiquity of these members. The most abundant bins in BGRL were 9, 3, 15, 12, and 11, affiliated to the genera *Limnohabitans*, *Methylotenera*, *Fluviicoccus*, *Deinococcus,* and *Limnohabitans*, respectively, all of which were present in the other samples in low to moderate abundances. PBW was dominated by bins 6, 1, 12, 2, and 11 (*Rhodoferax*, *Janthinobacterium*, *Deinococcus*, *Undibacterium* and *Limnohabitans*, respectively) of which bins 11 and 12 are shared with BGRL. Bins. 4, 7, 14, 10, and 5 (*Hydrocarboniphaga*, *Moraxellaceae* genus JAJNDL01, *Methylotenera*, *Pararheinheimera,* and *Novosphingobium*, respectively), were predominant in DBW, all of which showed low abundance in the other two samples. UPGMA clustering of metagenome samples on the basis of bin abundances using the Bray–Curtis dissimilarity showed that both groundwater samples (BGRL and DBW) could be grouped together, while the spring water (PBW) was grouped separately (Fig. 3c).

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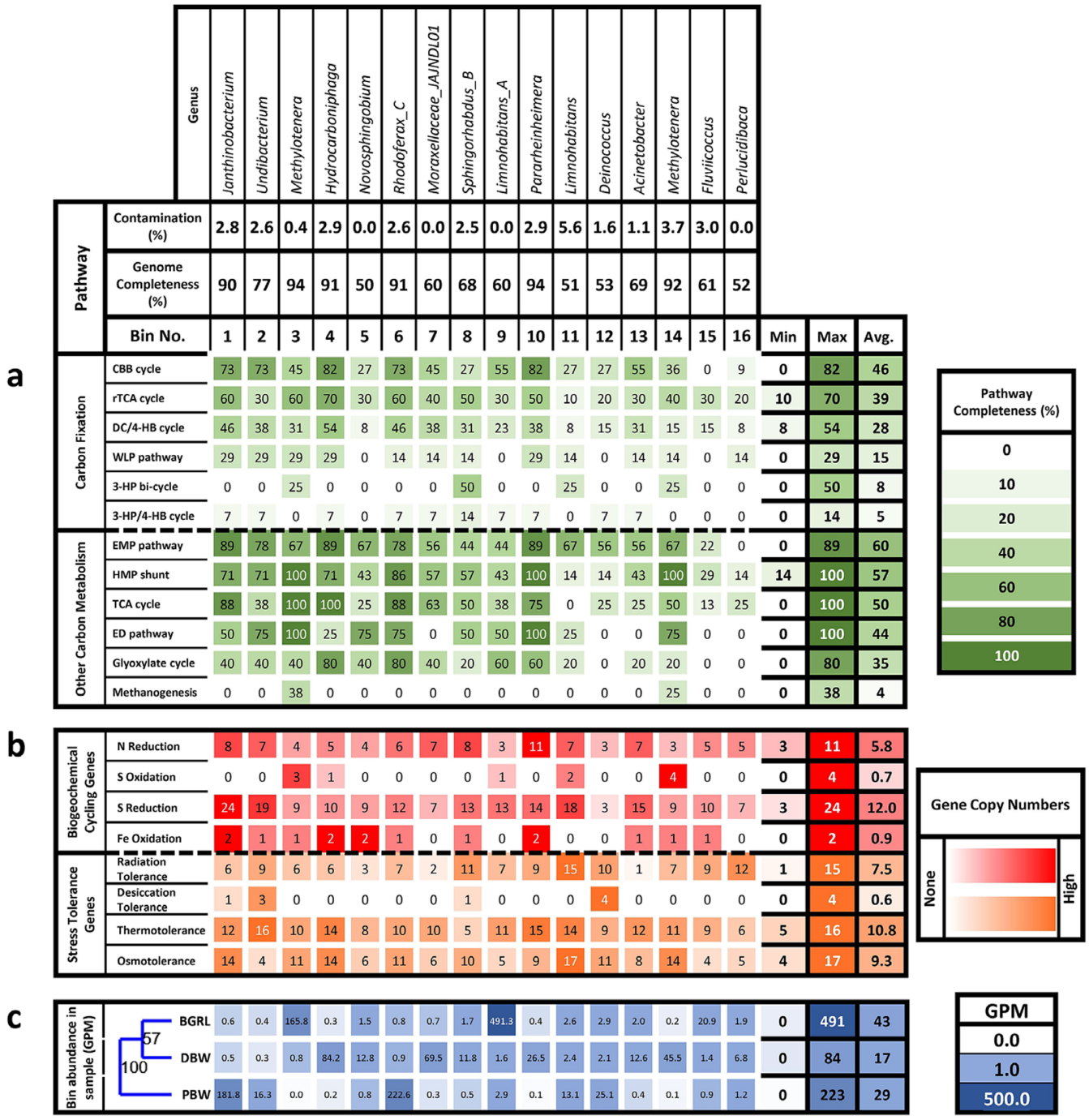


Figure 3. Heatmap of: (a) percentage completeness of carbon metabolism pathways in each bin; (b) abundance of genes involved in biogeochemical cycling and stress tolerance in terms of copies per bin; and (c) bin abundance in each sample expressed as genome copies per million filtered reads (GPM). The samples were clustered via unweighted pair group method with arithmetic mean (UPGMA) according to bin abundances based on the Bray–Curtis similarity index with a bootstrap of 1000.

Metabolic potentials of MAGs

Analyses of the genes related to carbon metabolism provided a broad overview of the genomic potential for carbon fixation and its utilisation via catabolic pathways (Fig. 3; Table S8). Genes encoding inorganic carbon fixation by six pathways were present in the reconstructed genomes. The most complete pathway for carbon fixation was the Calvin–Benson–Bassham (CBB) cycle, followed by the reductive tricarboxylic acid (rTCA or Arnon–Buchanan) cycle, the dicarboxylate–hydroxybutyrate (DC/4–HB) cycle, the Wood–Ljungdahl pathway (WLP), the 3-hydroxypropionate bi-cycle, and the 3-hydroxypropionate/4-hydroxybutyrate cycle. Among these, genes for the rTCA and DC/4-HB cycle were present in all the bins, although pathway completeness was low. The observed lack of completeness could be due to the limitation of the sequencing technique instead of the actual absence of genes, and it might be possible that at least some members of these microbial communities are capable of lithoautotrophic metabolism. Other carbon metabolism pathways that were detected include the hexose monophosphate shunt (HMP shunt or pentose phosphate pathway), the tricarboxylic acid cycle, and the Entner–Doudoroff pathway, which

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were complete in some of the bins. Because the presence of complete pathways was seen in bins with greater completeness, it is probable that the absence of genes is due to bin incompleteness. Incomplete genes were detected for the Embden–Meyerhof–Parnas pathway, glyoxylate cycle, and methanogenesis.

The bins were further assessed for the abundance of genes associated with biogeochemical cycles and stress tolerance (Fig. 3; Table S9). Based on the incompleteness of the reconstructed bins and their pathways, the absence of genes was not regarded as evidence of a complete lack of function. Furthermore, the presence of genes was compared in terms of the abundance of gene copies to determine the preponderance of specific metabolic functions. All bins showed the presence of nitrate reduction genes, while oxidative genes were not detected. Specifically, nitrate, nitrite, and nitric oxide reductases were detected. Similarly, sulfur reduction gene copies outweighed oxidative genes. However, iron oxidation genes were detected from most bins. Genes conferring tolerance against radiation, thermal, and osmotic stresses were detected from all bins, but desiccation tolerance genes were not detected from most bins.

Metagenomic comparison among the rock and groundwater systems

Comparing the metagenomic data sets revealed differences in the predominant carbon and energy metabolism pathways between groundwater and crustal (rock) microbiome (Fig. 4), as previously published (Dutta *et al.*, 2018). With respect to carbon fixation pathways, CBB was found to be the most abundant pathway across the groundwater system. Genes for WLP (*acsB*) were found to be the highest in one of the groundwater samples (BGRL) compared to other rocks and water samples. Genes responsible for methylotrophy were not detected in the water samples, whereas genes related to methylotrophy were detected in basalts and transition zone rock samples. Interestingly, genes responsible for methanogenesis (*mcrA*) were ubiquitous in the rocks and were absent in the groundwater ecosystem.

With respect to nitrogen and sulfur metabolism, groundwater and rock systems showed stark differences. The gene encoding for nitrogenase (*nifH*; plays an important role in nitrogen fixation) was ubiquitous in the rocks but only observed in one of the water samples (DBW). However, genes related to the conversion of nitrate to nitrite (both cytoplasmic [*nar*] and periplasmic [*nap*] nitrate reductase) were present in higher abundances in the water samples compared to the rocks. Genes involved in sulfate respiration (*apr* and *dsr*) were found to be most abundant in one of the groundwater samples (BGRL) compared to other rocks and water samples. Interestingly, genes involved in dissimilatory sulfate reduction were not observed in any other water samples except for BGRL. In the sulfur cycle, major distinctions across water and rock samples were observed with respect to sulfur oxidation and sulfate transport. Genes involved in sulfur oxidation and sulfate transport were higher in water samples than in rock samples.

Discussion

Geochemical characteristics and microbial abundance

Our geomicrobiological investigation demonstrated clearly a strong stratification of microbial community composition and function within the groundwater and surface water systems. Results indicated that different environmental factors, including nutrient sources present in a particular habitat, shaped microbial ecosystems. Deep subsurface aquifers hosted by crystalline igneous crusts are mostly isolated from surface activities and devoid of surface-derived carbon and energy sources (Kieft, 2016). The oligotrophic, typically extreme, ecosystems are predominantly driven by chemolithoautotrophy using locally available inorganic electron donors and energy sources. Microorganisms occupying these habitats are found to be endowed with the ability to use the local resources as nutrient substrates (Beaver and Neufeld, 2024; Kazy *et al.*, 2021; Kieft, 2016; Momper *et al.*, 2023).

The geochemical data obtained in this study presented the characteristic features of the igneous rock-hosted groundwater of the Deccan Traps, indicating the possible role of these local factors in impacting the inhabitant microbial communities. Among the major parameters tested, groundwater ecosystems of the Deccan Traps were found to be constrained by pH, TOC, TIC, Mg^{2+}, Ca^{2+}, NO_3^-, Fe^{3+}, and SO_4^{2-}. In comparison to various other continental subsurface water (*e.g.* Fennoscandian Shield, Precambrian bedrock of Witwatersrand basin, etc.) (Bell *et al.*, 2018; Lau *et al.*, 2016; Magnabosco *et al.*, 2016; Nyyssönen *et al.*, 2014; Purkamo *et al.*, 2016), groundwater from the Deccan Traps basaltic crust was found to be considerably deprived of organic carbon (3.5–6.4 times less than others), and corroborated well with the TOC level of deep basaltic rocks of the studied region reported earlier (Dutta *et al.*, 2018). The moderately alkaline nature of the groundwater of the Deccan Traps, along with elevated levels of Ca and Mg, was in line with the abundance of aluminium silicate or carbonate-rich minerals in the host rocks, including Ca/Mg bearing Mg-phyllosilicates, Mg-carbonates, clinopyroxene, calcic plagioclase, etc. (Dutta *et al.*, 2018). The alkalinity and abundance of Ca and Mg seemed to be more like a characteristic chemical property of igneous crust-hosted deep water, as also reported earlier in multiple studies (Itävaara *et al.*, 2011; Kieft *et al.*, 2005; Magnabosco *et al.*, 2016; Nyyssönen *et al.*, 2012; Purkamo *et al.*, 2016). Distinctly higher concentrations of Mg, Ca, NO_3^-, and PO_4^{3-} in two groundwater samples (BGRL and DBW) and the spring water (PBW) could be inferred as an outcome of subsurface rock–water interactions and different active biogeochemical processes, sourced by breakdown/weathering of various rock minerals affecting the water chemistry. Low bacterial abundance (up to 10^4 cells mL^{-1}) of the groundwater compared to other igneous crust-hosted water systems of comparable depths portrayed another characteristic property, which could be linked with the overall thermodynamic and nutritional constraints (including lack of readily metabolisable C and energy sources, reduced level of electron acceptors, etc.) of the igneous crust hosted groundwater (Kieft *et al.*, 2005; Purkamo *et al.*, 2017; Sahl *et al.*, 2008; Wu *et al.*, 2016a).

Microbial ecology of the water systems

Microbial communities retrieved from different parts of the water system of the igneous province of the Deccan Traps were characterised as having low microbial abundance, dominated by bacteria with limited species richness and abundance. Microbial communities in the groundwater were less diverse than the microbial communities of the surface water. Among the samples from the deep subsurface, BGRL showed higher abundances of archaeal presence compared to other groundwater samples (more archaeal ASVs corroborate with qPCR-based detection of archaea-specific 16S rRNA reads). In general, the predominance of bacteria over archaea in deep aquifer ecosystems has been reported to be a characteristic phenomenon (Kadnikov *et al.*, 2018). Nevertheless, a few archaea-based investigations (including the one from the Deccan Traps) indicated their distinct presence and highlighted biogeochemically

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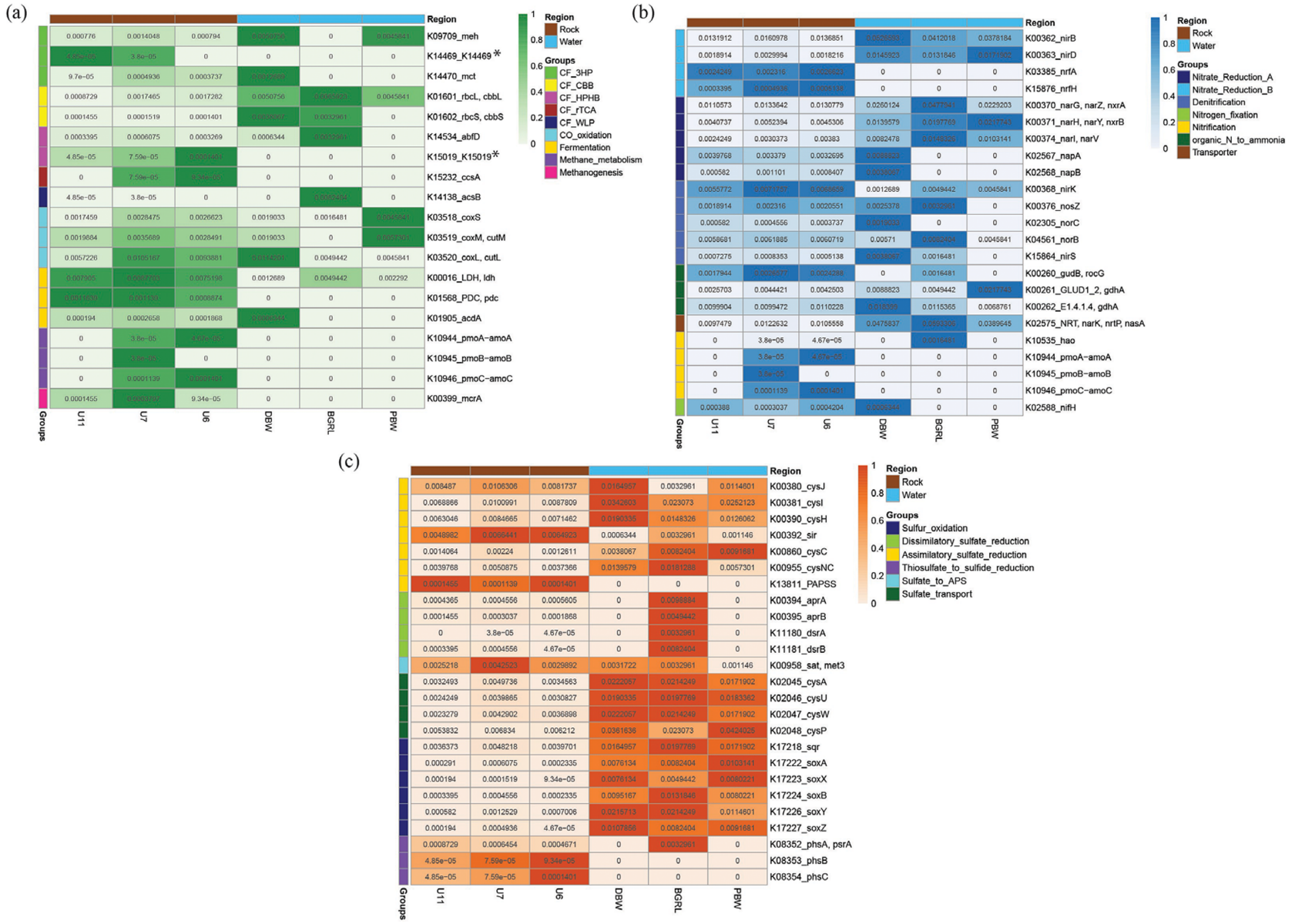


Figure 4. Heatmap showing occurrences (minimum–maximum scaled based on rows) of genes related to (a) carbon cycle, (b) nitrogen cycle, and (c) sulfur cycle across three rock samples and three water samples. The number represented in each cell of the heatmap denotes the relative percentage occurrences of genes, which is calculated based on the occurrence of a particular gene/total number of genes predicted × 100. The values are rounded to seven decimal points. The colour codes signify a particular gene's highest and lowest abundance across six samples for comparing rock and water samples. Nitrate_Reduction_A is a group of genes needed for the reduction of nitrate to nitrite, whereas Nitrate_Reduction_B is a group of genes involved in dissimilatory nitrate reduction to ammonium. The CF prefix in the carbon cycle heatmap signifies carbon fixation pathways. CF_3HP, 3-hydroxypropionate bi-cycle; CF_CBB, Calvin–Benson–Bassham (CBB) cycle; CF_HPHB, hydroxypropionate-hydroxybutyrate cycle; CF_rTCA, reverse tricarboxylic acid cycle; CF_WLP, Wood–Ljungdahl pathway. *Gene found in the CF_3HP and CF_HPHB pathways.

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relevant functions coupling Fe and S oxidation and C metabolism (Dutta *et al.*, 2019b; Probst *et al.*, 2018; Purkamo *et al.*, 2016; Wu *et al.*, 2016a). One of the most interesting findings was the prevalence of 16 ASVs as members of the core populations of this subsurface habitat; however, their total relative abundances varied across different groundwater samples (BGRL 4.69%, BW 12.17%, DBW 36.95%). The presence of a few ASVs as core communities of deep igneous crust ecosystems has been observed previously and identified to be of central importance in deep biosphere community function (Boada *et al.*, 2021; Sahu *et al.*, 2022; Yan *et al.*, 2020).

Our 16S rRNA gene-based community profiling provided an overview of the aquatic microbial ecosystems of the Deccan Traps. The presence of Pseudomonadota as the single most abundant phylum in groundwater samples, with its members known to be capable of performing various important biogeochemical transformations (of C, N, S, etc.), necessary for providing essential metabolic resources to the inhabitant microorganisms, was noticed. The predominance of Pseudomonadota (formerly Proteobacteria) corroborated previous reports on the cosmopolitan distribution of these bacteria in various subsurface water systems (groundwater, fracture-fault water, etc.) of Colorado, the Fennoscandian Shield, and the Witwatersrand basin (Lau *et al.*, 2016; Nyyssönen *et al.*, 2014; Onstott *et al.*, 2003; Purkamo *et al.*, 2016; Sahl *et al.*, 2008). The abundance of Pseudomonadota members also highlighted their metabolic versatility and major environmental importance within the deep biosphere ecosystems. Niche-specific distinct community composition across the subsurface environment (compared to their surface counterparts) indicated the role of local geochemical factors. Family-level community data, as well as the core ASV-based correlation analyses, confirmed the patterns of community assemblages and their relationship with geochemical parameters. Higher values of pH, NO_2^-, NO_3^-, and PO_4^{3-} influenced the abundance of *Burkholderiaceae*_A_595421, *Nevskiaceae*, *Sphingomonadaceae*_486827, PIVM01 (in class Gammaproteobacteria), *Methylophiliaceae,* and *Moraxellaceae.* The distinct patterns of microbial assemblages in groundwater (with the dominance of *Moraxellaceae*, *Methylophilaceae* and *Sphingomonadaceae* along with *Burkholderiaceae* and *Nevskiaceae*) could be inferred as their characteristic lineages with deep aquatic ecosystems, as also evidenced by several investigations on other subterranean water samples (Itävaara *et al.*, 2011; Jangir *et al.*, 2019; Nyyssönen *et al.*, 2014; Purkamo *et al.*, 2016). In particular, *Moraxellaceae*, *Burkholderiaceae*, etc. could be designated as resident bacterial taxa of the deep biosphere in crystalline groundwater.

Further analysis of the metabolic properties of various taxa detected in the deep subsurface of the Deccan Traps portrayed the broad functional abilities and their biogeochemical significance. One of the unifying themes that emerged was the primary role of the chemolithoautotrophic mode of metabolism, along with nitrate reduction. In line with the observations made by Deja-Sikora *et al.* (2019), our taxonomic data clearly indicated that inorganic carbon fixation coupled with sulfur/iron oxidation and nitrate reduction constituted the community's energy-circuit under the prevailing (relatively) nitrate-rich anoxic condition. Other energy metabolism pathways (*e.g.* H_2 or Fe^{2+} oxidation) could also be involved. Among the predominant bacterial taxa, *Acinetobacter* and *Methylotenera* were detected. Oxidation of sulfur compounds and denitrification have been well reported in other major taxa of *Moraxellaceae* (*Acinetobacter*) and *Methylophilaceae* (*Methylotenera*) (Y. Liu *et al.*, 2011; Song *et al.*, 2008; Su *et al.*, 2017). Utilisation of C1 compounds (*e.g.* methane, methanol, formate, etc.), other hydrocarbons (alkanes), and biomineralisation (of carbonates) under oligotrophic settings by these taxa were very relevant as these compounds can be generated in deep igneous systems through geogenic or biogenic synthesis (Chen *et al.*, 2021; Y. Liu *et al.*, 2011). The presence of the hydrocarbon degrading capability of subsurface microbial communities is further supported by the presence of *Novosphingobium*, *Hydrocarboniphaga* and *Sphingorhabdus* in the groundwater samples (Jeong *et al.*, 2016; H. Liu *et al.*, 2016; Segura *et al.*, 2017).

In contrast to the prevalence of the chemolithoautotrophic organisms in the deep groundwater, surface water ecosystems could be characterised through heterotrophic bacterial activities. The most abundant taxa therein, namely, *Nanopelagicaceae*, *Pseudomonadaceae*, UBA1268 (affiliated to Planctomycetota), *Chitinophagaceae*, etc., were reported earlier to occupy freshwater and eutrophic reservoirs, water column/streams and wetlands (Aizenberg-Gershtein *et al.*, 2012; Andrei *et al.*, 2019; Hosen *et al.*, 2017; Neuenschwander *et al.*, 2018; Newton and McLellan, 2015; Serra Moncadas *et al.*, 2024; Wang *et al.*, 2025). The presence of cyanobacterial members supported their role in providing photosynthetically fixed carbon that aids the growth of heterotrophic and chemoorganotrophic microbial groups. The spring water (PBW) microbiome displayed the presence of extreme stress-tolerant *Deinococcaceae* (*Deinococcus*), which corroborates well with our recent findings on similar organisms in deep granitic crusts underneath the Deccan Traps (Sahu *et al.*, 2022).

Core communities have been considered to represent the stable fraction of a community. Identifying these members and their geochemical drivers was considered to be imperative in gaining insights into the foundation (Shade and Handelsman, 2012; Yan *et al.*, 2020; Sahu *et al.*, 2022). Earlier studies of the endolithic microbial communities inhabiting the Archean granitoid basement underneath the Deccan Traps identified the presence of microbial communities whose abundances varied with the prevailing lithology and geochemistry (Sahu *et al.*, 2022). The variability of the abundances of core ASVs across various deep groundwater samples further indicated niche partitioning of the subsurface water system. Correlation analysis of these core ASVs with groundwater hydrochemistry alluded to the presence of both autotrophy and heterotrophy in the groundwater environment. In an oligotrophic deep subsurface environment, chemoautotrophic CO_2 fixation, with energy derived through oxidation of inorganic substrate coupled with NO_3 reduction, might be a plausible metabolic route to drive in the deep biosphere (Lau *et al.*, 2017). The products of autotrophy could be utilised by different heterotrophs in the community. The presence of autotrophy could be further validated by the fact that major taxonomic members of the groundwater samples have manifested similar metabolisms in previous reports. Iron or sulfur oxidation coupled with nitrate reduction-driven autotrophic carbon fixation has been reported in deep groundwater settings (Lau *et al.*, 2016; Lopez-Fernandez *et al.*, 2018).

Comparison of metagenomic bins and assessing the biogeochemical potential

A comparison of bin abundances across the metagenome samples revealed that groundwater communities were significantly different from spring water communities. This difference could be attributed to the distinct physicochemical conditions that prevailed in these two habitats. Because most bins were present in all the samples, inter-mixing of groundwater and spring water would be highly probable, allowing the presence of a few common microbial species. Nevertheless, the observed differences in the abundance of

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individual bins probably arose because each sample forms a microenvironment that allows the selection of a particular section of the total community.

On comparing the taxonomic lineages of the bins from metagenome data with 16S rRNA amplicon sequencing results, members of Pseudomonadota (formerly phylum Proteobacteria) remained the most prominent phylum, with representatives of classes Gammaproteobacteria and Alphaproteobacteria. Similarly, metagenome data also corroborated the status of Deinococcota (formerly phylum Deinococcus-Thermus) as the next most abundant phylum. The overall genome copies per million filtered reads were highest for BGRL, followed by PBW and DBW. This trend did not match what was seen in amplicon data, but the differences could be explained in light of practical limitations of sequencing technique rather than actual absence. Major families of groundwater samples as detected from whole metagenome analysis (*Burkholderiaceae*, *Moraxellaceae*, *Methylophilaceae*, *Nevskiaceae*, *Sphingomonadaceae*) were detected from amplicon analysis as well. On the other hand, preponderant surface water families (*Nanopelagicaceae*, *Chitinophagaceae*, *Verrucomicrobioaceae*, *Flavobacteriaceae*) were not represented in the genomes reconstructed from metagenome analysis. The taxonomy of reconstructed genomes thus corroborated the 16S rRNA gene amplicon-based analysis. *Burkholderiaceae* and *Alteromonadaceae* were low or sparse in amplicon data but had metagenomic bins affiliated to them, highlighting the superiority of whole metagenome-based community analysis. At a lower taxonomic level, metagenome data retained multiple genera (*i.e. Limnohabitans*, *Perlucidibaca*, *Acinetobacter*, *Hydrocarboniphaga*, *Methylotenera*) also detected in 16S rRNA gene amplicon sequencing, thus confirming their presence in the groundwater and spring water. Major taxa detected as core community members of the groundwater microbiome were represented by the reconstructed genomes as well, further validating our observations of the subsurface aquifer microbial communities.

Functional annotation of reconstructed genomes demonstrated a prevalence of chemoautotrophic CO_2 fixation pathways. The presence of chemoautotrophy is to be expected, considering the aphotic subsurface ecosystems of the deep biosphere have a minimal supply of photosynthetically produced organic carbon. The low organic carbon status of the igneous crust-hosted aquifers necessitates chemoautotrophy as the only metabolic route for primary production in subterrestrial food webs (Overholt *et al.*, 2022; Templeton and Caro, 2023). The specific pathways that are employed for carbon fixation vary across habitats, but CBB and rTCA cycles are frequently reported from groundwater studies, alongside WLP (Atencio *et al.*, 2023; Y. Li *et al.*, 2024; Momper *et al.*, 2017; Overholt *et al.*, 2022; Probst *et al.*, 2018; Wu *et al.*, 2016a). Pathways involved in fermentation were found to be complete and abundant. Notably, it has been reported previously that CO_2 fixation pathways like the CBB cycle can be used by mixotrophic bacteria in conjunction with sugar fermentation pathways to utilise the CO_2 liberated, which minimises loss of organic carbon. Recent studies have shown that organic carbon-lean deep terrestrial subsurface microbial communities have a predominance of multiple heterotrophic (glycolysis, respiratory and fermentation) pathways (along with chemolithoautotrophy) responsible for facilitating oxidation of locally available small and complex (even recalcitrant) organic compounds of both autochthonous and allochthonous types (Atencio *et al.*, 2023; Coskun *et al.*, 2024; Ijiri *et al.*, 2018; Momper *et al.*, 2023; Shimizu *et al.*, 2015; Valentin-Alvarado *et al.*, 2024). Our previous studies on oligotrophic, deep (up to 3000 mbs) crystalline igneous rock-hosted microbial communities within and below the Deccan Traps also showed the presence of both chemoautotrophic and heterotrophic pathways, including acetate metabolising and other fermentative metabolisms (Dutta *et al.*, 2018; Mandal *et al.*, 2022; Sahu *et al.*, 2022). Based on these reports and results obtained in the present study, we infer that deep aquifer microbiomes of the Deccan Traps are capable of an overall mixotrophic mode of metabolism, allowing complete cycling of carbon within this subterranean ecosystem through autotrophic as well as heterotrophic pathways.

The exploration of genes associated with redox reactions of inorganic compounds was able to support only a few of the metabolic functions expected from the assessment of the microbial community, as inferred from amplicon sequence analysis, but this may just be due to inadequate metagenome sampling depth. In spite of this limitation, the presence of a near-complete reductive half of the nitrogen cycle, represented by nitrite reductase, nitrate reductase, and nitric oxide reductase, was metagenomically confirmed. The information gathered from metagenome analysis can be regarded as a preliminary overview of the preferred choice of electron acceptors and donors for these microbial communities, implicating sulfate and oxides of nitrogen as potential electron acceptors. Such prevalence of nitrate and sulfate reducers and iron oxidisers has been reported from other studies of groundwater microbial communities as well, suggesting that these bacteria are key players in subterranean mineral mobilisation and geochemical cycling (Atencio *et al.*, 2023; Y. Li *et al.*, 2024; Momper *et al.*, 2017; Overholt *et al.*, 2022; Probst *et al.*, 2018; Wu *et al.*, 2016a). Because amplicon and metagenome-based studies only allow predictions of such functions, in vitro validation of microbial capacity to carry out the various biogeochemical reactions would be the conclusive proof that can be sought in future studies into the microbial diversity of this region. In addition, the depth of sequencing might also impact the detection of certain genes that are not abundant in the samples.

When stress tolerance genes were investigated, a paucity of desiccation tolerance genes was observed. This may be because the microflora was adapted for growth in water and not frequently exposed to water scarcity, or due to sequence incompleteness. However, the presence of radiation tolerance genes could confer desiccation stress resistance because radiation tolerance genes tend to be associated with desiccation stress resistance as well (Khan *et al.*, 2024). Thermotolerance genes detected may arise from deeper groundwater samples as temperature increases with greater depths (Bregnard *et al.*, 2023). Osmotolerance could be relevant to near-surface and deep subsurface microorganisms as a sudden influx of meteoric water or dissolution of rock minerals can cause sharp and/or localised changes in osmotic pressure (Or *et al.*, 2007; Sokol *et al.*, 2022).

Although differences in microbial communities and their functions were observed across subsurface rock (Dutta *et al.*, 2018) and water systems in the Deccan Traps, their foundations were very similar. These similarities in the bioenergetics of the system were probably due to the result of an exchange of resident microflora taking place during rock–water interactions and the prevalence of similar conditions in the subsurface igneous province. Such interactions were regarded as a major driver of nutrient cycling in the oligotrophic deep biosphere. Rocks provide the mineral solutes that are solubilised in water to serve as nutrients and energy sources for the geochemically active microorganisms inhabiting these niches (Meyer-Dombard and Malas, 2022). The overall data represent preferential recruitment of major metabolism across the aquatic and crustal provinces of the Deccan Traps.

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Data availability. The raw 16S rRNA gene sequencing data are available in the NCBI SRA database under BioProject ID PRJNA445925 (for water samples) and SRA Accession: SRR35284829 (for reagent control). Whole metagenome raw data and MAG sequences are available under NCBI BioProject ID PRJNA1341937. MAG sequences are also available under ENA Study Accession ID PRJEB100823. The annotated data for the whole metagenome is available at IMG GOLD under Analysis Project ID Ga0247434, Ga0247435 and Ga0247436.

Author contributions. PS: Conceptualisation (lead), data curation (lead), formal analysis (lead), funding acquisition (lead), investigation (lead), methodology (lead), project administration (lead), resources (lead), software (lead), supervision (lead), validation (lead), visualisation (lead), writing – original draft (lead), writing – review and editing (lead). AD: Conceptualisation (equal), data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), software (lead), validation (lead), visualisation (lead), writing – original draft (lead), writing – review and editing (lead). SM: Formal analysis (supporting), investigation (supporting), methodology (supporting), software (equal), validation (equal), visualisation (equal), writing – original draft (equal), writing – review and editing (equal). DM: Formal analysis (supporting), whole metagenome sequence analysis (equal), re-analysis of 16S rRNA amplicon data for validation (supporting), writing – review and editing (supporting). RPS: Data curation (supporting), formal analysis (supporting), methodology (supporting), software (supporting), writing – original draft (supporting), writing – review and editing (supporting). SDG: Data curation (equal), formal analysis (equal), investigation (supporting), methodology (equal), software (equal), writing – original draft (supporting), writing – review and editing (supporting). AG: Data curation (equal), formal analysis (equal), investigation (supporting), methodology (equal), software (equal), writing – original draft (supporting), writing – review and editing (supporting). HB: Formal analysis (supporting), software (supporting), visualisation (supporting), writing – original draft (supporting), writing – review and editing (supporting); am: formal analysis (supporting), investigation (supporting), methodology (supporting), resources (equal), supervision (supporting), validation (supporting), writing – review and editing (supporting).

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