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Outcrop analogue constraints on subsurface reservoir properties of the Puga geothermal field, NW Himalaya

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Abstract

There has been a large barrier in geothermal energy production in India due to the knowledge gap in understanding the subsurface uncertainties. In Puga, Ladakh, a significant amount of research has been done that estimates the availability of >5000 MWh of geothermal energy, but it remains untapped. This unrealised potential is largely due to a limited understanding of the reservoir characteristics. In this contribution, we provide a comprehensive review of literature on the Puga system and present new outcrop analogue data to develop a better understanding and conceptual model of the subsurface geothermal system. Based on the geological setting, we suggest the lithologies and structures exposed in cliffs adjacent to the Puga valley are analogous to the subsurface, to depths of at least a few kilometres. A 3-D model of the outcrop is developed from aerial imagery collected using drone (quadcopter), and used to characterise the fracture sets and foliation planes likely present in the subsurface. Areas with intensely developed fabrics demonstrate the mechanical and hydraulic significance of these anisotropies, while several generations of crosscutting fractures provide important zones of permeability. The distinctive relationship between faults in the outcrop and the valley fill provides evidence for recent movement on the faults. Further, a variety of mineral fillings were observed in fractures across the outcrop, including quartz±tourmaline veins, hydrothermal biotite, vuggy sub- and euhedral quartz, fine-grained iron oxides and iron-rich travertine, while several exposures near the base of the cliffs show clear advanced argillic and sulfuric alteration. We integrate these digital outcrop observations with constraints provided by the literature to
derive a conceptual model of the Puga geothermal system and develop an understanding of the
structural architecture of the reservoir.

**Keywords:** Puga, geothermal energy, outcrop analogue, paleofluid, Ladakh, Leh
1. Introduction

Increasing population and energy requirements have led to a many-fold increase in global energy consumption, while simultaneous environmental pressures (e.g., air pollution, climate change) demand new, cleaner energy sources (Abbass et al. 2022; Yi et al. 2023). Among these non-conventional energy sources, geothermal is considered to have the highest energy index based on environmental and techno-economic criteria (Jha and Puppala 2017a), providing an attractive choice for reliable baseload electric or direct-heat energy supply in regions with favourable geothermal manifestations (Fridleifsson 2003; Glassley 2010). In India, research efforts on geothermal energy started as early as 1862 (Guha 1986), and in 1967 the Indian government formed a Hot Spring Committee to investigate the possibility of domestic geothermal exploration (Shanker et al. 1991). However, the sector is still in its infancy, due in part to inadequate research: a large barrier to geothermal development is the subsurface uncertainties that increase investment risk (Chandrasekharam and Chandrasekhar 2015; Puppala et al. 2022).

In the Ladakh region, a combination of geography and climatic conditions present significant energy supply issues (Sharma and Thakur 2017). Micro-hydro is a proven technology and has been widely deployed, however, almost one-fourth of the installed units have failed in the Ladakh region (Ete and Prochaska 2009). Various sites identified for the development of larger hydro projects are in inaccessible terrain and remain entirely inaccessible during harsh winter months. In short, while hydropower opportunities exist, logistical challenges, winter ice formation, landslide and sediment blockage risks, threats to water security under climate change, and broader environmental impacts necessitate a more diverse energy supply (Sharma and Thakur 2017).

The Puga region, 175 km south of the Ladakh capital of Leh, has been identified as a high-potential site for geothermal energy production based on geological, geochemical, geophysical, and modelling studies (Arora et al. 1983; Gupta et al. 1975; Singh et al. 1983; Mishra et al. 1996; Azeez and Harinarayana 2007). Several boreholes have been drilled to examine the hydrogeological properties and temperature variations within the shallow subsurface. The total discharge from these boreholes is about 3000 t/h, with a maximum discharge from a single well of 40 t/h (Craig et al. 2013). The discharge temperature from some of the boreholes is >120 °C, and thermal studies indicate temperatures >220 °C at a depth of about 2.5 km (Craig et al. 2013). Previous studies have thus estimated the availability of >5000 MWh of geothermal energy at Puga, which could be used for heating, greenhouse cultivation, and electricity.
generation (Chandrasekharam 2005). Modeling studies have indicated a 90% probability that the Puga field could sustain a 20 MWe power plant (Craig et al. 2013).

In 2021, the Oil and Natural Gas Corporation Energy Centre Trust (OECT), Iceland Geosurvey (ISOR), the Union Territory administration, and the Ladakh Autonomous Hill Development Council signed a memorandum of understanding (MoU) to develop a pilot 1 MW geothermal plant at Puga (Patil, 2022, Sirur 2022). In August 2022, the first well drilled for this project encountered a shallow pressurised reservoir at a depth of 39 m and temperature of 120-130 °C, leading to a blowout and abandonment of the well (Sirur 2022). It is reported from earlier studies that 34 boreholes drilled in the region resulted in at least 17 blow-outs, with steam content between 15 and 20% (Shanker et al. 1991; Craig et al. 2013).

Hence, despite the clear potential and substantial geophysical research and shallow drilling, subsurface uncertainties and associated development risks remain high. We attribute this uncertainty in part to the limited number of studies characterising the local geology, which provides key geometric constraints and a conceptual understanding of subsurface structures and reservoir characteristics. Published maps of the Puga area generally have a regional focus and show significant inconsistencies between authors (e.g., Shanker et al. 1975; Epard and Steck, 2008; Buchs et al. 2019). In this contribution we attempt to address this knowledge gap by (1) synthesising published geological, geochemical, and geophysical interpretations to review the current understanding of the Puga geothermal system, (2) applying digital mapping techniques to derive a digital reservoir analogue based on extensive cliff exposures adjacent to the geothermal manifestations, and (3) integrating field and petrological observations to constrain this exposed paleo-geothermal system, and by analogy develop a conceptual model for the modern one.

1. Geological Overview

The Puga geothermal field is located to the south of the Indus Suture Zone (ISZ) in a structural dome of rapidly exhumed Tso Morari ultra high-pressure (UHP) gneisses (Harinarayana et al., 2006; Jha & Puppala, 2017a; Buchs et al. 2019) (Fig. 1). The formation mechanism of this dome is debated, but it clearly experienced UHP conditions (>90 km depth, 2.24–4.8 GPa, 450–760 °C) at ~50 Ma followed by rapid uplift to ~15 km depth by ~30-40 Ma followed by more gradual uplift at ~0.5 mm/year (Dutta and Mukherjee, 2021; Epard and Steck, 2008). The dome is currently subject to dextral transpression parallel to the ISZ, manifesting as dextral movement on the NW-SE striking Zildat fault (Fig. 1), and clearly neotectonic NW-dipping
normal faulting (Epard and Steck, 2008). The dome currently has a high thermal gradient (>100 °C/km) and surface heat flux (>468 mW/m²) (Chandrasekaram 2000, Sharma, 2010).

Geothermal manifestations at Puga include geothermal springs, mud pools, sulfur condensates, and borax deposits (Azeez and Harinarayana, 2007), stretched over a ~5 × 1 km section at the base of the Puga valley. Below these, a shallow reservoir is hosted by fluvial and glacial deposits and brecciated altered gneiss to depths of several hundred meters (Shanker et al. 2000). This shallow breccia is often highly silicified, and a large quantities of silica gel is ejected from shallow boreholes (Shanker et al. 2000).

A paleo hot zone was identified by Shanker et al. 2000 in a well, where epidote (pistacite) alteration occurred at 250 - 284 m depth, indicating temperatures of at least 200 °C. Solfataric and advanced argillic alterations along the northern margin of the valley also indicate paleo-fumarole activity associated with acidic fluids (Shanker et al. 2000). Several exposed eruption craters and eruption breccia deposits indicate that boiling and steam separation were also more vigorous in the past (Shanker et al. 2000).

Geophysical evidence indicates a conductive deeper reservoir is hosted in presumably intact gneiss below this shallow reservoir, at a depth of ~1.5 – 2 km (Harinarayana et al., 2004), though this has never been drilled into. Several authors have speculated that this reservoir results from fluid flow along an inferred continuation of the Kiagar Tso Fault (KTF) (Azeez and Harinarayana 2007), although little evidence is given for this assertion. Shanker et al. (1976) also speculate that the Puga geothermal field is confined by a concealed graben structure parallel with Puga valley. Other authors infer magmatic intrusions below the Puga geothermal field (Harinarayana et al. 2006). This wide range of geological interpretations emphasizes the need for more geological data to help (1) interpret geophysical and geochemical data and (2) develop more robust conceptual models of the Puga geothermal system and (3) determine the key controls on fluid movement (and potential extraction), especially within the deeper geothermal system.

2. Logging and hydrogeochemical studies

Geothermal waters at Puga are generally neutral to mildly alkaline and fall on the boundary between the sodium bicarbonate and sodium chloride regions on a Piper diagram (Saxena and D’Amore, 1984). Thermal logging studies from boreholes drilled into the shallow reservoir indicate significant temperature gradients, from 0.4 to 4 °C/m (Gupta et al. 1974). Interpolation
of this well data suggests the thermal gradient is higher in the eastern zone of the valley (Jha and Puppala 2017b).

The geochemistry of thermal spring waters has been used by many authors to estimate the reservoir temperature (e.g., Chowdhury et al., 1974; Gupta & Sukhija, 1974; Shanker et al., 1991; Thussu, 2002; Craig et al., 2013; Tiwari et al., 2016). Cation geothermometers indicate reservoir temperature ranging from 220–260 °C, while oxygen-isotope thermometry suggests a value closer to 180 °C. Isotopic values of δ18O (-14 ‰) and δD (-122 ‰) have been interpreted to indicate water-rock interaction at high-temperature zones at depth (Tiwari et al. 2016). Relatively constant Cl/B ratios (0.9 to 1.0) indicate a single reservoir of hot water with varying degrees of dilution. High Li, Rb, Cs, and B concentrations (and low calcium and magnesium concentration) in these waters have been interpreted to result from intensive water-rock interaction (Shanker et al. 1991) or evolved magmatic source (Handa, 1976; Saxena and D’Amore, 1984). The presence of sulphur and borax deposits in the valley as well as volatile constituents such as Sr (40 to 400 ppm), Ba (20 ppm), Cu (2 ppm), and Li (5.4 to 6.6 ppm) also point to some magmatic contribution (Gupta and Sukhija 1974; Shanker et al. 1975). Tritium concentration was found to be generally <8 TU (Gupta and Sukhija 1974), indicating a long turnover time or deeper water source. Steller et al., (2019) reported remarkably consistent boron isotope values of -12 to -15 δ11B for springwaters at Puga, and significantly more negative values (-30 to -40 δ11B) associated with amorphous silica and diatom-rich spring deposits. They interpret these results to indicate a granitic source for boron in the geothermal fluids, and extensive fractionation during the formation of amorphous silica on the surface or in the shallow subsurface.

The stable isotope plot of D and 18O, however, indicates a meteoric origin (Tiwari et al. 2016). The composition of δD and δ18O in glacial meltwaters is also close to geothermal waters, further indicating a meteoric source (Shanker et al. 1991). Studies have shown that hot spring systems of meteoric origin closely associated with recent volcanism may be partially (1 to 5%) of magmatic source (White 1969). Though direct evidence of recent volcanism is absent in the region, it appears to be true for the thermal waters of Puga (Gupta and Sukhija 1974). Infiltration to deeper levels could attain heat through a geothermal gradient and also possibly through interaction with a cooling magmatic body (Shanker et al. 1991). Thus, the geothermal water of Puga could be of mixed meteoric and magmatic sources.

3. Geophysical studies
A range of geophysical surveys have been conducted at Puga, including seismic, gravity, magnetic, magnetotelluric, and self-potential studies. The seismic data show that the depth of unconsolidated valley fill varies significantly, between 15 and 230 m across the area (Ravi Shanker et al. 1975; Arora et al. 1983), while the magnetic and gravity surveys suggest a set of N-S trending structures lie beneath the main geothermal manifestations (Arora et al. 1983).

Electrical resistivity methods have delineated conspicuous conductive zones that are interpreted as geothermal reservoirs (Harinarayana et al. 2006). D.C. resistivity surveys suggest hot water channels in the central part of the valley, whereas, in the western and eastern parts of the valley, it is absent (Singh et al. 1983). A shallow conductive zone (200–300 m) in the central part of the valley mapped by magnetotelluric studies correlates well with conductive zones indicated by shallow electrical resistivity studies (Gupta et al. 1975; Arora et al. 1983; Singh et al. 1983; Mishra et al. 1996). This spreads over an area of 3–3.5 km² below thermal manifestations and extends to about 300 m in depth. Beneath this, a high resistive layer is thought to represent the basement gneisses (Harinarayana et al. 2006). However, a second conductive zone is imaged at ~2 - 5 km depth and interpreted to represent a deep reservoir (Harinarayana et al. 2006). Another conductive anomaly exists deeper still, from ~8 km depth, and has been interpreted as evidence for magmatic activity at depth (Azeez & Harinarayana, 2007).

Several studies have attempted to integrate these various geophysical datasets to develop conceptual models for the Puga reservoirs (Jha and Puppala 2018; Jha et al. 2020; Puppala and Jha 2021). Resistivity inversions and petrophysics data were used to infer porosity, thermal conductivity, density, specific heat, radioactive heat capacity, and permeability to generate a 3D block heterogeneity model to a depth of 4 km. A coupled fluid flow and heat transport model was then used to estimate energy recovery factors of 8-38%, and electrical power potential of 1.2 - 50.4 MWe with 12% conversion efficiency from the depths of 250 m and 1875 m respectively over 50 years. The authors acknowledge, however, that the relationship between resistivity and key rock properties (e.g., permeability) is non-unique, and that their model does not consider fracture-confined flow or multiphase and multicomponent processes. Hence, while a wealth of geophysical data has been collected at Puga, we suggest that detailed geological constraints that might aid its interpretation are currently lacking.

4. Methodology
The study of analogue systems, and detailed characterisation of analogue outcrops, is commonly applied in the oil and gas industry to develop a qualitative and quantitative understanding of subsurface reservoirs (e.g., Aydin 2000; Agosta et al. 2009; Iadanza, Sampalmieri, and Cipollari 2015). Some authors (e.g., Brogi et al. 2016, Liotta et al. 2021) have translated this approach to geothermal studies, studying fossil systems to understand the deep roots of nearby active systems and providing key constraints on the relationships between geological structures and geothermal resources (Liotta et al. 2021).

This study integrates primary data collected using uncrewed aerial vehicle (UAV) imagery and digital outcrop mapping techniques with constraints provided by the literature (reviewed in the previous sections) to derive an updated conceptual model of the Puga geothermal system (Fig. 2). A petrographic study of rock samples collected from the analogue outcrop is also integrated to better interpret its significance and link structures with past geothermal activity.

5.1. Structure from motion photogrammetry

Drone surveys were conducted using a DJI Mavic Air 2 to collect >2800 digital photographs (4000×3000 pixels) covering the Puga valley floor, geothermal manifestations within it, and the adjacent ~250 m high cliffs (Fig. 3a). The UAV was flown automatically at an above-ground height of ~65 m above the valley area with the camera in nadir orientation. To image the cliffs, flight lines were flown manually with the camera alternated between ~45 and 60° off-nadir along horizontal flight lines at ~3 different elevations. The photos were collected with a 90% overlap, resulting in ~1600 images covering the valley area and ~1200 covering the cliffs. The UAV Flight lines are shown in Fig. 3.

Agisoft Metashape Professional 1.8.4 was then used to reconstruct dense 3-D models of the outcrop and valley floor using structure from motion multi-view stereo (SfM-MVS) (Khanna et al. 2020; Thiele et al. 2021). The resulting dense point cloud was meshed and textured (by back-projecting the original image data) and, for the valley floor region, converted to an orthomosaic and associated DEM with 5.54 cm/pix and 11.1 cm/pix resolution respectively. These were georeferenced directly using the onboard UAV GPS and subsequently refined by fitting it to ALOS PALSAR DEM data using the iterative-closest point method implemented in CloudCompare (Girardeau-Montaut 2016)

5.2. Field measurements and sample collection
A mapping traverse (Fig. 3) was also conducted along the base of the Puga cliffs to provide structural measurements, field observations, and samples that assist the interpretation of the digital outcrop model. The orientation of the dominant shallow-dipping foliation and cross-cutting joints, faults, and veins were measured at regular (~10-20 m) intervals where outcrops were accessible, using the RockLogger app. Samples of the host rock, altered horizons, and fracture fill were also collected along this traverse (Fig. 4).

### 6. Results and Interpretation

#### 6.1. Digital outcrop model

Recent uplift and glacial denudation of the Puga area has resulted in significant ~250 m high cliffs just north of the Puga geothermal site. Given the broadly dome-shaped geometry of the Tso Morari nappe (Epard and Steck, 2008), we suggest that the lithologies and structures exposed in these cliffs will be analogous to the subsurface below Puga, to depths of at least several kms. That said, the fracture sets in these outcrops need to be interpreted with caution, as some will relate to unloading and exhumation processes, and hence exist only in the comparatively shallow subsurface (e.g., Terry, 1987).

In the following, we present a preliminary interpretation of the ~3 × 0.25 km digital outcrop model captured at Puga (Fig. 3). Fractures and foliation planes were interpreted using the dense point cloud data and the Compass plugin (Thiele et al., 2017) in the CloudCompare software (v2.11 alpha) and, where the topography of the outcrop was sufficient to constrain a structure’s 3-D orientation, strike and dip measurements extracted by plane-fitting (cf., Thiele et al., 2017; Thiele et al., 2019).

A detailed analysis of these results will be the subject of a subsequent publication, but we include some general results here to highlight the usefulness and relevance of the analogue outcrop for subsurface studies.

Firstly, field inspections and the digital outcrop mapping (Fig. 3) shows the main gneissic foliation (Fig. 4) dips shallowly (10-30°) to the north-east across the whole area, consistent with previous regional-scale mapping (Epard and Steck, 2008). The intensity of this fabric varies locally (Fig. 4a-h), but always defines a clear anisotropy. Areas with intensely developed fabric generally also contain abundant fabric-parallel joint sets, demonstrating the mechanical significance of these fabrics (even though these joints likely formed at quite shallow depths during unloading).
A distinctive set of more steeply (30-60°) NE dipping fractures crosscuts this fabric, and have previously been interpreted by Dutta and Mukherjee (2021) to represent brittle top-down shear structures associated with the extrusion of the Tso Morari nappe. These tectonic fracture zones can thus be expected to continue to significant depths, and should be considered as potential (albeit unfavourably oriented) flow pathways.

Lastly, and possibly most significantly, the digital outcrop model reveals several moderately to steeply (45-80°) NW dipping normal faults and associated damage zones. These clearly crosscut all of the previously mentioned structures, and have been interpreted to result from neotectonic dextral transpression in the Ladakh area (Epard and Steck, 2008). Importantly, as already noted in passing by Epard and Steck (2008), hot springs in the Puga valley appear to be spatially associated with these faults (Fig. 3c). A distinctive escarpment crosscuts recent scree deposits along strike of one of these normal faults (center of Fig. 3c), suggesting it could still be active (Epard and Steck, 2008). The distinctive relationship between these faults and the valley fill (Fig. 3c) provides further evidence for recent movement on these faults.

### 6.2. Evidence for paleofluid flow

The analogue outcrop also records a variety of evidence for past geothermal activity, which can help develop conceptual models for the current system and disentangle the relationship between the exhumed structures and paleo fluid flow. A variety of mineral fillings were observed in fractures across the outcrop (Fig. 5), including: recrystallized and often deformed quartz±tourmaline veins that we interpret relate to early syn-metamorphic fluids (Fig. 5a, b), foliation-parallel fractures infilled with hydrothermal biotite (Fig. 5c, d), late ~50 cm thick veins and pods filled with vuggy sub- and euhedral quartz and fine-grained iron oxides (Fig. 5e, f) and open joint surfaces encrusted in highly porous iron-rich travertines (Fig. g, h). These structures attest to a long history of fluid communication through the Tso Morari gneisses, including presumably recent geothermal activity that formed the vuggy quartz veins and travertine encrustations.

Significant sericitisation was also observed in several parts of the digital outcrop model (Fig. 5). This tended to form in elongated ~1 m thick lenses parallel to the main foliation, recording patchy but significant fluid-rock interaction, potentially associated with areas of higher permeability due to foliation-parallel microfracturing. The intensity of sericitisation within
these zones was found to increase near crosscutting joint sets (Fig. 5a, b), emphasising also the importance of these structures as fluid pathways.

Finally, several exposures near the base of the cliffs show advanced argillic and sulfuric alteration (Fig. 6c, 6c-e), as has been previously described by several previous authors (Steller et al. 2019, Pandey et al. 2020). Primary gneissic foliation was still preserved in some areas of advanced argillic alteration (Fig. 6c), while the solfataric alteration appears to be associated mostly with overlying breccia deposits (Fig. 6d, e).

7. Discussion

7.1 Conceptual model of Puga geothermal field

A major challenge in the Puga field is the understanding of the fracture networks that presumably control fluid communication to the surface. A three-dimensional thermal-hydrogeomechanical model has been conducted to investigate the impact of engineered hydraulic fractures and well patterns on the performance of heat production (Gudala et al. 2022). The study suggests that the geothermal life, reservoir impedance, and heat power are dependent on the number of natural (and engineered) hydraulic fractures, which are influenced considerably in the multistage model of the Puga geothermal reservoir. However, this study did not have the required data to adequately include naturally occurring fracture networks in the model, and also did not consider the potentially important role of non-lithostatic stresses associated with the significant topography and tectonic activity in the region.

Given this, detailed outcrop analysis is paramount to characterize and discover heterogeneities within the geological units and provide quantitative and conceptual geological constraints for future reservoir models. Considering the low porosity and permeability of the host rock, geothermal fluid movement is considered to be significantly fracture controlled. Our preliminary structural analysis and petrological study serve to characterize the main fracture patterns and to identify possible fluid pathways. Outcrop analogue studies in other regions have provided important input in understanding the geothermal reservoirs (Aretz et al., 2016, Brogi et al. 2016, Zucchi et al., 2017 Liotta et al. 2021).

Based on these observations, and our review of the literature (geological, hydrogeochemical, and geophysical studies), we propose a schematic conceptual model of the Puga geothermal field (Fig. 7). While many details need to be further resolved, we suggest that neotectonic normal faults and associated fracture sets (damage zones) provide the crucial flow pathways
linking the shallow and deep geothermal reservoirs. In the shallow reservoir, a combination of
valley fill breccia and dilated basement fractures provide permeable zones hosting the
geothermal fluids. These are likely affected by shallow stress rotations caused by relatively
rapid unloading and exhumation and the significant topography in the region, promoting flow
along favourably oriented structures. Silicification and silica gel formation reported in the
literature (Shanker et al., 2000) also suggests that mineral precipitation and permeability
clogging also significantly affects the shallow reservoir.

Below this shallow reservoir the gneiss becomes largely impermeable as fractures (and
foliation-parallel) fluid pathways become clamped by a sub-vertical $\sigma_1$, with fluid movement
confined to the relatively steep dipping normal faults. Below this aquitard, controls on
permeability in the deep reservoir remain uncertain, although we speculate that the foliation-
parallel sericitized alteration lenses observed in the analogue outcrop could have formed at
similar depths. Hence, we hypothesise that a combination of elevated fluid pressures and
increased tectonic compression at depth facilitate foliation-parallel fluid flow in the deep
reservoir, resulting in stacked lenses of geothermal fluid that are periodically tapped by the
crosscutting normal faults.

Lastly, we suggest that the combination of fossilised advanced argillic and solfataric alteration
and modern-day alkaline bicarbonate-chloride hydrogeochemistry are best explained by the
presence of a waning magmatic system at depth, which provides heat and some fluid
components (e.g., boron, lithium, sulphur) to the geothermal system. Recharge and mixing with
meteoric waters descending along adjacent normal faults is also likely, as indicated by $\delta D$ and
$\delta^{18}O$ isotope systematics (Tiwari et al., 2016).

7.2 Comparison of Puga geothermal field to Yangbajing geothermal field, China

The geological setting of Puga is similar to Yangbajing geothermal field, in China which is
located at a similar elevation (4290 to 4500 m) close to the convergent collision zone between
the Indian and Eurasian plates (Wang and Guo 2010, Zhang et al. 2019). Yangbajing is the first
high-temperature geothermal power station in China, and was launched in 1977. The total
installed capacity at present is 26.18 MW, which contributed to 50% of Lhasa’s summer power
supply and 60% of winter power supply (Zhu et al. 2015, Zheng and Pan, 2009).

The geothermal system is located in an active fault zone within a metamorphic core complex
consisting of quartzite, biotite schist, gneissose granite, and granitic migmatite (Wang and Guo
Yangbajing is also a convective system that consists of shallow and deep reservoirs. The shallow reservoir is hosted by unconsolidated Quaternary alluvium and altered Himalayan granite, with temperatures ranging from 150 to 165 °C at depths between 180 and 280 m (Zhang et al. 2019). The deep reservoir is associated with a fault zone crosscutting the Nyainqentanglha core complex and fractured Himalayan granite. The deep reservoir consists of two parts: the upper part, with a temperature of 248 °C at depths ranging from 950 to 1350 m, and the lower part with temperatures as high as 329°C below a depth of 1850 m (Zhang et al. 2019, Yuan et al. 2021).

In Yangbajing, the wastewater has a concentration of B, As, and F above the World Health Organization (WHO) limit (0.5, 0.01, and 1.5 mg/L) for drinking water (Wang and Guo 2010). The wastewater is drained at Zangbo river causing harmful effects on the health of villagers consuming the river water (Li et al., 2003, Wang and Guo 2010). Considering the similarity in geological settings and reservoir characteristics, the working model of the Yangbajing geothermal field in China could be adapted to provide a potential model for geothermal energy production at Puga. Furthermore, challenges and environmental impacts at the Yangbajing site should be considered when planning developments at Puga. For example, wastewater at Yangbajing has concentration of B, As, and F above the World Health Organization (WHO) limit (0.5, 0.01, and 1.5 mg/L) for drinking water (Wang and Guo 2010). The wastewater is drained at Zangbo river causing harmful effects on the health of villagers consuming the river water (Li et al., 2003, Wang and Guo 2010). Poor management of wastewater from geothermal power plants in Yangbajing should be a lesson for the implementation of proper management at Puga.

7.3 Research gaps and future studies

Finally, we suggest that de-risking the currently proposed geothermal development at Puga requires significantly more research to provide the crucial geological and hydrological context for sustainable power production. Specifically, a better understanding of the following controls on reservoir performance is required:

1. A better understanding of the current stress field at Puga, which will involve a potentially complex combination of unloading, deglaciation, topography, and ongoing tectonic transpression.

2. Detailed characterisation of the fracture and fault network that controls fluid flow at Puga, and its interaction with the stress field to provide connected permeability.
3. Assessment of potential seismic activity or deformation on neotectonic faults at the Puga site. Moderate seismic events (with moment tensor solutions indicating association with normal faults) have been recorded in the area (Hazarika et al. 2017, Kanna et al. 2017), suggesting that seismic hazards, potential triggered seismicity, and the possible role of the seismic cycle in generating permeability for recharge of the shallow reservoir need to be investigated.

4. More research into the fluid source, fluid-rock interactions and recharge pathways to resolve recharge and sustainability, including (i) the relative importance of deep (magmatic) vs shallow (meteoric) waters, (ii) potentially significant scaling issues associated with silica and borax precipitation, and (iii) ensure sustainable management of the shallow-reservoir to prevent detrimental effects on the environmentally and culturally significant Puga reserve.

5. Investigations on core samples from wells for direct comparison of outcrop analogues and the reservoir.

8. Conclusions

This study presents a literature review and new outcrop analogue dataset for the Puga geothermal field. The main conclusions of this study are summarized below:

- The exposed fossilized geothermal system provides key constraints on the active system at depth, especially regarding the key fluid flow pathways in otherwise impermeable host rocks.
- We identify that neotectonics normal faults likely serve as the main fluid flow pathways, and thus provide a first-order control on the geothermal system.
- Finally, we identify several key knowledge gaps that should be addressed to help mitigate technical and environmental risks associated with any future geothermal development at Puga. These are – better understanding of stress field, 3D fracture and fault network characterization, fluid source, fluid-rock interactions and recharge pathways, and characterization of rocks (core samples) from the subsurface geothermal reservoir.
Declarations

Acknowledgment

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Authors’ contribution

PK and ST conceptualized the study and PK acquired funding for it. HZ and ST wrote the first draft. PK wrote parts of the manuscript. HZ, ST, and PK participated in the field work. HZ performed the laboratory work on cuttings samples and HZ and ST worked on thin sections. PK acquired the drone imagery datasets. HZ developed 3D models from drone imagery, and ST worked on the fracture mapping from 3D models. HZ and ST are joint first authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

Not applicable


resources, development, and applications in China: Current status and prospects. Energy, 93, 466–483. https://doi.org/https://doi.org/10.1016/j.energy.2015.08.098


Figure 1: Figure showing the map of India (A), simplified geology overview map after Epard and Steck 2008 (B), and detailed geology map of Puga after Shanker et al. 1975 (C).

Figure 2: Overview of the study workflow.

Figure 3: Reservoir analogue outcrop adjacent to the Puga hot springs site (a). Structural measurements (b) extracted from the digital outcrop model (c) have been plotted using a lower-hemisphere stereographic projection, and highlight several sets of fractures and faults that likely controlled fluid circulation prior to their exhumation. Fault scarps observed in young scree deposits along the strike of the mapped normal faults suggest neotectonic activity (Epard and Steck, 2008). These also appear to correlate with the main thermal manifestations, suggesting they could serve as a conduit for the geothermal fluids. Background imagery in (a) is from Bing maps.

Figure 4. Selection of gneissic fabrics observed in outcrop and corresponding crossed-polar photomicrographs. Schistosity is moderately well developed where orthogneisses contain large relict quartz and feldspar grains (augen textures; a, b). More strongly deformed areas have intensely developed schistosity defined by muscovite (c,d) and partially recrystallized quartz ribbons (e,f). Quartz-rich lenses containing strongly aligned micas embedded within a recrystallised quartz matrix (g,h) are also common, and sometimes folded (e.g., top left of c). These high-strain recrystallised fabrics result in very low primary permeability and are described in detail by Dutta and Mukherjee (2021).

Figure 5. Fractures observed in the Puga analogue outcrop containing various fillings that demonstrate paleofluid flow. Synmetamorphic quartz veins are abundant, mostly in fabric-parallel orientations, but also in crosscutting shear-zones (a) that show microstructural evidence of significant high-temperature deformation (b). Foliation parallel microfractures (c,d) are also sometimes filled with biotite, indicating fabric-parallel fluid flow at high temperatures. Late fracture-filling massive and sub- to euhedral quartz veins (e, f) and porous, iron-rich travertine deposits lining joint surfaces (g, h) are interpreted to form due to precipitation from fracture-confined flow of geothermal fluids.

Figure 6. Examples of sericitic (a,b), advanced argillic (c) and solfataric alteration (d, e) observed at Puga. This appears to be controlled by fracture zones (a) and foliation (c) in the gneiss, while also forming polymictic breccias (e) that are interpreted to be welded valley fill and scree deposits.

Figure 7: Conceptual model of the Puga geothermal field based on the literature review and digital outcrop data presented in this study.
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