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Geothermal energy from abandoned oil and gas wells in Pakistan: A review

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ABSTRACT

Cleaner geothermal energy is an environment friendly and low-cost alternative of fossil fuel for space heating or electricity generation. Initially, a big drilling investment can be avoided by utilizing hundreds of available oil and gas wells in Pakistan to exploit geothermal energy. Previously acquired wells data such as: borehole temperature (BHT), lithostratigraphic logs, subsurface structure (fault/fracture), porosity, permeability and other well parameters are effectively utilized for preliminary geothermal reservoir evaluation. This review study utilized well data from sixty wells from different areas to evaluate geothermal systems in addition to thermal gradient and geothermal play type. Optimistic potential of geothermal energy from abandoned oil and gas wells (AOGWs) is present in the country with seven hottest sites in the central and lower Indus Basin. As a sustainable development goal (SDG-7), recycling AOGWs to harness geothermal energy won't just remove prospecting risks and drilling expense, yet in addition control the pollution and mitigate climate change.

HIGHLIGHTS

- Geothermal gradient has been reviewed to identify hotspots and nearby aligned AOGWs
- Thermal potential of wells for power generation, and domestic or industrial heating
- Possible utilization of geothermal energy w.r.t. potential and geopolitical location

1. INTRODUCTION

Fossil fuel is not a perpetual source of energy, nor is it environment friendly. It is high time to shift the paradigm to the cleaner, sustainable, and renewable energy sources. Geothermal energy has gained huge recognition as a cleaner substitute of conventional energy sources owing to its low greenhouse gas emissions, sustainable power supply, low environmental effects, and global availability. Electricity production from geothermal resources has augmented remarkably in the last few decades. In 1975, the geothermal electricity capability of the world was 1,300 MW (Bertani, 2012); which has been increased to 15,854 MW by the end of 2021 (Richter, 2022). Pakistan is still generating 64% of its electricity from fossil fuel (NEPRA, 2020), consequently emitting 180 Mt of CO_2 every year (Abas et al., 2017). The exploitation of geothermal energy demands high initial investment for drilling which can be omitted by retrofitting abandoned wells. The AOGWs are big financial and serious environmental risks worldwide. Recycling AOGWs for heat mining is one-solution cohesive approach to deal the key issues viz. electricity crisis, environmental pollution, deteriorating economy, and global warming.

The prime implications of geothermal energy include electricity generation, air conditioning, and industrial heating (Majorowicz & Grasby, 2010). Conventionally, geothermal energy has been exploited from volcanic, hydrothermal, and highly permeable sedimentary plays. But with the advent of modern binary fluid plants, deep borehole heat exchanger (DBHE) and reservoir stimulation techniques, the unconventional plays having low temperature, less permeability, and less conductive lithology have also become energy producers (Moeck, 2014; Raymond, J. & Gosselin, 2010; Raymond & Therrien, 2008).

Several researchers have contributed to develop scientific understandings of geothermal systems. (Bu et al., 2012; Cheng et al., 2014; Davis & Michaelides, 2009; Ghoreishi-Madiseh et al., 2014; Kujawa et al., 2006) have attempted to numerically model the production of heat from petroleum wells. (Bu et al., 2012) presented a tridiagonal matrix algorithm to model rock-fluid heat exchange. In this article, we have a reviewed the key geological parameters which influence geothermal performance and potential. It was shown that the amount of power production is chiefly dependent on geothermal gradient and rate of fluid flow in a well. As far the geothermal resources of Pakistan are concerned, few researches (Gondal et al., 2017; Mughal, 1998; Younas et al., 2016; Zaigham, 2005) have explored convection-dominated shallow and surficial resources such as volcanic and hydrothermal plays. But when it comes to AOGWs, (J. Ahmad, 2014) first suggested reuse of AOGWs followed by an awakening review of (Mehmood et al., 2017) discussing few potential zones of the country. Recently, a book chapter by (Munawar et al., 2022) attempted to address abandoned fields without reservoir characterization and quantitative assessment.

This article comprehensively assesses geothermal feasibility of selected AOGWs in Pakistan by recognizing their thermal potential and reservoir properties quantitatively. AOGWs offer a range of data required for evaluation of reservoir, such as porosity, permeability, subsurface structure (fault/fractures), lithostratigraphic logs, and borehole temperature (BHT). We have reviewed available data to find suitable AOGWs, their thermal output, and possible application. Furthermore, for the very first time, geothermal play types in Pakistan are devised following the catalog of (Moeck, 2014) which is based on geology and thermodynamics of reservoir. Another objective of this study is to suggest appropriate method to harness heat out of wells.

2. GEOTHERMAL PLAY TYPES

Ordinarily, geothermal plays were categorized on the basis of enthalpy and thermodynamics. (Haenel et al., 1988; Hochstein, 1988; Muffler, 1979) proposed three basic categories viz. (1) low temperature, (2) moderate temperature, & (3) high temperature play. But later on, various scientists realized that thermal parameters alone are insufficient to sort geothermal plays (Lee, 2001). Feasible heat mining from a certain play insists on contemplation of some geologic features along with enthalpy (Williams et al., 2011). Thence, (Moeck, 2014) devised a comprehensive catalog which considers geologic parameters in addition to enthalpy such as; tectonic setting, structure (fault/fracture), stress regime, thermal regime, hydrogeologic regime, mode and medium of heat flow, fluid dynamics, fluid chemistry, and lithofacies. These geologic parameters significantly influence the thermal potential and reservoir quality. Figure 1 summarizes this classification scheme.

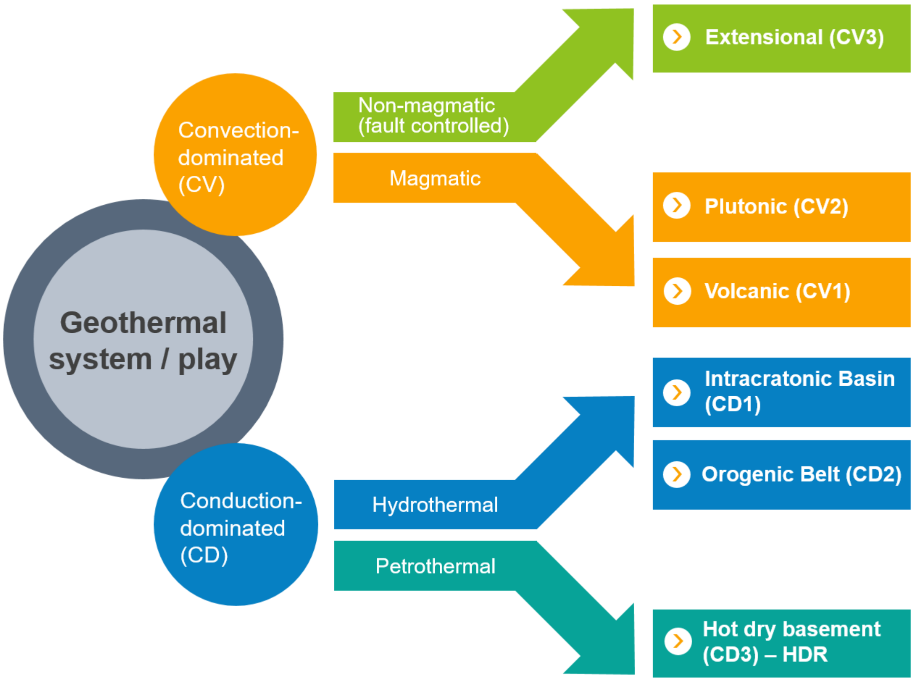

Figure 1: Geothermal play classification (based on catalog of Moeck, 2014)

Pursuant to thermal flow mechanism, geothermal systems are broadly grouped into active or convection-dominated (CV) plays, and passive or conduction-dominated (CD) plays. As geology control heat transfer mechanism, reservoir architecture and permeability, consideration of geologic attributes further divides these broad groups into distinct play types which are discussed below.

2.1 Convection-dominated (CV) geothermal plays

These plays, also called active geothermal plays, originate in the regions of active tectonism (Nukman & Moeck, 2013) and volcanism (Deon et al., 2012). Such plays contain high thermal potential developed by active mass flow in either magmatic or non-magmatic regime (Gianelli & Grassi, 2001).

Magmatic plays encompass ascending of magma from mesosphere to shallow lithosphere (plutonic) or onto the surface (volcanic). When rising magma finds some conduit through lithosphere and erupts onto the surface, the play is called volcanic type – magmatic play (CV1) (Fig. 1). The other type of magmatic geothermal plays is plutonic type – magmatic play (CV2) in which magma is entrapped within lithosphere finding no passage to the surface. This magma cools to form plutonic bodies (e.g., sill, dike, stock, laccolith, lopolith and batholith) which are common in young orogens. Thermal potential of plutonic type (CV2) plays can be estimated by age of magmatism (McCoy-West et al., 2011).

Non-magmatic (CV3) plays are characterized by fault controlled extensional regimes. As the name suggests, these plays don't involve magmatism rather hot fluids in extensional basin convect along deep faults/fractures developed above upwelling asthenosphere (Reed, 1983). That is the reason for high thermal gradient in thin skin zones. Typical targets to hit CV3 play include weaker zones or faults in dilatational setting (Faulds et al., 2010).

2.2 Conduction-dominated (CD) geothermal plays

As the name suggests, these plays don't involve any active mass flow, rather heat energy is transmitted passively through conduction in solid medium. These passive geothermal plays are either controlled by lithofacies (hydrothermal type), or faults (petrothermal type) (Fig. 1).

Hydrothermal CD plays have low enthalpy and are principally steered by lithology or may have minute impact of fault system. Due to no association of mass flow, deep reservoirs are heated by regular geothermal gradient in either intracratonic basin or orogenic belts. Hot aquifer deep inside the craton is referred to as "hydrothermal – intracratonic type (CD1) play" (Fig. 1). Fluvial sediments are predominant lithofacies of such plays where the focus is to hit on good reservoir with suitable temperature. Whereas in orogenic belts, there are frequent high permeable zones and deep-rooted faults through which meteoric water flow and form hot springs on the surface (Grasby & Hutcheon, 2001). Such plays are termed as "hydrothermal – orogenic type (CD2) plays" (Fig. 1).

Petrothermal HDR – CD3 plays comprise of tectonically inactive hot dry basement which lie beneath hydrothermal (CD1 & CD2) plays (Moeck, 2014). Heat mining through CD3 plays relies on natural faults or artificial fractures because these high enthalpy plays originally lack fluid storage and pore space. There are two main sources of heat in petrothermal plays viz. conduction from upper mantle and radioactivity within igneous basement. Basement rocks are crystalline in nature and have insignificant reservoir properties. However, a couple of stimulation techniques (acid and hydraulic fracking) are available to boost reservoir quality (Genter et al., 2000; Zimmermann et al., 2008).

3. GEOTHERMAL PLAYS OF PAKISTAN

Pakistan is naturally gifted with all type of geothermal plays. Volcanism in Koh-i-Sultan represent convection-dominated (CV1) geothermal system. While, Plutonism inside Chagai magmatic complex embody CV2 play. Hot springs and geysers form hydro-geothermal plays (CD2) which are frequently distributed especially in tectonically deformed areas of the country. But, geysers around volcanoes (e.g., Koh-i-Sultan, Chagai) and in Gilgit indicate some convective source. There are more than 80 mud volcanoes in the country which also typify CV1 plays. Most of these mud volcanoes are discovered in Baluchistan Geothermal Zone with noteworthy manifestations in Gwadar peninsula, Lasbela, and Makran coastal belt. Extensional fault system present in Upper Indus (Salt Range) and southern part of Lower Indus form CV3 plays. When it comes to abandoned petroleum fields, conduction is the dominant mode of heat transfer. After absorbing heat from pervious conductive rocks, water flows across the wells in or near orogenic belts and shallow depth wells in intracratonic basin making CD2 and CD1 hydro-geothermal plays, respectively. AOGWs with depth greater than 4000m are characteristically dry and form HDR (CD3) – petrothermal play. Such HDR petrothermal plays are extensively encountered in numerous AOGWs drilled in Indus Basin. Igneous basement beneath sedimentary basins also forms the CD3 – petrothermal play having higher enthalpy as compared to plays established in sedimentary sequence. As igneous rocks are impervious in nature, stimulation by hydraulic or acid fracturing will make basement adequate for water circulation.

4. GEOTHERMAL RESERVOIR CHARACTERIZATION

A geothermal reservoir is also called natural heat exchanger which refers to a volume of rock having enough heat potential to support profitable exploitation. Process of heat mining is mainly dictated by geothermal gradient and geologic features of reservoir. Therefore, it is essential to study reservoir characteristics for selecting a lucrative AOGW and extraction method (Fig. 2). Several parameters such as porosity, permeability, fault and fractures, fluid volume and saturation, rock-fluid interaction, thermal gradient, lithofacies, and mineralogy can affect thermal potential of a reservoir (Fig. 2). Storage and transport of fluids is highly sensitive to fractures and karstification in addition to matrix porosity (Bohnsack et al., 2020). Rock mineralogy, density, porosity and texture can effectively control thermal diffusivity of the reservoir (Stober & Bucher, 2014). This section discusses the main factors by which a geothermal reservoir is characterized (Fig. 2).

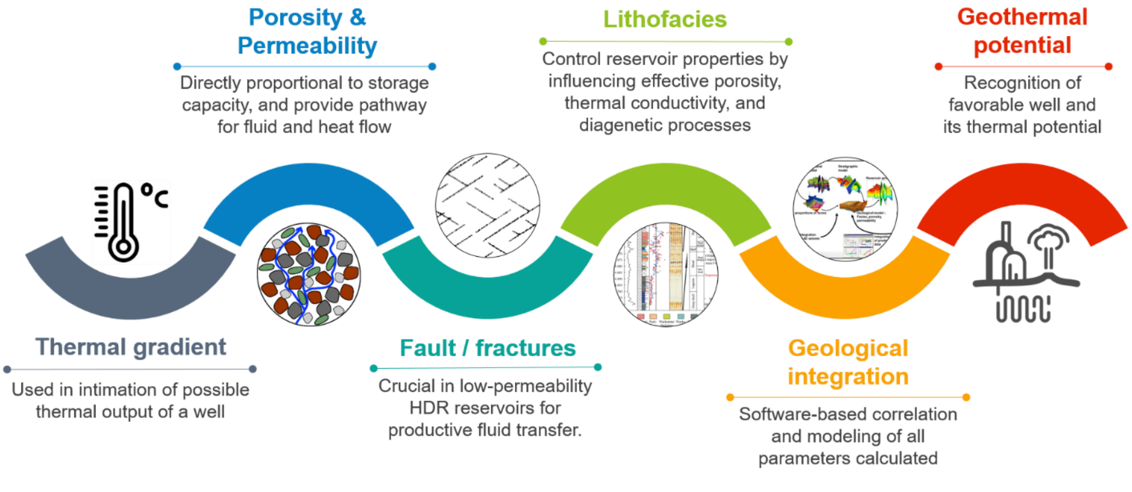

Figure 2: Schematic illustration of geothermal reservoir characterization

4.1 Geothermal gradient

Geothermal gradient is not uniform throughout the globe due to variation in conductivity of rocks and heat flow pathways. It is the key parameter in speculating the possible thermal output through a well. Outlet temperature of greater than 130ºC can be achieved through 4km deep well having geothermal gradient of 3ºC/100m. Well with outlet temperature greater than 150ºC can produce electricity on large-scale using flash steam or dry steam power plant (Fig. 3). Whereas outlet temperature between 90ºC and 150ºC is adequate for closed loop – binary fluid plant. Geothermal gradient and possible outlet temperatures of about sixty AOGWs are analyzed in this study for their viability in power production.

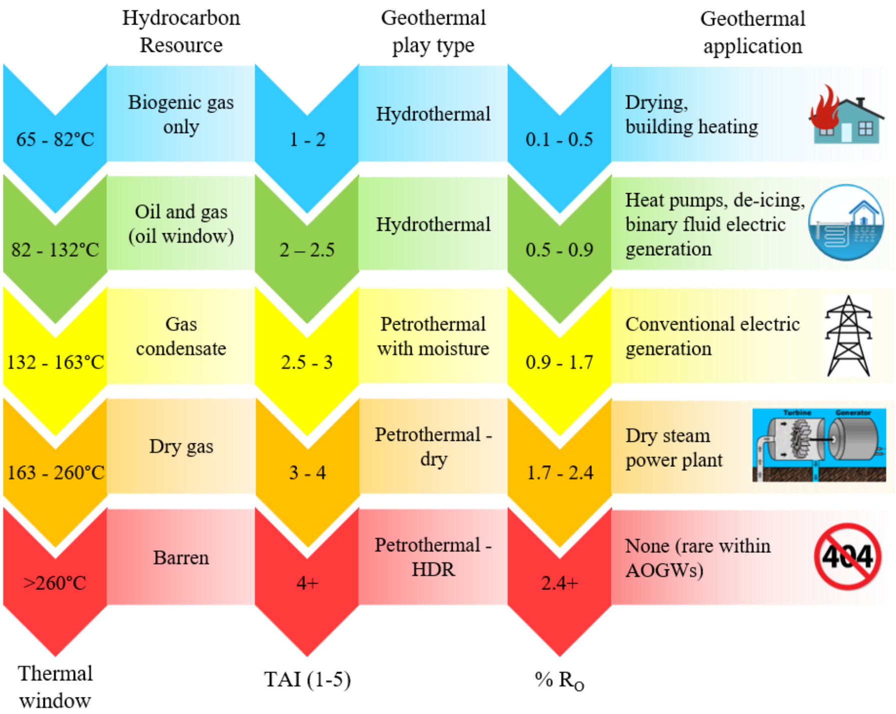

Figure 3: Relationship of hydrocarbon thermal window with geothermal resource and its possible utilization (after Munawar et al., 2022)

Geothermal gradient can also speculate the reservoir quality (porosity and permeability); as degree of compaction is direct function of burial temperature (Shou et al., 2006). Potential geothermal reservoirs are deep in crust, but with reduced reservoir quality. Since fluid saturation is also temperature dependent, proper characterization study of geothermal reservoir is crucial. There are several approaches to estimate thermal maturation. Two common parameters i.e., vitrinite reflectance (% R_O) (Tissot & Welte, 1984) and Thermal Alteration Index (TAI) (Waples, 1985) are correlated with geothermal play type and possible application in Figure 3. Geochemical tools used to estimate thermal maturation include biomarkers, geothermometers, isotopic ratios, mercury and CO_2 concentration. Furthermore, curie depth estimated by aeromagnetic survey and low resistivity anomalies identified by magnetotelluric survey can help initially delineate geothermal reservoirs.

4.2 Porosity (Φ) & permeability (k)

Fluid flow and storage capacity are critical to pore space and pore connections in the rock. Connectivity of pores distribute fluid flow channel for rock-fluid heat exchange (Winterleitner et al., 2018). These parameters can be calculated by direct as well as indirect methods. Direct method includes laboratory testing of core samples or computation from digital rock. On the other hand, indirect method implies calculation from geophysical logs run in the borehole. Results of both methods can be compared to obtain an empirical relationship which is helpful in computational fluid dynamics (CFD) and permeability modeling (Bohnsack et al., 2020). Permeability is primarily dependent on lithofacies and burial, but secondarily on diagenetic processes. As discussed previously, the pore space reduces with burial depth. The rate of chemical reactions (e.g., dissolution, precipitation) also speeds with temperature which may grow authigenic minerals in the voids. Although fluid flow depends on several factors like hydraulic pressure, fluid viscosity, grain size, sorting and packing etc., but karstification and vuggy porosity in carbonates, and intergranular porosity in clastics are main contributors to fluid flow and storage. Most of the reservoir formations in Pakistan exhibit reasonable porosities and permeabilities (Jaswal et al., 1997; Khalid et al., 2015; Munawar et al., 2022; S. B. Shah et al., 2019) making them promising geothermal reservoir candidate. Our work appraises the quantitative porosity and permeability of reservoir formations in section 6.

4.3 Fault & fractures

Faults and fractures act as fluid conduit that can remarkably improvise heat exchange rate in low permeability HDR reservoirs. Frictional heat produced by faults also add up to the thermal gradient near fault zone. In Indus Basin, majority of the carbonates reservoirs possess complex fracture system to support fluid flow. Flow pattern in such reservoirs can be determined by analysis of fracture corridor (Basir et al., 2013; Roehl & Choquette, 1986) using lithologic core data (Song et al., 1998), sonic log (Hsu et al., 1987), rock physics and seismic data (Lumley & Behrens, 1998). Gravity method also help in recognition of subsurface fault/fractures along with geometry of dense anomalous bodies. (Cacas et al., 2001) presented discrete fracture network models to report geometry and anisotropy of individual fracture set. Anisotropy can be examined through pre-stack data (Ikawa & Mercado, 2010) while fracture orientation and intensity can be studied through geometrical post-stack attributes (Basir et al., 2013; Zhang et al., 2015). Ant-track attributes enhance the fracture visualization (Ngeri & Amakiri, 2015) which can be combined with geometric attributes like dip azimuth (Rijks & Jauffred, 1991), coherency (Marfurt et al., 1998) and curvature (Hart et al., 2002) for better forecasting fractures and subtle fault displacements (Silva et al., 2005; Zhang et al., 2015).

4.4 Lithofacies

Lithofacies is a basic geologic control on reservoir architecture, its porosity and permeability. According to (Bohnsack et al., 2020), various permeability models have shown that the effective porosity is determined by lithofacies and related parameters like grain size, grain packing, sorting, pore geometry, cementation factor. In open-loop configuration, the fluid directly interacts with the rock which may alter reservoir architecture due to dissolution, precipitation and thermo-geomechanical deformation (Pandey & Singh, 2021). Increasing stratum temperature promotes authigenic mineralization (Cyziene et al., 2006). For instance, kaolinite and smectite alter into illite which congests the throats and fine pores, subsequently reducing permeability (Lander & Bonnell, 2010). Apart from diagenetic processes, geothermal gradient also influences rock rupture strength. High temperature enhances compressive strength of reservoir. Thermal conductivity (Brigaud & Vasseur, 1989), P-wave velocity (Eberhart-Phillips et al., 1989; Han et al., 1986), thermal diffusivity (Bagdassarov & Dingwell, 1994), specific heat capacity (Clauser & Huenges, 1995), and Young's modulus (Chang et al., 2006; Griffiths et al., 2017) are inversely proportional to pore space in dry rocks. However, P-wave velocity (Eberhart-Phillips et al., 1989; Han et al., 1986) and thermal conductivity (Brigaud & Vasseur, 1989) are directly related with clay content.

5. GEOTHERMAL ENERGY EXTRACTION FROM AOGW

Heat extraction from AOGW implies retrofitting borehole into heat exchanger. There are two configurations available to do that; (1) open-loop, and (2) closed-loop. Open-loop system is more complicated and challenging in the sense that injection of fluid from one well and extraction from other well. Injected fluids are allowed to penetrate deep into reservoir in order to absorbs heat. In case of HDR reservoir, simple open loop configuration upgraded to enhanced geothermal system (EGS) is utilized which involves fracking to produce artificial permeability. (Evans et al., 2011) reported that EGS system can generate 3.5 MW electricity and 25 MW heat energy when boiling water is obtained at a rate of 50 kg/s. But unfortunately, the process of artificial fracking is expensive and threatening to nearby population due to risk of induced seismicity. Furthermore, the open-loop method often encounters some working issues like fluid loss, corrosion and scaling, pore clogging in reservoir, permeability loss, dissolution/precipitation of minerals. Direct rock-water interaction is the root cause of all above issues which restrict the production life of reservoir although the heat may still be available in it. Contrarily, opting closed-loop method can avoid the aforementioned problems, because in this method, the fluid does not touch directly with the rocks rather it is circulated in a closed and cased channel preventing addition of toxins into circulating water from subsurface. Hence, closed-loop technology also eliminates the risk of aquifer contamination. Deep borehole heat exchanger (DBHE) is a classical closed-loop system used to harness heat energy from AOGW (Fig. 4a). But past experiments and simulation studies have divulged that deprived heat conductance of some rocks is pivotal hindrance to the performance of DBHE. Thus, it is imperative to discover some unconventional method to improve thermal conductivity of rock concerning proficient recovery of heat.

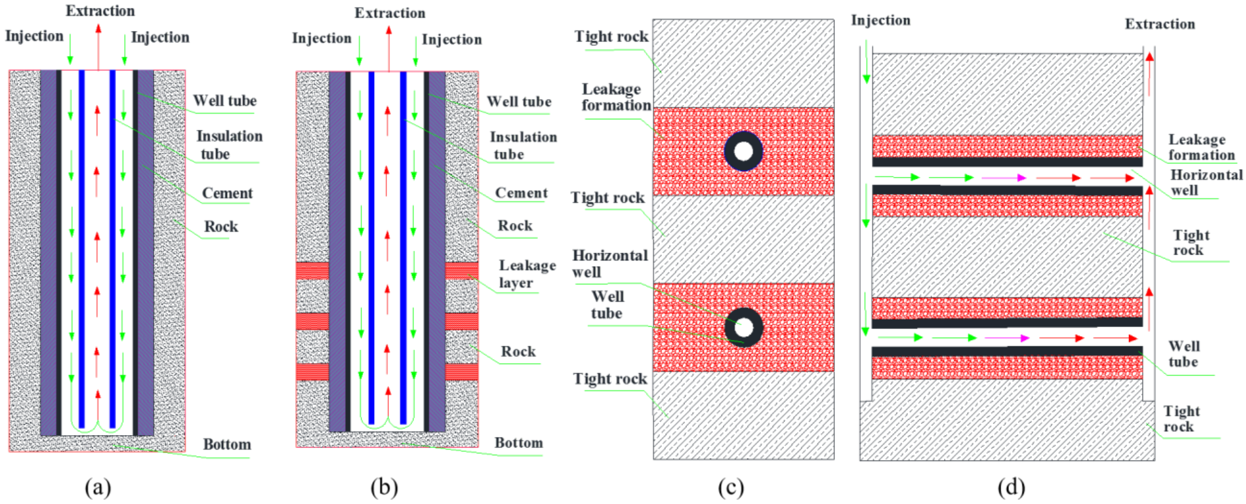

Figure 4: Closed-loop configurations. (a) DBHE wellbore assembly; (b) SWEDBHE wellbore assembly with leakage layers; (c) Cross-sectional view of DWEDBHE (double-well EDBHE); (d) Side view of DWEDBHE

Depleted oil and gas reservoir contains rich fracture sets and fluid storage capacity that should be exploited ingeniously to enhance heat transfer in the rocks. Triggered by this, (He & Bu, 2020) put forward a novel enhanced deep borehole heat exchanger (EDBHE) model in which a composite material (graphene mud) is injected into fractured (leakage) formation as shown in Figs. 4b, 4c and 4d. This leakage formation with saturated composite material draws heat from distant reservoir to the wellbore. The process of filling is also easier if we adjust the viscosity, back pressure, and density of composite material (He & Bu, 2020).

EDBHE technology possess many advantages over open loop or ordinary DBHE, which are listed below. But when it comes to mineral or elemental recovery from circulating fluid, EDBHE cannot do that, which is also the only limitation of closed-loop technology.

- The main advantage of EDBHE is its greater thermal conductivity owing to injection of composite material (graphene mud) into reservoir rock.
- Closed-loop channel will exchange heat (through conduction) but not the fluid from geothermal reservoir. Therefore, it can also be applicable in low porosity/permeability reservoirs.
- No dependence on natural aquifer makes it operable in various HDR-CD3 plays. In this way, problems like corrosion, scaling, and recharge are also wiped out.

- As fluid chemistry remains unaltered, EDBHE assures clean energy from clean process due to no mass exchange between fluid-rock.
- 2.36 times extra energy output than ordinary DBHE (He & Bu, 2020).

6. GEOTHERMAL ENERGY POTENTIAL OF PAKISTAN

Heat beneath our feet actually originates from the core and flows outward to the surface. But its potential is not uniform everywhere due to heterogenous crust. Different potentials are observed in different areas and depths, and in different play types as discussed earlier. On one side, geothermal energy approaches to the surface at some locations in the form of volcanism, geysers, hot springs and fumaroles. On the other side, profound penetrating down to thousands of meters is needed to approach the reservoir of appropriate temperature. In Pakistan, drilling for petroleum exploration started in 1960s and reached to the number of 1123 exploratory wells as of June 2020. Out of these, hydrocarbon has been discovered only from 411 wells. The remaining are abandoned (MNPR, 2020). Out of these abandoned wells, about sixty wells are assessed in this study for their feasibility in power generation.

Pakistan is situated at convergence of Indian, Arabian, and Eurasian Plate. This area has rich geothermal systems of both CD and CV plays. CD plays are distributed in orogenic belts, Himalayan Foreland and intracratonic Indus platform. While, CV plays are available in Chagai Magmatic Arc, seismotectonic zones along Indus suture, and some places of Gilgit-Baltistan (Mughal, 1998). Besides fractures, hundreds of faults (Fig. 5) are active in Karakoram Block, NW Himalayas, Sulaiman Province, Kirthar Province, Kohistan Magmatic Arc, Kharan Basin and Makran Accretionary Zone (Kazmi & Jan, 1997). These faults serve as fluid conduit and produce frictional heat to intensify geothermal gradient in the area.

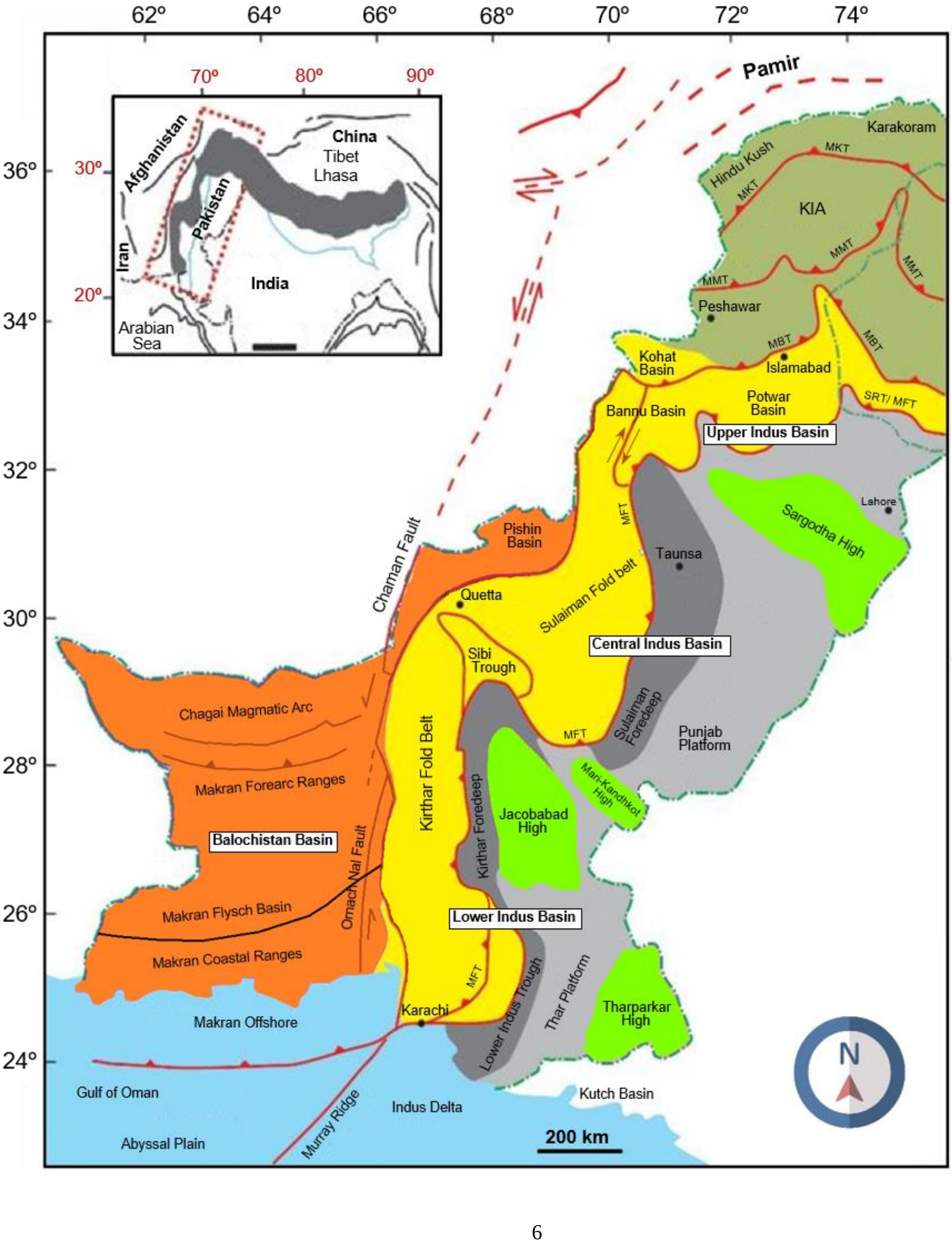

Figure 5: Basin tectonic map of Pakistan (modified from Kazmi & Jan, 1997; Ullah et al., 2020)

Previous researchers (I. Ahmad & Rashid, 2010; M. A. Khan & Raza, 1986; Mughal, 1998; Zaigham, 2005) devised three geothermal zones of Pakistan viz. (1) Himalayan collisional zone or northern geothermal system, (2) Chagai Magmatic Complex in Baluchistan, and (3) Indus Basin zone. Indus Basin zone is least explored due to fact that no such surficial geothermal source exist in this area and drilling is required to exploit and prove the geothermal reserve. It is also worth mentioning here that previously, AOGWs were not considered for geothermal energy exploration in Pakistan. Recently, worldwide utilization of AOGWs for geothermal energy extraction has brought significance to Indus Basin where 95% of the total AOGWs are drilled.

6.1 Northern geothermal zone

This zone is constrained between Main Boundary Thrust (MBT) in the south and geographic border with China in the north. This region is comprised of three mightiest mountain ranges named Karakoram, Himalaya and Hindukush. Seismotectonic sutures are the main facilitator for heat transfer here. Frequent surface showings in the form of geysers, fumaroles and hot springs especially in north Himalayan valleys are associated with perennially flowing hydrothermal orogenic type - CD2 plays of upto 140ºC temperature. Main Karakoram Thrust (MKT) is triggering hydrothermal discharge to the surface in Dasu, Budalas and Murtazabad (Shuja, 1986). While, hot springs in Sassi and Mushkin in Gilgit-Baltistan, and Tatta Pani in Azad-Kashmir are linked with Main Mantle Thrust or MMT (Zaigham, 2005). Other orogenic type CD2 – hydrothermal plays are Garam Chashma Valley in Chitral (Calkins et al., 1981), Rawat village in Yasin district, and Pechus glacier near Mastuj (Bakr, 1965). Nanga Parbat Haramosh Massif (NPHM) hosts a CV2 plutonic play developed by Pleistocene magmatism (Kazmi & Jan, 1997). Along the faulted margins of NPHM, there is remarkable hydrothermal activity making CD2 play (Zaigham, 2005). Northern Geothermal zone is deprived of AOGWs. There are about ten wells; some of which are active and some are in developmental stage, that is why their data is inaccessible at the moment.

6.2 Baluchistan geothermal zone

Lying in the west of Indus Basin, Baluchistan Geothermal Zone comprises of Baluchistan Basin and Chagai Complex which is a part of Tethyan Magmatic Belt. Chagai Complex also called Chagai Magmatic Arc contains CV1 and CV2 magmatic plays. This arc is developed by subduction of Arabian Plate underneath Eurasian Plate (Fig. 5). This arc is deemed as dormant since quaternary volcanism, but ongoing hydrothermal activity below Sinjrani volcanics, and H_2S emanation and sulfur mineralization in acidic hot springs and fumaroles around Koh-i-Sultan implies the presence of some active convection source in Chagai Complex (Shuja, 1986). Todaka et al. (1999) reported that the temperature of springs on the surface is less than ambient temperature. But (Shuja & Khan, 1984) calculated 160ºC temperature of hydrothermal reservoir around Koh-i-Sultan using silica geothermometer. Mud diapirism, hot springs and geysers are also common in Baluchistan. Out of 80 mud volcanoes discovered, majority are situated in coastal areas of Makran, Lasbela and Gawadar.

Pertaining to the thermal potential of AOGWs in Baluchistan Geothermal Zone, there are less than sixty wells; all of which are abandoned. The geothermal gradient recorded at 3624m deep Garr Koh is 2.55ºC/100m (M. A. Khan et al., 1991), whereas 3ºC/100m at Gwadar (Fig. 8). Calcareous mudstone of Miocene Parkini Formation lies from 2175m to 4200m in Garr Koh area (M. A. Khan & Raza, 1986). Maximum stratum temperature of approximately 115ºC can be achieved along with structural complexities in this well; which is sufficient for power generation. Gwadar-1 located in Makran Offshore near Gwadar Peninsula exhibit geothermal gradient of 2.1ºC/100m. This well has total depth 3810m hitting Talar Formation (Table 1). Kech Band-1 has a thermal gradient of 1.5ºC/100m and total depth of 3349m (M. A. Khan et al., 1991). Dhak-1 & 2 are 2562m and 4454m deep penetrating Late Miocene Parkini formation (Raza et al., 1990). These coastal wells have geothermal gradient of 1.95ºC/100m and 1.70ºC/100m respectively (M. A. Khan & Raza, 1986). Jal Pari 1-A is Makran Offshore well having geothermal gradient of 1.48ºC/100m (M. A. Khan & Raza, 1986). This well has total depth of 2007m penetrating Pliocene Hinglaj Formation (Table 1). Depth of all AOGWs in Baluchistan Basin is not more than 4500m and they are met with repeated sequence due to structural complexities. Since all of the wells in Baluchistan Basin are abandoned, they can be recycled to extract geothermal energy. Based on high thermal potential and geopolitical location (CPEC – China Pakistan Economic Corridor), Garr Koh-1, Dhak-2, and Gwadar-1 (Table 1) are promising for electricity generation in Baluchistan.

Table 1: Geothermal characterization of AOGWs in Baluchistan Basin.

Oil/gasfield	Total depth m	Formation at well bottom	Lithology	Geothermal gradient ºC/100m	Outlet Temperature ºC	Suitability for electricity generation
Garr Koh-1	3624	Parkini	Mudstone, Sst.	2.55	114	✓
Kech Band-1	3349	-	-	1.5	72	✗
Dhak-1	2562	Parkini	Mudstone, Sst.	1.95	70	✗
Dhak-2	4454	Parkini	Mudstone, Sst.	1.7	97	✓
Jal Pari 1-A *	2008	Hinglaj	Mudstone, Sst.	1.48	50	✗
Gwadar-1 *	3810	Talar	Sandstone	1. 2.1	2. 100	**3.** ✓

*** Makran Offshore**

6.3 Indus geothermal zone

This zone is comprised of Indus Basin in Pakistan which covers about 5 lac square kilometer area of NW portion of the Indian Plate. About 15km thick sedimentary succession from Precambrian to recent is preserved here (Fig. 6) in which CD plays are available. Extensive drilling has been deployed with approximately 600 wells abandoned. Indus Basin can be divided into upper, central and lower Indus basin. Geothermal prospect of AOGWs in these three divisions is reviewed in the following.

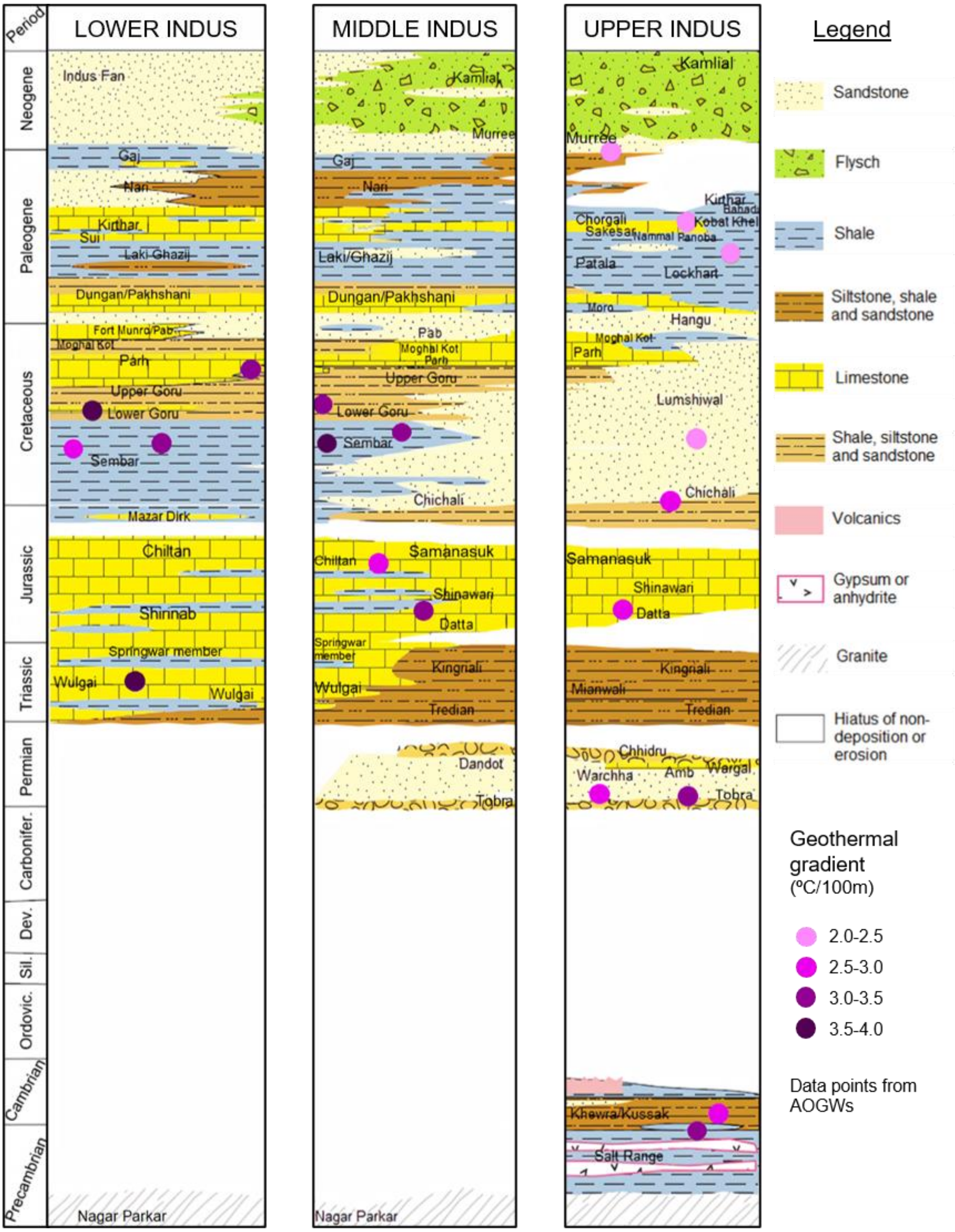

Figure 6: Geothermal gradient at generalized stratigraphy of Upper, Central and Lower Indus Basin. Figure modified from (Munawar et al., 2022; Wandrey et al., 2004). Geothermal data from (M. A. Khan & Raza, 1986).

<u>6.3.1 Upper Indus Basin</u>

It is comprised of northern Punjab Platform, Cis and Trans-Indus Salt Range, Potwar Plateau, and Bannu Basin (Fig. 5). Being top tier oil-prone zone, this area has more than 20 oilfields (Wandrey et al., 2004). With a stratigraphic sequence spanning from Precambrian to recent (Fig. 6), this region has average geothermal gradient of 2°C/100m where the oil window is present between 2750m and 5200m depth. Reservoir lithofacies in this area are alluvial and shoreface sandstones of Cambrian, terrigenous sandstones of Jurassic and Permian, carbonates of Paleogene shelf, and alluvial sandstones of Miocene (M. W. A. Iqbal & Shah, 1980; S. M. .

Shah et al., 1977). Kherwa Sandstone, Kussak Formation, and Jutana Dolomite from Cambrian; Tobra, Wargal, and Amb Formation from Permian; Datta Sandstone from Jurassic; Lumshiwal Formation from Cretaceous; Lockhart Limestone, Patala, and Nammal Formations from Paleocene; Bhadrar, Chorgali, and Sakesar Limestone from Eocene; and Murree Formation from Miocene are proven hydrocarbon reservoir in Potwar region (M. A. Khan & Raza, 1986). Out of these reservoirs, sandstones have porosity between 5% and 30%, with an average of 12% to 16%. Permeability of these rocks range from 1 mD to more than 300 mD, with an average of 4 to 17 mD (M. A. Khan & Raza, 1986).

(Khalid et al., 2015) calculated mean porosities of Paleocene to Jurassic succession came across Injra and Nuryal Well in western Potwar sub-basin. These wells have geothermal gradient of 2ºC/100m and 2.1ºC/100m respectively. Early Jurassic-Datta Sandstone is a quality reservoir (Φ=19-23%, k=2.1-6.1 mD) and is encountered at bottom of Injra and Nuryal (Table 2). According to (Khalid et al., 2015), the porosity of Early Eocene Chorgali Formation in western Potwar sub-basin is 12-15%, Early Eocene Sakesar Limestone is 6-10%, Early Miocene Murree Formation is 11-14%, Middle Miocene Kamlial Formation is 12-15%, and Late Miocene Chinji Formation is 15-17%. Carbonates constitute about 60% of the total reservoir rocks in Upper Indus Basin, in which karstification, and fracture porosity on strike with structural trend facilitate fluid migration (Jaswal et al., 1997). Such reservoirs include Eocene Sakesar and Chorgali Formation encountered in Adhi, Balkassar, Dakhni, Dhulian, Dhurnal and Meyal oilfield. Sakesar Limestone has average porosity of 12% and permeability of 51.14mD recorded in Balkassar-7, 8 and OXY-01 (Table 2). As compared to this, Chorgali Formation in this region owns better reservoir properties with mean porosity of 18% and permeability of 116 mD (S. B. Shah et al., 2019). Naturally fractured Wargal Limestone of Late Permian age also acts as good reservoir in Dhurnal field. Mahesian and Qazian Well have thermal gradient of 2.05ºC/100m and 2.3ºC/100m respectively (M. A. Khan & Raza, 1986). These wells are drilled to 5150m and 4700m depth respectively, hitting Infracambrian Salt Range Formation. Apart from carbonate reservoirs, Early Cambrian Khewra Sandstone and Kussak Formation are 3 to 4km deep reservoirs and possess good petrophysical properties with formation temperature of 90ºC to 120ºC. (Ghazi et al., 2015) calculated log derived mean porosity of Khewra Sandstone as 14-22% and permeability between 20 and 58 mD. It is encountered at bottom of Adhi, Missa, Kiswal, and Rajian oilfield. Geothermal gradient of 2.05ºC/100m to 2.3ºC/100m is available along Paleozoic to Eocene succession that lies between 2400 to 5100m depth in Adhi oilfield (M. A. Khan & Raza, 1986). Another excellent sandstone reservoir i.e. Permian Warchha Sandstone of about 82m thickness and effective porosity from 27 to 35% is present at depth of 2500m in Adhi well (Ghazi et al., 2014). It is anticipated that abandoned wells drilled down to 5km penetrating Khewra Sandstone in Adhi oilfield can supply outlet temperature of about 135ºC.

AOGWs in Kallar Kahar region are neither so deep nor so hot (1.7ºC/100m) to produce steam for electricity generation, however, can be utilized in domestic heating. Kallar Kahar wells are not more than 3200m deep, hitting Salt Range Formation (M. A. Khan & Raza, 1986). Geothermal gradient in this area is just 1.7ºC/100m that makes this field inadequate for electricity generation. On the other side, Dhulian oilfield indicates thermal outlet of 135ºC at depth of 5200m (Table 5). There are four wells drilled so far in this oilfield, named Dhulian-2, 3, 42 and 4 whose geothermal gradient ranges from 2ºC/100m to 2.3ºC/100m (M. A. Khan & Raza, 1986). These wells have Precambrian to Tertiary succession (missing upper Jurassic and Cretaceous) between depths of 2400m and 5300m. Meyal-4, Meyal-5 and Meyal-6 located in the east of Dhulian oilfield maintain temperature gradient between 2.15 and 2.3ºC/100m (M. A. Khan & Raza, 1986). These wells are 4900m deep where Datta Sandstone of 127ºC is encountered (Ghazi et al., 2014). Toot oilfield of western Potwar sub-basin also contains similar succession. Toot-5 and Toot-9 are 4850m deep and hold thermal gradient of 2.18ºC/100m to 2.4ºC/100m respectively. Alike Adhi and Dhulian, Toot oilfield also have got thermal outlet of 135ºC at depths of 4800m. To summarize, all AOGWs, except those of in Kallar Kahar region (low thermal potential), can be reused to exploit geothermal energy using closed-loop technology (Table 5). But for open-loop EGS; Qazian, Mahesian, Toot, Dhulian, Meyal, Adhi, and Balkassar are more promising owing to their good reservoir properties (Table 2).

Table 2: Geothermal reservoir characterization of AOGWs in Upper Indus (Kohat-Potwar) Basin

Oil/gas field	Reservoir Formation	Lithology	Porosity (Φ) %	Permeability (k) mD	Reservoir Depth m	Formation Temperature ºC
Injra	Datta	Sandstone	19-22	4	4625	110
Nuryal	Datta	Sandstone	20-23	6	4760	120
Dhurnal	Wargal	Limestone	15-24	3-12	5500	135
Mahesian	Khewra	Sandstone	14-19	20-45	4000	104
Qazian	Khewra	Sandstone	18-22	30-55	3500	102
Kallar Kahar	Salt Range	Marl, shale	10	-	3200	75
Chanda	Lockhart	Limestone	3	<1	4230	85
Toot	Datta	Sandstone	9	74	4700	130
Dhulian	Lockhart	Limestone	11	<2	2800	82
	Datta	Sandstone	8.5	2-869	2900	85

	Warcha	Sandstone	27-35	10-50	3300	95
Meyal	Chorgali	Shaly Lst.	16	85	3700	102
	Sakesar	Limestone	10	38	3800	105
	Datta	Sandstone	15-40	500	4300	127
Adhi	Warcha	Sandstone	30-40	30-60	2500	77
	Khewra	Sandstone	15-21	25-50	4500	121
Balkassar	Sakesar	Limestone	12	51.14	2550	74
	Chorgali	Shaly Lst.	18	116	2450	72

6.3.2 Central Indus Basin

Central Indus Basin is demarcated by Sargodha High (Pezu uplift) in the north, and Sukkar Rift and Mari-Jacobabad High in the south (Fig. 5). According to (Kemal et al., 1992), oblique convergence of India with some microplates making the southern margin of Eurasia, created these highs together with wrench faults and regional arches. This area is comprised of Sulaiman Fold Belt, Sulaiman Foredeep and Punjab Platform (Raza et al., 1989) (Fig. 5).

Principal reservoir rocks of Central Indus Basin include Habib Rahi Limestone (HRL), Sui Main Limestone (SML), Lumshiwal Formation, Lower Goru and Chiltan Formation (Wandrey et al., 2004). (Khalid et al., 2020) quantified porosity of Lumshiwal Formation in different AOGWs of this basin as varying between 12 and 32%. While, porosity and permeability of SML varies from 6.7 to 28.4% and 0.1 to 12.9 mD respectively (Tainsh et al., 1959). SML is proven gas reservoir in Sui, Loti, Kandra, Kandhkot, Bhadra and Qadirpur. Lower Goru in Kadanwari gasfield has porosities ranging from 12 to 23% and permeability from 0.7 to 5 mD (Table 3) (Khan and Khan 2018). Southern plain margin of Sargodha High is drilled with Budhuana, Karampur, Kamaib, Tola and Sarai Sidhu wells. Despite of the good reservoir character, very low geothermal gradient of 1.12 to 1.71ºC/100m exist in these wells. Tola-1 reaches Warcha Sandstone at shallower depths (1810m) with average porosity of 27%, (N. Ahmad et al., 2021). Since, these five wells were not drilled to greater depths, and could not achieve higher bottom hole temperatures, thus are insignificant for electric production.

On the other side, wells (especially Dhodak) drilled in Sulaiman Foredeep possess exceptional geothermal potential. Three AOGWs of maximum 5km depth are available in Sulaiman Foredeep viz. Dhodak, Domanda and Sakhi Sarwar. Geothermal gradient of 3.2ºC/100m is recognized in Dhodak field, which falls to 2.1ºC/100m in Domanda and Sakhi Sarwar. Extraordinary thermal output of 180ºC can be attained through Dhodak field, while, Domanda and Sakhi Sarwar wells evince thermal output of 130ºC. Dhodak Well encounters Pab Sandstone (Φ=15-20%, k=10 mD) at depth of 2400m (I. Khan et al., 2016; Moghal et al., 2012). Conspicuously, AOGWs in Sulaiman Foredeep are appropriate for geothermal power plant. However, the utmost geothermal gradient (i.e., 4.1ºC/100m) is held in the middle of Sulaiman Basin where Giandari Well is drilled. As stated by (Quadri & Shuaib, 1986), Giandari Well is drilled down to 3659m reaching Parh Formation and fractured Chiltan Formation at its bottom. In the west of Giandari, well-known Sui and Mari gas fields exist having average thermal gradient of 3ºC/100m and 3.2ºC/100m respectively. Habib Rahi Limestone (HRL) act as gas reservoir in Mari gas field, but unfortunately, it has very poor petrophysical quality to meet extraction requirements. Contrarily, Qadirpur gas field has excellent thermal potential along with average porosity of 23% in SML (Ali et al., 2005). Temperature gradient in Qadirpur gas field is between 2.5 and 3ºC/100m with maximum well depth of 4703m reaching SML (News, 2009). Two other wells i.e. Jandran and Tadri are drilled down to 4400m and 4000m depth respectively (M. A. Khan & Raza, 1986). Both have geothermal gradient of 2.4ºC/100m. Jadran Well has penetrated Chiltan Formation having porosity 3-10% and permeability 0.1-4 mD, at depth of 2500m (M. Iqbal et al., 2017).

To sum up, the abandoned wells in Sulaiman Foredeep (Dhodak, Domanda and Sakhi Sarwar), Giandari from central region of Sulaiman Basin, and few from Sui and Qadirpur gas fields have enough potential to produce power. Heat mining from Jandran, Tadri, Kadanwari and Sawan field is satisfactory for domestic heating or small-scale power plant. While, AOGWs in southern plain margin of Sargodha High are inappropriate for heat mining owing to their very low intrinsic heat energy.

Table 3: Geothermal reservoir characterization of AOGWs in Central Indus Basin.

Oil/gasfield	Reservoir Formation	Lithology	Porosity (Φ) %	Permeability (k) mD	Reservoir Depth m	Formation Temperature ºC
Kadanwari	Lower Goru	Sandstone	16-23	700-5000	3400	110
Sawan	Lower Goru	Sandstone	15	6-48	3300	105
Qadirpur	SML	Limestone	6-29	0.5-13	4600	150
Dhodak	Pab	Sandstone	15-20	10	2400	98

Domanda	Ghazij	Mixed	9-16	0.1-12	3400	94
Giandari	Chiltan	Limestone	2-9	0.1-6	3659	170
Sui	Lower Goru	Sandstone	12	1000	2000	82
Mari	Sembar	Shale	2-6	0.1-4	3400	130
Jandran	Chiltan	Limestone	3-10	0.1-4	2500	82
Tola-1	Warcha	Sandstone	27	15-60	1810	50
Sarai Sidhu	Khewra, Kussak	Sandstone	5-20	10-50	2800	52
	Salt Range	Marl, shale	5-10	-	3150	58
Karampur	Khewra, Kussak	Sandstone	5-20	10-50	1800	45
	Salt Range	Marl, shale	5-10	-	2200	50

6.3.3 Lower Indus Basin

Lower Indus Basin starts from Sukkar Rift and extends offshore to the Murray Ridge in Arabian Sea. As shown in figure 5, this basin is comprised of Kirthar fold Belt, Kirthar foredeep, Thar Platform, Karachi Trough and offshore Indus (Quadri & Shuaib, 1986). Khairpur-2 and Jacobabad Well penetrate low porous and low permeable Takatu Formation (equivalent of Chiltan Limestone) at depth of 2700m and 2100m respectively (Siddiqui, 2004). Geothermal gradient in both wells is 2.5ºC/100m. Owing to low thermal output and poor reservoir quality (Table 4), both of these wells are implausible for electric generation (Table 5). This geothermal gradient further declines to 1.7ºC/100m in south-west of Jacobabad Well, where Jhatpat Well. Contrarily, Lakhra field having more than five AOGWs is worthy for heat mining. Lakhra-1 is 3200m deep and proffer temperature gradient of 3.3ºC/100m (M. A. Khan & Raza, 1986) and 130ºC outlet. To the S-W of Lakhra field, there are Sunbak and Sari Singh wells which also exhibit good potential with temperature gradient of 2.7ºC/100m and 3ºC/100m respectively.

Two geothermal regimes are identified by (M. A. Khan & Raza, 1986) in Badin Block. One is eastern regime with lower temperature gradient, and other is western regime with higher temperature gradient. Four wells named Patar, Digh, Badin and Nabisar present in eastern regime have temperature gradients between 2.1ºC/100m and 2.3ºC/100m. All wells in eastern regime of Badin Block are abandoned except Patar. All have thermal output hardly exceeding 100ºC (except Badin-4 i.e., 106ºC). Thence, Nabisar and Digh can be recycled for domestic heating, while Badin-4 can support low scale electricity generation. Contrarily, five wells (viz. Talhar, Tarai, Khaskeli, Damiri and Mirpur-Batoro) available in western regime of Badin Block manifest higher thermal energy storage due to Cretaceous-Paleocene basaltic lava flows. Damiri has highest temperature gradient of 4ºC/100m, Talhar, Tarai and Khaskeli have gradients between 2.65 to 3.1ºC/100m, and 2.9ºC/100m in Mirpur-Batoro X1 (M. A. Khan & Raza, 1986). Out of these wells, Damiri is most favorable for extensive power production via flash steam or dry steam power plant, while other four wells can be recycled for binary fluid plant.

Table 4: Geothermal reservoir characterization of Lower Indus and Offshore Indus AOGWs.

Oil/gasfield	Reservoir Formation	Lithology	Porosity (Φ) %	Permeability (k) mD	Reservoir Depth m	Formation Temperature ºC
Khairpur	Takatu	Limestone	3-9	0.1-4	2700	88
Jhatpat	Wulgai	Mixed	5-10	20-300	4500	96
Lakhra	Chiltan	Limestone	4-9	0.1-5	3200	125
Nabisar	Wulgai	Mixed	6-8	25-300	3000	88
Digh	Wulgai	Mixed	6-8	25-300	3000	85
Badin	Chiltan	Limestone	4-7	0.1-4	3800	105
Patar	Chiltan	Limestone	5-10	0.1-8	3100	94
Talhar	Sembar	Shale	11	1-7	3000	103
Khaskeli	Lower Goru	Sandstone	20	212	2500	97
Damiri	Lower Goru	Sandstone	10-30	50-300	3200	150

Mirpur-Batoro	Lower Goru	Sandstone	18-25	32-1000	2000	80
Karachi-1	Korara	Shale	4-6	<1	3000	93
Karachi-2	Korara	Shale	4-6	<1	3800	136
Dabbo Creek *	Lower Goru	Sandstone	20	50-4000	3500	150
	Sembar	Shale	3-8	0.1-5	4300	180
Paitiani Creek *	Mughal Kot	Shaly Lst.	2-6	-	2600	85
Korangi Creek *	Mughal Kot	Shaly Lst.	2-6	-	4100	136
Marine A-1 *	Gaj	Sandstone	20-25	100-500	2800	90
Marine B-1 *	Gaj	Sandstone	20-25	100-500	3700	118
Pak-G2 1 *	Laki	Limestone	26	50-200	4400	56
Kekra-1 *	Laki	Limestone	20-28	50-200	5343	82

***Offshore Indus**
Note: Depth of offshore wells mentioned here is taken from sea level. However, their formation temperature is speculated by geothermal gradient incrementing downward from sea floor to formation depth.

In offshore Indus, around fourteen wells have been drilled so far with depth upto 5km from sea level. In deep water Indus offshore; Kekra-1 and Pak-G2 1 discovered Paleocene-Eocene reefal limestone at depth greater than 5km from sea level (Gong et al., 2020). While, Marine A1, B1 and C1 are drilled in shallow shelf of Indus offshore. These wells have geothermal gradients of 2.43ºC/100m, 2.6ºC/100m and 2.27ºC/100m, respectively. Coastal region of Kirthar Basin also falls in high potential areas, where Five wells viz. Paitiani Creek, Dabbo Creek, Korangi Creek, Karachi-1 and Karachi 2 are reviewed (Table 5). Dabbo Creek-1 indicated extraordinary geothermal gradient of 3.7ºC/100m exhibiting stratum temperature of 180ºC at well bottom where early Cretaceous Sembar Shale is encountered. Since shale has poor reservoir quality, sandstone of Lower Goru overlying Sembar Shale own excellent reservoir behavior with stratum temperature of upto 150ºC (Table 4). Similarly, Korangi Creek-1 also hold high thermal storage required for geothermal power plant. But Paitiani Creek-1 fails to qualify for this purpose due to its lower temperature gradient and shallow depth (Table 5). Karachi-1 and Karachi-2 express the gradient of 2.3ºC/100m and 3ºC/100m respectively. Karachi-2 can be recycled for steam power plant after some stimulation of reservoir because the Korara Shale present at well bottom exhibit poor reservoir properties. Whereas Karachi-1 is inappropriate for utilization as it neither has good reservoir rock, nor enough heat reserve (Table 4 & 5).

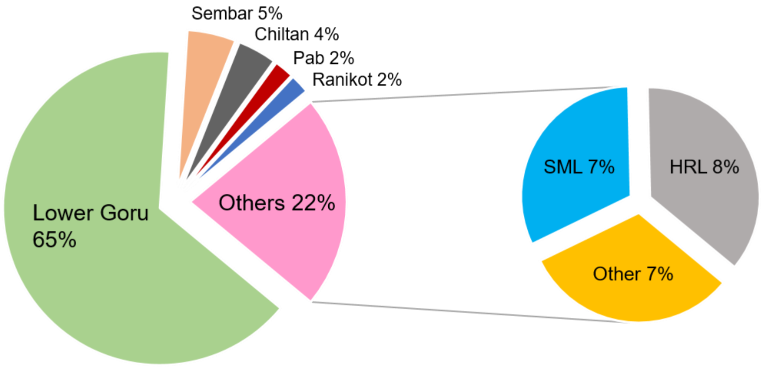

Figure 7: Proportion of AOGWs drilled in various reservoir units of Lower Indus Basin (after Ehsan et al., 2018)

Major reservoirs in Kirthar Province are Lower Goru Formation (early to middle Cretaceous), Pab Sandstone (late Cretaceous), and Ranikot Group (early Paleocene). Wells in this basin meet Chiltan Formation at mean depth of 3578m, Sembar at 3542m, Goru at 2359m, and Pab Sandstone averagely at 2254m (Ehsan et al., 2018). Pab Sandstone encountered in Zamzama, Mehar, Bhadra, Bhit and Mazarani gas fields possess very good reservoir quality ($\Phi = 20\%$ and k = upto 3 Darcy) required for efficient water circulation (Beswetherick & Bokhari, 2000). Lower Goru has utmost worth as geothermal reservoir in Lower Indus Basin due to its high porosity/permeability and more depth among other reservoir formations. (Wandrey et al., 2004) reported its effective porosity range from 16 to 30% and permeability from 1 to 2000 mD. Around 65% of the wells in Lower Indus Basin hit Lower Goru Formation at well bottom (Fig. 7). It acts as potential reservoir formation in 50+ AOGWs (including Damiri, Duphri, Khaskeli, Kato, Turk, Lashari, Bhatti, Matli, and Tando Adam) dug in Sanghar district, Badin, Mirpurkhas, and Hyderabad district. Lower Goru is an excellent reservoir while Upper Goru is an excellent seal/cap rock (Raza et al., 1990) which makes this formation favorable for carbon geological storage (CGS). Despite of enhancing thermal potential of reservoir, CGS also mitigate climate change by reducing the concentration of atmospheric CO_2.

7. DISCUSSION

Figure 8 illustrates the potential geothermal zones, significant AOGW locations, and distribution of different play types in Pakistan. Thermal gradient of all studied AOGWs have geothermal gradient ranges from 1ºC/100m to 4.1ºC/100m and outlet temperature from 40ºC to 180ºC. The region between, Badin, West Bahawalpur, East Sibi and Karachi own high gradient of 4ºC/100m. To deal with the reservoir quality, Indus Basin sandstones have porosities between 5 and 30%, with an average of 12 to 16%. Their permeability varies between 1 mD and 2 D, with mean range of 5 to 300 mD; which makes these reservoirs adept at fluid transportation. When it comes to carbonates and shales, most of them are naturally fractured by frequent diastrophism in the country. Otherwise, little stimulation can renovate for into heat exchanger.

More than 700 abandoned wells are available throughout Pakistan; many of which manifest remarkable reserve of heat energy for power production. Although the electric production – feasible AOGWs are widely distributed in whole country, the utmost geothermal resource potential is exhibited by seven particular fields of Central and Lower Indus Basin, which are; Qadirpur, Dhodak, Giandari and Sui gas field of the Central Indus, and Damiri, Karachi-2 and Dabbo Creek-1 of the Lower Indus. All these plays ensure outlet temperature of greater than 140ºC which is idyllic for commercial scale production using flash steam or dry steam power station.

By virtue of advanced closed-loop binary fluid plants, wells with outlet temperature at a minimum of 90ºC can also generate electricity. Moreover, EDBHE technology has enabled heat extraction from low porosity/permeability reservoirs. Circulating fluid in EDBHE absorbs heat from conductively heated cased-channel. This technology somewhat reduces the importance of reservoir quality parameters which have great significance in open-loop EGS technology. Table 5 summarizes AOGW based geothermal energy potential of the Indus Basin. Possible outlet temperatures of production wells were calculated by incrementing downward the geothermal gradient of the well assuming moderate surface temperature. This outlet temperature is then used in this study to assess power production feasibility. It is reviewed that several AOGWs in Sulaiman Foredeep, Himalayan Foredeep, and Kirthar Basin have the potential to bestow clean, sustainable, and carbon-free energy to the country. Furthermore, the real time datasets that can be gathered easily such as injection water and outlet water temperatures and reservoir rock thermal conductivity can be used to comprehend this study.

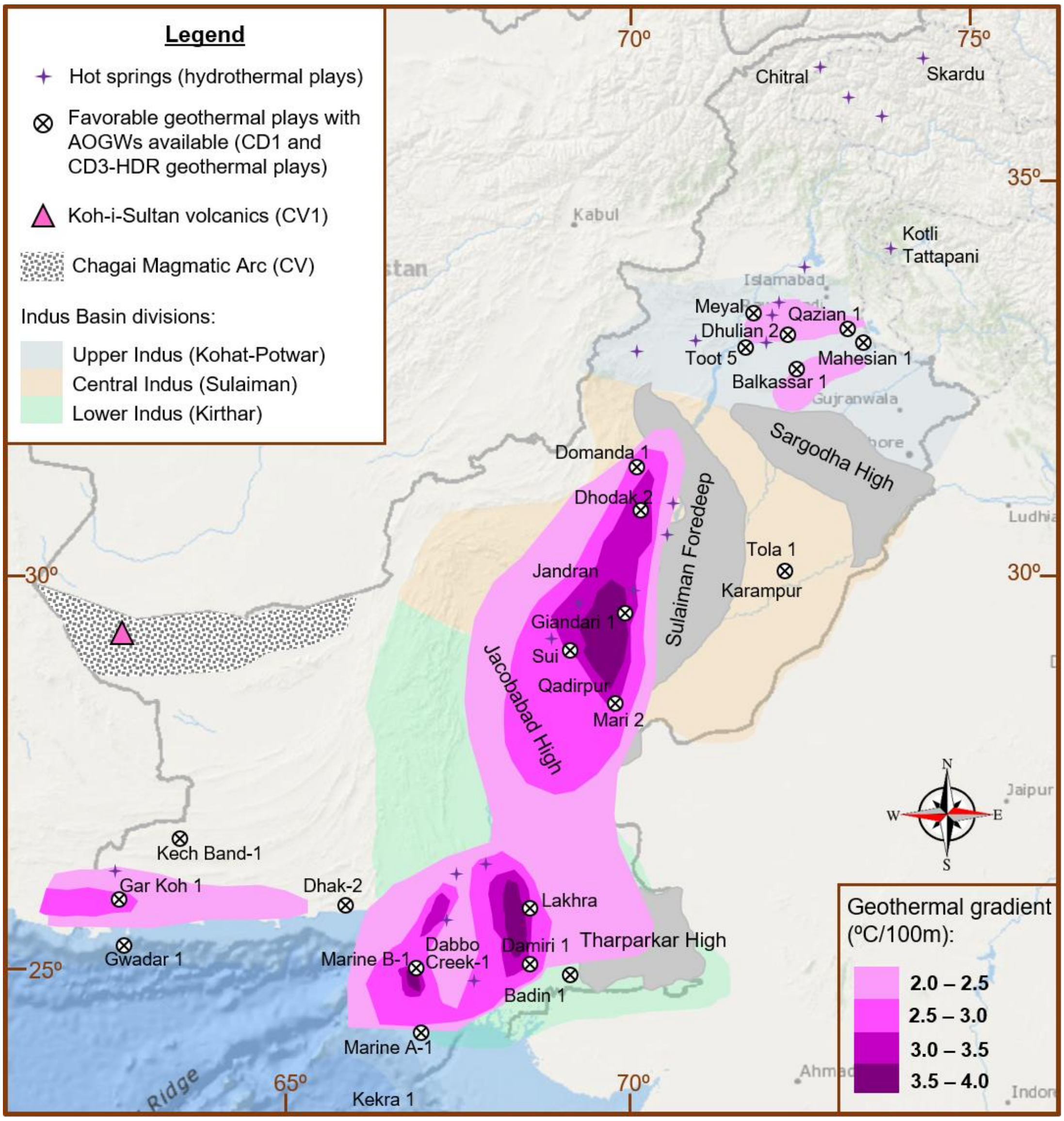

Figure 8: Map showing potential geothermal areas of Pakistan with significant well location (modified from Bakr, 1965; M. A. Khan & Raza, 1986; Mughal, 1998; Munawar et al., 2022)

Table 5: Geothermal potential of Indus Basin on the basis of AOGWs

	Geothermal site (AOGW)	Geothermal gradient (ºC / 100m)	Drilled depth (m)	Outlet temperature (ºC)	Suitability for electricity generation
Upper Indus Basin	Qazian	2.3	5150	~138	✓
	Mahesian	2.05	4700	~116	✓
	Adhi oilfield	2.2	5100	~132	✓
	Balkassar	2.05	5200	~127	✓
	Karsal	2.05	5200	~127	✓
	Injra	1.8-2.1	4625	~112	✓
	Nuryal	1.9-2.3	4760	~122	✓
	Dhurnal	2.1	5500	~136	✓
	Kallar Kahar	1.7	3200	~75	✖
	Dhulian-2, 3, 42 and 43	2.0-2.3	5300	~135	✓
	Meyal-4, 5 and 6	2.15-2.3	4900	~130	✓
	Toot-5	2.18	4850	~128	✓
	Toot-9	2.4	4850	~137	✓
Central Indus Basin	Karampur-1	1.3	3034	~60	✖
	Kamaib-1	1.2	2298	~50	✖
	Tola-1	1.6	1830	~50	✖
	Sarai Sidhu-1	1.12	3280	~59	✖
	Budhuana-1	1.5	1279	~40	✖
	Qadirpur	2.8	4703	~152	✓
	Kadanwari	2.6	3500	~112	✓
	Sawan	2.6	3400	~110	✓
	Dhodak	3.2	5000	~180	✓
	Domanda	2.1	5000	~126	✓
	Sakhi	2.2	5000	~131	✓
	Giandari	4.1	3659	~170	✓
	Sui	3.0	4000	~140	✓
	Mari	3.2	3400	~130	✓
	Jandran	2.4	4400	~126	✓
	Tadri	2.4	4000	~118	✓
Lower Indus Basin	Khairpur	2.5	2700	~88	✖
	Jacobabad	2.5	2100	~72	✖
	Jhatpat	1.7	4500	~98	✓

	Lakhra-1	3.3	3200	~126	✓
	Sunbak	2.7	2000	~75	✘
	Sari Singh	3.0	3080	~112	✓
	Digh	2.1	3400	~93	✓
	Nabisar	2.2	3055	~88	✘
	Badin-4	2.2	3870	~106	✓
	Patar	2.3	3300	~97	✓
	Talhar	2.7	3060	~104	✓
	Khaskeli	3.0	2630	~100	✓
	Damiri	4.0	3500	~160	✓
	Mirpur-Batoro X1	2.9	3051	~110	✓
	Karachi-1	2.4	3035	~93	✓
	Karachi-2	3.0	3946	~140	✓
Offshore Indus	Dabbo Creek-1	3.7	4354	~180	✓
	Paitiani Creek-1	2.45	2659	~86	✘
	Korangi Creek-1	2.8	4140	~136	✓
	Marine-A1	2.43	2850	~85	✘
	Marine-B1	2.6	3810	~115	✓
	Marine-C1	2.27	1950	~62	✘
	Kekra-1	2.0	5693	~82	✘
	Pak-G2 1	1.7	4750	~56	✘

7.1 Findings

- In the Upper Indus Basin, all AOGWs except those of in Kallar Kahar region (due to poor thermal potential) can be retrofitted into closed-loop heat exchangers. But for open-loop EGS; Qazian, Mahesian, Toot, Dhulian, Dhurnal, Meyal, Adhi, and Balkassar are more favorable because of their good reservoir properties. However, AOGWs in Kallar Kahar can be utilized for drying, de-icing and building heating.

- In Central Indus Basin, wells of Dhodak, Domanda and Sakhi Sarwar fields in Sulaiman Foredeep, Giandari in central Sulaiman Basin, and Sui and Qadirpur gas fields are promising for power production. Heat extraction from Jandran, Tadri, Kadanwari, and Sawan field can be satisfactory for domestic or industrial purposes. While, AOGWs in southern plain margin of Sargodha High are inappropriate for recycling owing to their poor intrinsic heat energy.

- In the Lower Indus Basin, Dabbo Creek-1, Korangi Creek-1, Karachi-2, Damiri and Lakhra field is feasible for commercial scale electricity production. Whereas Jhatpat, Sari Singh, Badin-4, Talhar, Khaskeli, Mirpur-Batoro X1, Digh, Karachi-1, and Marine-B1 are suitable for domestic/industrial heating purposes and small-scale power production using binary fluid plant. The rest are insignificant for heat mining.

- In Baluchistan Geothermal Zone, Garr Koh-1 and Gwadar-1 are more preferable for geothermal operation owing to their good potential and geopolitical location (CPEC linked Gwadar port district). Coastal well Dhak-2 also own satisfactory thermal reserve for port related industry and low scale electricity generation. While, Kech Band-1, Dhak-1, and Jal Pari 1-A have insufficient thermal potential.

7.2 Recommendation

Although several highly porous and permeable reservoirs required open-loop EGS are available in the study area, closed-loop EDBHE technology is recommended whose pros are already discussed. Apart from large investment, EGS requires reservoir stimulation which impose the risk of induced tremors in the vicinity of geothermal plant. Generally, the exploitable heat in AOGWs is available at greater depths where rocks are usually dry and impervious. Open-loop system is inoperable in HDR plays (which have negligible porosity/permeability) without reservoir stimulation. On the other hand, closed-loop technology can be operated efficiently in all type of plays. Furthermore, it resolves various technological, geological, functional, and performance related challenges the geothermal industry is facing for its frequent implementation. An advanced EDBHE technology presented in this work comes in single-well (SWEDBHE) as well as double-well (DWEDBHE) models and proffer improved heat recovery as compared to ordinary DBHE. It is because the EDBHE involves injecting composite material like graphene mud which enhances the transport of heat from reservoir to closed-loop channel. Furthermore, the real time datasets such as injection and extraction water temperatures and reservoir rock thermal conductivity are needed to be deployed with geothermal simulation for practical implementation of AOGW based geothermal plan in Pakistan.

9. CONCLUSION

It is found that abandoned petroleum fields in the Indus Basin host tremendous amount of heat energy. Out of sixty wells reviewed in this study, forty wells which are distributed in the Indus and Baluchistan geothermal zone are capable of electricity generation owing to their high geothermal gradient and promising reservoir properties. Out of these forty AOGWs, seven wells named Qadirpur, Dhodak, Giandari, Sui, Damiri, Karachi-2, and Dabbo Creek-1 present in central and lower Indus Basin have highest thermal potential in the country, hence are most favorable for power generation on large scale. The rest are capable of domestic or industrial heating, and small to medium scale electricity production using closed-loop binary fluid power station.

REFERENCES

Abas, N., Kalair, A., Khan, N., & Kalair, A. R. (2017). Review of GHG emissions in Pakistan compared to SAARC countries. *Renewable and Sustainable Energy Reviews*, *80*(March), 990–1016. https://doi.org/10.1016/j.rser.2017.04.022

Ahmad, I., & Rashid, A. (2010). Study of Geothermal Energy Resources of Pakistan for Electric Power Generation. *Energy Sources, Part A: Re*, 826–838. https://doi.org/10.1080/15567030802606210

Ahmad, J. (2014). The geothermal energy potential of Pakistan clean sustainable solution for our energy future. *Transactions - Geothermal Resources Council*, *38*, 571–576.

Ahmad, N., Khan, S., & Al-shuhail, A. (2021). Seismic data interpretation and petrophysical analysis of kabirwala area tola (01) well, central Indus basin, Pakistan. *Applied Sciences (Switzerland)*, *11*(6). https://doi.org/10.3390/app11062647

Ali, A., Ahmad, Z., & Akhtar, G. (2005). Structural Interpretation of Seismic Profiles integrated with Reservoir Characteristics of Qadirpur Area. *Pakistan Journal of Hydrocarbon Research*, *Vol 15 (2005): PJHR*.

Bagdassarov, N., & Dingwell, D. (1994). Thermal properties of vesicular rhyolite. *Journal of Volcanology and Geothermal Research*, *60*(2), 179–191. https://doi.org/https://doi.org/10.1016/0377-0273(94)90067-1

Bakr, M. A. (1965). *Thermal springs of Pakistan*. https://www.osti.gov/biblio/5176172

Basir, H. M., Javaherian, A., & Yaraki, M. T. (2013). Multi-attribute ant-tracking and neural network for fault detection: A case study of an Iranian oilfield. *Journal of Geophysics and Engineering*. https://doi.org/10.1088/1742-2132/10/1/015009

Bertani, R. (2012). Geothermal power generation in the world 2005-2010 update report. *Geothermics*. https://doi.org/10.1016/j.geothermics.2011.10.001

Beswetherick, S., & Bokhari, S. (2000). The subsurface appraisal of the Bhit Gas field, a case study. *Proceedings of the SPE-PAPG Annual Technical Conference 2000, Islamabad Pakistan*, 239–257.

Bohnsack, D., Potten, M., Pfrang, D., Wolpert, P., & Zosseder, K. (2020). Porosity–permeability relationship derived from Upper Jurassic carbonate rock cores to assess the regional hydraulic matrix properties of the Malm reservoir in the South German Molasse Basin. *Geothermal Energy*, *8*(1). https://doi.org/10.1186/s40517-020-00166-9

Brigaud, F., & Vasseur, G. (1989). Mineralogy, porosity and fluid control on thermal conductivity of sedimentary rocks. *Geophysical Journal International*, *98*(3), 525–542. https://doi.org/10.1111/j.1365-246X.1989.tb02287.x

Bu, X., Ma, W., & Li, H. (2012). Geothermal energy production utilizing abandoned oil and gas wells. *Renewable Energy*. https://doi.org/10.1016/j.renene.2011.10.009

Cacas, M., Daniel, J.-M., & Letouzey, J. (2001). Nested geological modelling of naturally fractured reservoirs. *Petroleum Geoscience*, *7*. https://doi.org/10.1144/petgeo.7.S.S43

Calkins, J. A., Jamiluddin, S., Bhuyan, K., & Hussain, A. (1981). Geology and mineral resources of the Chitral-Partsan area, Hindu Kush Range, northern Pakistan. In *Professional Paper*. https://doi.org/10.3133/pp716G

Chang, C., Zoback, M., & Khaksar, A. (2006). Empirical relations between rock strength and physical properties in sedimentary rocks. *Journal of Petroleum Science and Engineering*, *51*, 223–237. https://doi.org/10.1016/j.petrol.2006.01.003

Cheng, W. L., Li, T. T., Nian, Y. Le, & Xie, K. (2014). Evaluation of working fluids for geothermal power generation from abandoned oil wells. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2013.12.039

Clauser, C., & Huenges, E. (1995). Thermal Conductivity of Rocks and Minerals. In *Rock Physics & Phase Relations* (pp. 105–126). https://doi.org/https://doi.org/10.1029/RF003p0105

Cyziene, J., Molenaar, N., & Sliaupa, S. (2006). Clay-induced pressure solution as a Si source for quartz cement in sandstones of the Cambrian Deimena Group . In *Geologija* (Vol. 53, pp. 8–21).

Davis, A. P., & Michaelides, E. E. (2009). Geothermal power production from abandoned oil wells. *Energy*. https://doi.org/10.1016/j.energy.2009.03.017

Deon, F., Moeck, I., Sheytt, T., & S. Jaya, M. (2012). *Preliminary Assessment of the Geothermal System of the Tiris Volcanic Area, East Java, Indonesia*. https://doi.org/https://doi.org/10.3997/2214-4609.20148147

Eberhart-Phillips, D., Han, D.-H., & Zoback, M. D. (1989). Empirical relationships among seismic velocity, effective pressure, porosity, and clay content in sandstone. *GEOPHYSICS*, *54*(1), 82–89. https://doi.org/10.1190/1.1442580

Ehsan, M., Gu, H., Akhtar, M. M., Abbasi, S. S., & Ehsan, U. (2018). A geological study of reservoir formations and exploratory well depths statistical analysis in sindh province, southern lower indus basin, Pakistan. *Kuwait Journal of Science*, *45*(2), 84–93.

Evans, K., Deichmann, N., & Heinrich, C. (2011). *Abstract Volume 9 th Swiss Geoscience Meeting - 20 . Deep Geothermal Energy*. *9*(November 2011).

Faulds, J., Coolbaugh, M., Bouchot, V., Moeck, I., & Oğuz, K. (2010). Characterizing Structural Controls of Geothermal Reservoirs in the Great Basin, USA, and Western Turkey: Developing Successful Exploration Strategies in Extended Terranes. *Proceedings World Geothermal Congress*, 25–29.

Genter, A., Traineau, H., Bourgine, B., Ledesert, B., & Gentier, S. (2000). Over 10 years of geological investigations within the HDR Soultz Project, France. In *World Geothermal Congress 2000*.

Ghazi, S., Ali, S., Sahraeyan, M., & Hanif, T. (2014). An overview of tectonosedimentary framework of the Salt Range, northwestern Himalayan fold and thrust belt, Pakistan. *Arabian Journal of Geosciences*, *8*. https://doi.org/10.1007/s12517-014-1284-3

Ghazi, S., Khalid, P., Aziz, T., Sajid, Z., & Hanif, T. (2015). Petrophysical analysis of a clastic reservoir rock: a case study of the Early Cambrian Khewra Sandstone, Potwar Basin, Pakistan. *Geosciences Journal*, *20*. https://doi.org/10.1007/s12303-015-0021-6

Ghoreishi-Madiseh, S. A., Templeton, J., Hassani, F., Al-Khawaja, M. J., & Aflaki, E. (2014). Geothermal energy extraction from decommissioned petroleum wells. *ISRM International Symposium - 8th Asian Rock Mechanics Symposium, ARMS 2014*.

Gianelli, G., & Grassi, S. (2001). Water–rock interaction in the active geothermal system of Pantelleria, Italy. *Chemical Geology - CHEM GEOL*, *181*, 113–130. https://doi.org/10.1016/S0009-2541(01)00276-5

Gondal, I. A., Masood, S. A., & Amjad, M. (2017). Review of geothermal energy development efforts in Pakistan and way forward. In *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2016.12.097

Gong, J., Liao, J., Liang, J., Lei, B., Chen, J., Khalid, M., Haider, S. W., & Meng, M. (2020). Exploration prospects of oil and gas in the Northwestern part of the Offshore Indus Basin, Pakistan. *China Geology*, *3*(4), 633–642. https://doi.org/https://doi.org/10.31035/cg2020051

Grasby, S., & Hutcheon, I. (2001). Controls on the distribution of thermal springs in the southern Canadian Cordillera. *Canadian Journal of Earth Sciences - CAN J EARTH SCI*, *38*, 427–440. https://doi.org/10.1139/cjes-38-3-427

Griffiths, L., Heap, M. J., Xu, T., Chen, C., & Baud, P. (2017). The influence of pore geometry and orientation on the strength and stiffness of porous rock. *Journal of Structural Geology*, *96*. https://doi.org/10.1016/j.jsg.2017.02.006

Haenel, R., Rybach, L., & Stegena, L. (1988). *Fundamentals of Geothermics BT - Handbook of Terrestrial Heat-Flow Density Determination: with Guidelines and Recommendations of the International Heat-Flow Commission* (R. Haenel, L. Rybach, & L. Stegena (eds.); pp. 9–57). Springer Netherlands. https://doi.org/10.1007/978-94-009-2847-3_2

Han, D., Nur, A., & Morgan, D. (1986). Effects of porosity and clay content on wave velocities in sandstones. *GEOPHYSICS*, *51*(11), 2093–2107. https://doi.org/10.1190/1.1442062

Hart, B. S., Pearson, R., & Rawling, G. C. (2002). 3-D seismic horizon-based approaches to fracture-swarm sweet spot definition in tight-gas reservoirs. *Leading Edge (Tulsa, OK)*. https://doi.org/10.1190/1.1445844

He, Y., & Bu, X. (2020). A novel enhanced deep borehole heat exchanger for building heating. *Applied Thermal Engineering*, *178*(April), 115643. https://doi.org/10.1016/j.applthermaleng.2020.115643

Hochstein, M. (1988). Assessment and modelling of geothermal reservoirs (small utilization schemes). *Geothermics*, *17*, 15–49. https://doi.org/10.1016/0375-6505(88)90004-1

Hsu, K., Brie, A., & Plumb, R. A. (1987). A New Method for Fracture Identification Using Array Sonic Tools. *Journal of Petroleum Technology*, *39*(06), 677–683. https://doi.org/10.2118/14397-PA

Ikawa, H., & Mercado, G. (2010). A Case Study of Seismic Anisotropy Analysis on Multi-Azimuth OBC Seismic Data in an Offshore Carbonate Oil Field, U. A. E. *Society of Petroleum Engineers - 14th Abu Dhabi International Petroleum Exhibition and*

Conference 2010, ADIPEC 2010, *2*. https://doi.org/10.2118/137986-MS

Iqbal, M., Nazeer, A., Ahmad, H., Murtaza, G., Limited, P., & Karachi. (2017). *HYDROCARBON EXPLORATION PERSPECTIVE IN MIDDLE JURASSIC-EARLY CRETACEOUS RESERVOIRS IN THE SULAIMAN FOLDBELT, PAKISTAN*.

Iqbal, M. W. A., & Shah, S. M. I. (1980). *A guide to the stratigraphy of Pakistan*.

Jaswal, T. M., Lillie, R. J., & Lawrence, R. D. (1997). Structure and Evolution of the Northern Potwar Deformed Zone, Pakistan1. *AAPG Bulletin*, *81*(2), 308–328. https://doi.org/10.1306/522B431B-1727-11D7-8645000102C1865D

Kazmi, A. H., & Jan, M. (1997). *Geology and Tectonics of Pakistan*.

Kemal, A., Balkwill, H. R., & Stoakes, F. A. (1992). Indus basin hydrocarbon plays. *New Directions and Strategies for Accelerating Petroleum Exploration and Production in Pakistan.*, Oil and Gas Development Corporation, Islamabad, 78.

Khalid, P., Akhtar, S., & Khurram, S. (2020). Reservoir Characterization and Multiscale Heterogeneity Analysis of Cretaceous Reservoir in Punjab Platform of Middle Indus Basin, Pakistan. *Arabian Journal for Science and Engineering*, *45*. https://doi.org/10.1007/s13369-020-04443-4

Khalid, P., Yasin, Q., Sohail, G., & Kashif, J. M. (2015). Integrating core and wireline log data to evaluate porosity of Jurassic formations of Injra-1 and Nuryal-2 wells, Western Potwar, Pakistan. *Journal of the Geological Society of India*, *86*(5), 553–562. https://doi.org/10.1007/s12594-015-0346-9

Khan, I., Ahmad, S., Arif, M., & Ali, N. (2016). Impact of diagenetic and depositional fabric on reservoir quality; a synthesis from Late Cretaceous and Early Paleocene sandstones in Eastern Sulaiman Range, Pakistan. *Arabian Journal of Geosciences*, *9*(5), 388. https://doi.org/10.1007/s12517-016-2372-3

Khan, M. A., & Raza, H. A. (1986). the Role of Geothermal Gradients in Hydrocarbon Exploration in Pakistan. *Journal of Petroleum Geology*, *9*(3), 245–258. https://doi.org/10.1111/j.1747-5457.1986.tb00388.x

Khan, M. A., Raza, H. A., & Alam, S. (1991). PETROLEUM GEOLOGY OF THE MAKRAN REGION: IMPLICATIONS FOR HYDROCARBON OCCURRENCE IN COOL BASINS. *Journal of Petroleum Geology*, *14*(1), 5–18. https://doi.org/https://doi.org/10.1111/j.1747-5457.1991.tb00295.x

Khan, M. J., & Khan, H. A. (2018). Petrophysical logs contribute in appraising productive sands of Lower Goru Formation, Kadanwari concession, Pakistan. *Journal of Petroleum Exploration and Production Technology*, *8*(4), 1089–1098. https://doi.org/10.1007/s13202-018-0472-1

Kujawa, T., Nowak, W., & Stachel, A. A. (2006). Utilization of existing deep geological wells for acquisitions of geothermal energy. *Energy*. https://doi.org/10.1016/j.energy.2005.05.002

Lander, R., & Bonnell, L. (2010). A model for fibrous illite nucleation and growth in sandstones. *Aapg Bulletin - AAPG BULL*, *94*, 1161–1187. https://doi.org/10.1306/04211009121

Lee, K. (2001). Classification of geothermal resources by exergy. *Geothermics*, *30*, 431–442. https://doi.org/10.1016/S0375-6505(00)00056-0

Lumley, D. E., & Behrens, R. A. (1998). Practical Issues of 4D Seismic Reservoir Monitoring: What an Engineer Needs to Know. *SPE Reservoir Evaluation & Engineering*, *1*(06), 528–538. https://doi.org/10.2118/53004-PA

Majorowicz, J., & Grasby, S. E. (2010). High potential regions for enhanced geothermal systems in Canada. *Natural Resources Research*. https://doi.org/10.1007/s11053-010-9119-8

Marfurt, K. J., Kirlin, R. L., Farmer, S. L., & Bahorich, M. S. (1998). 3-D seismic attributes using a semblance-based coherency algorithm. *GEOPHYSICS*, *63*(4), 1150–1165. https://doi.org/10.1190/1.1444415

McCoy-West, A., Milicich, S., Robinson, T., Bignall, G., & Harvey, C. (2011). GEOTHERMAL RESOURCES IN THE PACIFIC ISLANDS: THE POTENTIAL OF POWER GENERATION TO BENEFIT INDIGENOUS COMMUNITIES. *PROCEEDINGS*.

Mehmood, A., Yao, J., Yan Fun, D., & Zafar, A. (2017). Geothermal Energy Potential of Pakistan on the Basis of Abandoned Oil and Gas wells. *Journal of Petroleum & Environmental Biotechnology*, *08*(03), 3–7. https://doi.org/10.4172/2157-7463.1000332

MNPR. (2020). *INVESTMENT OPPORTUNITIES IN PAKISTAN UPSTREAM PETROLEUM SECTOR*. Ministry of Energy (Petroleum Division). http://www.mpnr.gov.pk/Detail/MTMyZTRiMjItMTA4YS00MTJlLTg1NjUtY2IxMTc0MzYyNGFj

Moeck, I. S. (2014). Catalog of geothermal play types based on geologic controls. In *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2014.05.032

Moghal, M., Saqi, M. I., & Jamij, M. A. (2012). *Hydrocarbon Potential of Tight Sand Reservoir (Pab Sandstone) in Central Indus Basin-Pakistan**.

Muffler, L. J. P. (1979). Assessment of geothermal resources of the United States: 1978. In *Circular*. https://doi.org/10.3133/cir790

Mughal, M. N. (1998). Geothermal Resources of Pakistan and Methods for Early Stage Exploration. *United Nations University., UNU Geothermal Training Program, Iceland. Report; 1998: 9*, *9*, 239–254.

Munawar, M. J., Bu, X., Rehman, S. U., Ahsan, N., Hassan, H. A. R., & Talha, M. (2022). *16 - Abandoned oil and gas wells for geothermal energy: Prospects for Pakistan* (Y. Noorollahi, M. N. Naseer, & M. M. B. T.-U. of T. P. of A. W. Siddiqi (eds.); pp. 315–340). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-323-90616-6.00016-6

NEPRA. (2020). State of Industry Report 2020. *Regulations*, *53*(9), 1689–1699.

News, T. (2009). *OGDC discovers gas at Qadirpur deep wellNo Title*. https://www.thenews.com.pk/archive/print/161630-ogdc-discovers-gas-at-qadirpur-deep-well

Ngeri, A., & Amakiri, A. (2015). Ant-Tracker Attributes: An Effective Approach To Enhancing Fault identification And Interpretation. *IOSR Journal of VLSI and Signal Processing (IOSR-JVSP)*, *5*, 2319–4200. https://doi.org/10.9790/4200-05626773

Nukman, M., & Moeck, I. (2013). Structural controls on a geothermal system in the Tarutung Basin, north central Sumatra. *Journal of Asian Earth Sciences*, *74*, 86–96. https://doi.org/10.1016/j.jseaes.2013.06.012

Pandey, S., & Singh, M. (2021). Artificial Neural Network to Predict the Thermal Drawdown of Enhanced Geothermal System. *Journal of Energy Resources Technology*, *143*, 1–19. https://doi.org/10.1115/1.4048067

Quadri, V., & Shuaib, S. . (1986). Hydrocarbon Prospects of southern Indus Basin, Pakistan. *AAPG Bulletin*, *70*, 730–747.

Raymond, J., R. T., & Gosselin, L. (2010). Low-temperature geothermal energy in mining environments. *CIM Journal*, *1*(2), 140--149.

Raymond, J., & Therrien, R. (2008). Low-temperature geothermal potential of the flooded Gaspé Mines, Québec, Canada. *Geothermics*. https://doi.org/10.1016/j.geothermics.2007.10.001

Raza, H. A., Ahmed, R., Ali, S. M., & Ahmad, J. (1989). Petroleum Prospects; Sulaiman Sub-Basin, Pakistan. *Pakistan Journal of Hydrocarbon Research*, *1 No. 2*.

Raza, H. A., Ali, S. M., & Ahmed, R. (1990). Petroleum Geology of Kirthar Sub-basin and Part of Kutch Basin. *Pakistan Journal of Hydrocarbon Research*, *Vol 2 No 1 (1990): PJHR*.

Reed, M. J. (1983). Assessment of low-temperature geothermal resources of the United States; 1982. In M. J. Reed (Ed.), *Circular*. https://doi.org/10.3133/cir892

Richter, A. (2022). *ThinkGeoEnergy's Top 10 Geothermal Countries 2021 – installed power generation capacity (MWe)*. ThinkGeoEnergy Research (2022). https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2021-installed-power-generation-capacity-mwe/

Rijks, E. J. H., & Jauffred, J. C. E. M. (1991). Attribute extraction: An important application in any detailed 3-D interpretation study. *The Leading Edge*, *10*(9), 11–19. https://doi.org/10.1190/1.1436837

Roehl, P. O., & Choquette, P. W. (1986). Carbonate Petroleum Reservoirs. *Carbonate Petroleum Reservoirs*. https://doi.org/10.1016/0037-0738(90)90081-4

Shah, S. B., Abdullah, W., & Shuib, M. (2019). Petrophysical properties evaluation of Balkassar oilfield, Potwar Plateau, Pakistan: implication for reservoir characterization. *Himalayan Geology*, *40*, 50–57.

Shah, S. M. ., Ahmed, R., Cheema, M. ., Fatmi, A. ., Iqbal, M. W. ., Raza, H. ., & Raza, S. . (1977). *Stratigraphy of Pakistan* (Geol. Surv).

Shou, J. F., Zhang, H. L., Shen, Y., Wang, X., Zhu, G. H., & Si, C. S. (2006). Diagenetic mechanisms of sandstone reservoirs in China oil and gas-bearing basins. *Acta Petrologica Sinica*, *22*, 2165–2170.

Shuja, T. ., & Khan, A. . (1984). *Prospects of geothermal energy in Pakistan*.

Shuja, T. A. (1986). Geothermal areas in Pakistan. *Geothermics*, *15*(5), 719–723. https://doi.org/https://doi.org/10.1016/0375-6505(86)90083-0

Siddiqui, N. (2004). Sui Main Limestone: Regional geology and the analysis of original pressures of a closed-system reservoir in central Pakistan. *Aapg Bulletin - AAPG BULL*, *88*, 1007–1035. https://doi.org/10.1306/012004200150

Silva, C., Marcolino, C., & Lima, F. (2005). Automatic Fault Extraction Using Ant Tracking Algorithm in the Marlim South Field, Campos Basin. *Seg Technical Program Expanded Abstracts*, *24*. https://doi.org/10.1190/1.2148294

Song, X., Zhu, Y., Liu, Q., Chen, J., Ren, D., Li, Y., Wang, B., & Liao, M. (1998). Identification and Distribution of Natural Fractures. In *SPE International Oil and Gas Conference and Exhibition in China* (p. 7). Society of Petroleum Engineers.

https://doi.org/10.2118/50877-MS

Stober, I., & Bucher, K. (2014). Geothermal Energy: From Theoretical Models to Exploration and Development. In *Geothermal Energy: From Theoretical Models to Exploration and Development*. https://doi.org/10.1007/978-3-642-13352-7

Tainsh, H. R., Stringer, K. V, & Azad, J. (1959). Major Gas Fields of West Pakistan. *AAPG Bulletin*, *43*(11), 2675–2700. https://doi.org/10.1306/0BDA5F3F-16BD-11D7-8645000102C1865D

Tissot, B. P., & Welte, D. H. (1984). *Petroleum Formation and Occurrence*. Springer Berlin Heidelberg. https://books.google.com.pk/books?id=wMsZAQAAIAAJ

Todaka, N., Shuja, T. ., Jamiluddin, S., Khan, N. ., Pasha, M. ., & Iqbal, M. (1999). *A preliminary study of geothermal energy resources of Pakistan*.

Ullah, R., Fengjuin, N., Xin, Z., Cheng-yong, Z., Ali, A., & Pengfei, Z. (2020). *Uranium Traps in Phreatic Sandstone-type Prospect, Taunsa Area, Dera Ghazi Khan, Eastern Sulaiman Range, Pakistan: Evidences from Autoradiography and Optical Microscopy*.

Wandrey, C. J., Law, B. E., & Shah, H. a. (2004). Sembar Goru/Ghazij Composite Total Petroleum System, Indus and Sulaiman-Kirthar Geologic Provinces, Pakistan and India. *USGS Bulletin*, 29. https://doi.org/http://pubs.usgs.gov/bul/b2208-c/

Waples, D. W. (1985). *Geochemistry in petroleum exploration*. IHRDC Press,Boston, MA. https://www.osti.gov/biblio/5563367

Williams, C. F., Reed, M. J., & Anderson, A. F. (2011). Updating the Classification of Geothermal Resources. *Proceedings of 36th Workshop on Geothermal Reservoir Engineering*, 7. http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2011/williams.pdf?

Winterleitner, G., Schütz, F., Wenzlaff, C., & Huenges, E. (2018). The Impact of Reservoir Heterogeneities on High-Temperature Aquifer Thermal Energy Storage Systems. A Case Study from Northern Oman. *Geothermics*. https://doi.org/10.1016/j.geothermics.2018.02.005

Younas, U., Khan, B., Ali, S. M., Arshad, C. M., Farid, U., Zeb, K., Rehman, F., Mehmood, Y., & Vaccaro, A. (2016). Pakistan geothermal renewable energy potential for electric power generation: A survey. *Renewable and Sustainable Energy Reviews*, *63*, 398–413. https://doi.org/10.1016/j.rser.2016.04.038

Zaigham, N. A. (2005). Geothermal Energy Resources of Pakistan. *World Geothermal Congress 2005*, *April*, 24–29.

Zhang, X., Li, T., Shi, Y., & Zhao, Y. (2015). The Application of Fracture Interpretation Technology Based on Ant Tracking in Sudeerte Oilfield. *Acta Geologica Sinica - English Edition*. https://doi.org/10.1111/1755-6724.12307_12

Zimmermann, G., Brandt, W., & Telegrafenberg, P. (2008). *RESULTS OF STIMULATION TREATMENTS AT THE GEOTHERMAL RESEARCH WELLS IN GROßSCHÖNEBECK/GERMANY*.

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LIST OF ABBREVIATIONS

AOGW	Abandoned oil and gas well
HDR	Hot dry rock
BHT	Borehole temperature
EGS	Enhanced geothermal system
DBHE	Deep borehole heat exchanger
EDBHE	Enhanced deep borehole heat exchanger
CD	Conduction-dominated
CV	Convection-dominated
D	Darcy (unit of permeability)

Mt	Million Tons
R_O	Vitrinite reflectance
TAI	Thermal Alteration Index
MFT	Main Frontal Thrust
SRT	Salt Range Thrust
MBT	Main Boundary Thrust
MMT	Main Mantle Thrust
KIA	Kohistan Island Arc
CGS	Carbon geological storage
CPEC	China-Pakistan Economic Corridor