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Geological Results from the Drilling of the Northwest Sabalan Geothermal Project, Iran

Ian Bogie[1], Khosrow Khosrawi [2]and Behnam Talebi[2]

[1] Sinclair Knight Merz Ltd, PO Box 9806 Newmarket, Auckland, New Zealand

ibogie@skm.co.nz

[2] SUNA Renewable Energy Organisation of Iran, Yadegar-e-Emam Highway, Poonak-e-Bakhtary Ave, Shahrak Ghods, Tehran, Iran

kh_khosrawi@yahoo.com

talebib@iranenergy.org.ir

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ABSTRACT

Three deep exploration wells drilled in the Northwest Sabalan geothermal project initially encountered Quaternary terrace deposits and Pliocene trachyandesitic volcanics. The most northerly of the wells continued into a sequence of Pliocene to Neogene volcanics before drilling down the dip of a sequence of Eocene volcanics and running along a disconformity with Paleozoic meta-litharenite. Similar Eocene volcanics were encountered in the other wells, with the most southerly well penetrating a Miocene monzonite batholith and surrounding hornfels. Diorite porphyry dykes were found in the two southern wells with the youngest known dykes being found in the most southerly well. There is a complex alteration pattern produced by hydrothermal events associated with the monzonite and the two phases of dyke intrusion. Illite-rich zones around faults that are the main drilling targets in the wells represent the current alteration. New well targets off the current pads and the requirement for more southerly drilling have been identified. Two of the three wells are considered to be commercially productive and represent the first successful exploration of an intraplate trachyandesite volcano thus encouraging exploration in similar settings in Iran and elsewhere, most notably Turkey.

1. INTRODUCTION

The Northwest Sabalan Geothermal Project is located in the northwestern portion of the Sabalan volcano, a very large trachyandesitic stratovolcano in the province of Ardebil in the northwest of Iran (Figure 1). The area has been previously referred to as the Meshkin Shahr geothermal prospect (Bogie *et al.*, 2000). The project area is within a valley, which on satellite and aerial photograph imagery can be seen to be a major structural zone. Warm and hot springs with neutral Cl-SO_4, acid Cl-SO_4 and acid SO_4 chemistries are found within the valley (Bogie *et al*, 2000). These plot in the immature area of the Giggenbach (1992) Na-K-Mg plot giving geothermometry temperatures of approximately 150°C. One of these, the Gheynarge spring (Figure 2), has a Cl concentration of 1800 mg/kg. Tritium analyses of this spring water indicate no recent interaction with the atmosphere.

An MT survey (Bromley *et al*. 2000) established the existence of a very large zone of low resistivity (≈70 km^{2}) in the project area. Satellite imagery interpretation identified a large area (≈10 km^2) of surficial hydrothermal alteration in lower elevation parts of the project area, with much of the low resistivity area in the valley covered by Quaternary terrace deposits. The presence of surficial hydrothermal alteration was confirmed by fieldwork. XRD analyses of this alteration reveals the presence of interlayered illite-smectite clays (which are conductive and will have formed at depth) indicating that at least some of the alteration and the resistivity anomaly is relict. At higher elevations unaltered rocks cover the zone of low resistivity. To define a target area for drilling an area of very low resistivity (< 4 Ωm) associated with the thermal features was initially selected.

The early interpretation of the MT work (Bromley *et al*. 2000) shows low resistivities persisting to depth. However, once the relatively shallow occurrence of the conductive smectitic clays was established from the wells the MT data was reinterpreted in terms of the elevation of the base of the conductor. A conductive zone increasing in elevation to the south can be partially distinguished from the much larger and deeper resistivity anomaly to the west. This new interpretation is indicative of the current system's upflow occurring south of the drilled wells (Talebi *et al*., 2005).

Exposed at the surface in the valley are altered Pliocene volcanics, an unaltered Pleistocene trachydacite dome (Ar-Ar dated at 0.9 Ma) and Quaternary terrace deposits (Bogie *et al*., 2000).

Figure 1: Location Map

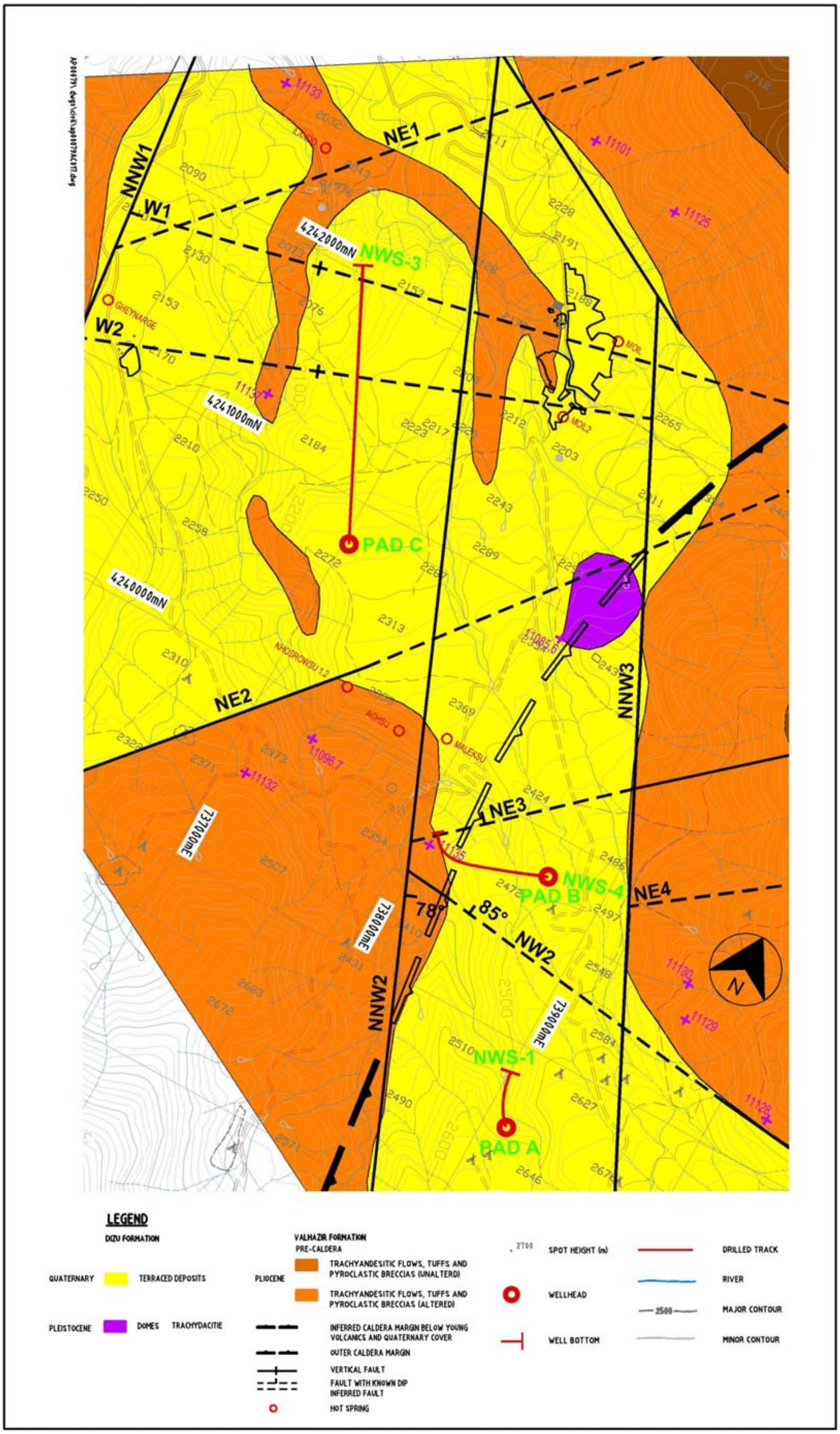

Figure 2: Geological Map

On the basis of the results of the MT survey and the presence of hot springs with significant Cl concentrations a three well exploration programme was undertaken. Two top holes were also drilled for reinjection of waste brine from well test discharges and as possible later stage production wells.

A regional Miocene monzonite batholith was interpreted to make up the deep reservoir on the basis of a gravity high that extended from the area of the monzonite's surface exposure in the west into the project area and beyond. Some contribution to the gravity high from Eocene volcanics was also anticipated (Bromley *et al.*, 2000).

The isotopic composition of the spring waters and their seasonal variation in flow with little change in temperature or chemistry suggested that a large regional ground water aquifer overlies the potential geothermal reservoir. The initial interpretation of the MT supported this. Therefore, in order to access the deep reservoir, and to find structural permeability within it, a deep well exploration programme was adopted. The topography of the valley limits the location of drill pads to interconnected terraces requiring that two of the wells to be directional to access and extensively test the resistivity anomaly at depth.

The wells were geologically logged with every 3 m cutting interval examined with a binocular microscope. Selected cuttings and all the cores were examined petrographically on site and at SKM's home office in Auckland. Selected samples were analysed by XRD, both in Iran by the Geological Survey of Iran and New Zealand by SKM. Suitable samples were subjected to fluid inclusion analysis at SKM's home office.

2. DEEP WELLS

2.1 Well NWS-1

NWS-1 (Figure 2) was sited at the highest surficial elevation (2630 masl) of the three wells above the resistivity anomaly as originally interpreted. It is a vertically drilled well that developed a significant inclination near its bottom and it has a measured depth of 3197 m.

NWS-1 penetrated the surficial Quaternary terrace deposits and Pliocene trachyandesitic volcanics previously described (Bogie *et al*, 2000) to encounter strongly altered Eocene andesites (Epa unit of Emami, 1994). These consist of relatively sparse phenocrysts of plagioclase in a groundmass of plagioclase laths; original mafics are unrecognizable. This andesite is exposed to the west of the project where similarly to that in the well it contains abundant secondary epidote (Emami, 1994), which is thus relict.

The Miocene monzonite batholith was encountered at 1618 masl where it persists on and off to the bottom of the well at - 570 masl. It is hydrothermally altered. The monzonite examined west of the project is unaltered, but further afield it contains quartz veins with narrow zones of surrounding phyllic alteration, thus at least some of the alteration within the monzonite in NWS-1 is possibly relict. The nature of the contact between the Eocene andesite and monzonite in NWS-1 is obscured by intense hydrothermal alteration. The monzonite encountered in the well is a fine grained porphyritic border facies in comparison to the coarser grained surficial exposures. It consists of phenocrysts of plagioclase, biotite and hornblende in an equigranular fine grained groundmass of quartz and orthoclase, with minor magnetite and accessory apatite, zircon and titanite.

In addition to the fine grained texture of the monzonite in NWS-1, the presence of biotite hornfels in the well (usually as a mixture with the monzonite) suggests that the well was drilled on or near the monzonite's margin. The hornfels retains a ghost of a clastic texture sufficient to identify its precursor as the Paleozoic meta-litharenite exposed to the west of the project. The hornfels consists of granular quartz, biotite and opaques with rare diopside.

Cutting the monzonite and possibly the hornfels are dykes of diorite porphyry. These can only be clearly characterised in core, where there is an older intensely altered diorite porphyry possibly associated with the Pliocene volcanics. It is cut by younger weakly altered diorite porphyry, possibly Quaternary in age. Deeper in the well in more intensely altered zones there is a complex mixture of dykes, monzonite and possibly hornfels. Whether the deeper dykes belong to the older or younger diorite porphyry can not be definitively established, although the intense alteration found would suggest the dykes consist of the older diorite porphyry. Only monzonite is found in the deepest part of the well.

There is a complex hydrothermal alteration pattern through the well. It is likely that much of the alteration in the Eocene andesite and at least some of the alteration in the monzonite are associated with Miocene hydrothermal activity in or near the monzonite batholith. This has produced epidote-albite-chlorite-quartz-pyrite alteration in both the Eocene andesite and the monzonite. Zones of illite-quartz-pyrite-anhydrite alteration are found in the vicinity of the older diorite porphyry, and this partially overprints orthoclase-garnet alteration within the dykes themselves. Rare lazulite deep in the well may also be associated with this alteration event. On top of this older alteration there is alteration produced by the current hydrothermal system. This is expressed in a smectitic clay rich cap that has produced the resistivity anomaly found by the MT survey and has produced narrow zones of illite-quartz-pyrite alteration associated with permeable zones.

Fluid inclusions record some of the earlier alteration conditions with rare primary inclusions in anhydrite from 1595 m MD homogenising at 325°C, but with secondary inclusions indicating temperatures of approximately 230°C matching the temperatures indicated by the current illitic alteration and downhole temperature measurements.

The well encountered losses of circulation between 600 and 1400 m that corresponded to zones of increased veining and intensity of illite-quartz-anhydrite-pyrite alteration. These features are interpreted to be structures that have their surface traces obscured by the terrace deposits and it wasn't until 2900 m that one of the faults mapped at the surface was possibly reached. The well track responded by going significantly off vertical in an orientation that suggested that it was running along the NNW2 fault (Figure 2) and there were accompanying circulation losses.

2.2. Well NWS-3

This well (NWS-2R is a top hole next to NWS-1) was drilled 3 km northwest of NWS-1 at an elevation of 2277 masl to test the northward extension of the resistivity anomaly (Figure 2). It was drilled directionally NNW with

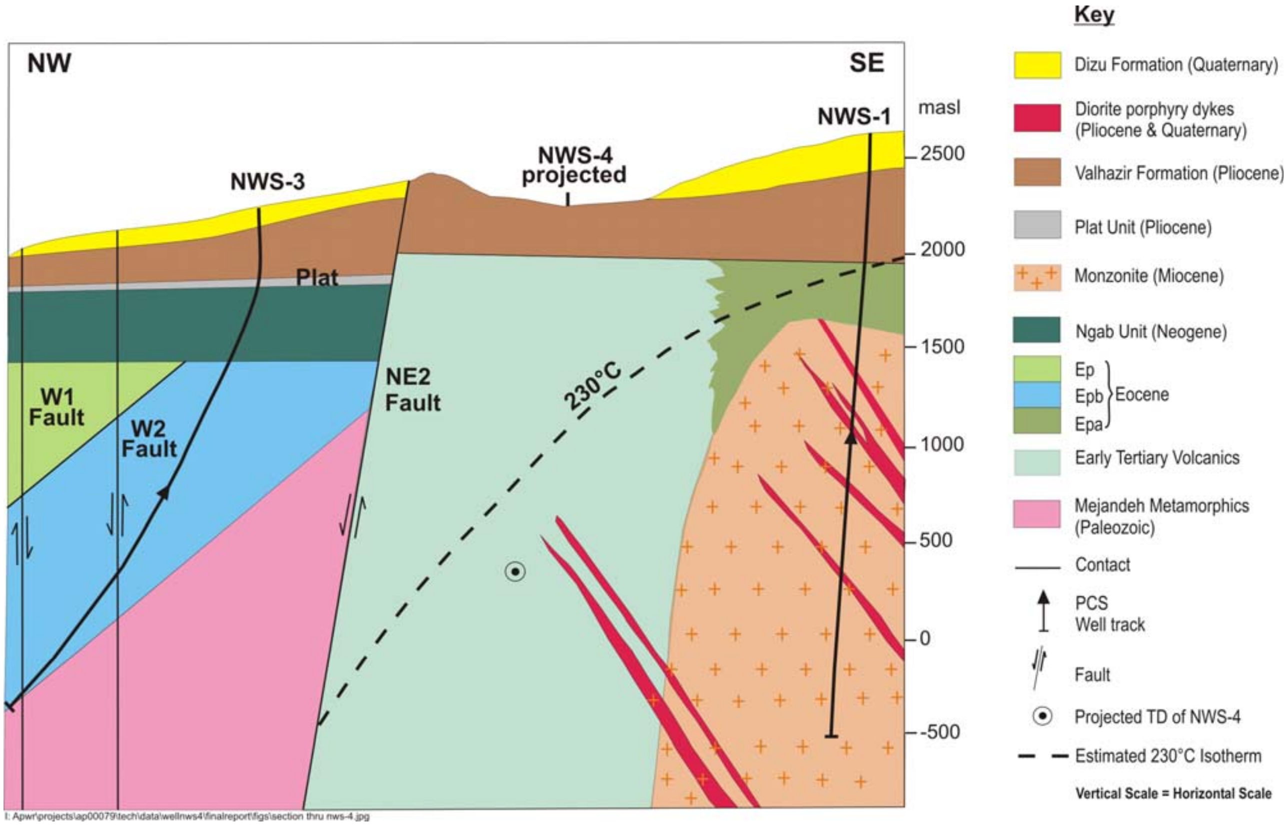

Figure 3 Geological Cross Section

a measured depth of 3177 m. After penetrating the Quaternary terrace deposits and surficial Pliocene volcanics, older Pliocene and Neogene andesitic and basaltic volcanics (the Plat and Ngab units of Emami, 1994) were found. The presence of ghosts of olivine allows the identification of the basalts, despite strong hydrothermal alteration. These units outcrop south of the project area and are possibly older parts of the Sabalan volcanic pile deposited in a structural low in comparison to the Eocene andesites found in NWS-1. Beneath the Plat and Ngab units an apparently very thick sequence of andesitic laharic breccias, pyroclastics and lava flows was found, that except for its thickness best matches the Epb unit of Emami (1994). Examination of regional structural trends suggest that the well was drilled down the northward-dipping limb of an anticline sub-parallel to the dip and thus this unit is not as thick as it first appeared.

Near the well's bottom the well track inclination increased to match the regional structural dip on the Epb unit and some Paleozoic meta-litharenite was found intermixed with the volcanics. This was interpreted to indicate that the well's track was guided down the contact between the volcanics and the much harder metamorphics, clipping a fault scarp in the process. The meta-litharenite consists of granular intergown quartz, amphibole, albite and opaques indicative of greenschist facies metamorphism. The lack of phyllosilicates means that the rock only has a poorly penetrative cleavage. In outcrop to the west it also contains thin bands of marble with margins metasomatised to garnet and epidote along with bands of epidote that represent fully metasomatised marble. Much of the epidote found near the well's bottom is thus likely to be metamorphic rather than hydrothermal.

A shallow zone of smectitic clay responsible for the resistivity anomaly was found with deeper chlorite-calcite-quartz alteration with limited zones of illite-quartz-pyrite alteration. As there is limited permeability in the well the majority of the deeper alteration appears to be relict.

Material suitable for fluid inclusion work from NWS-3 is sparse. Early anhydrite veining at 1600 m MD contains secondary inclusions with homogenisation temperatures averaging 230°C that may have formed during the later stages of the alteration event that has produced the illitic zones. Later calcite veins from the same core contain primary inclusions indicating a temperature of 150°C at 1600 m, in agreement with later downhole measurements. These temperatures also agree with the geothermometry temperatures of the waters from the Gheynarge spring. As these springs have a similar Cl concentration to that calculated for the reservoir Cl concentration in NWS-1, the Gheynarge waters are likely to have undergone conductive cooling and re-equilibration to lower temperatures, since leaving the deep reservoir. This implies that they have moved through an area of low permeability, possibly corresponding to the laharic breccias of the EPb unit that have currently only been recognised north of the NE3 fault and thus this fault may effectively mark the northern boundary of the potentially productive field.

There was little sign of any permeability while drilling the well with no losses. After completion the well flowed artesianally suggesting that it may have been drilled under near balanced conditions and completion tests located two zones of limited permeability at 2016 and 2664 m corresponding to vertical orientations of the W2 and W1 faults respectively. These dips are in agreement with the linear surface traces of the faults over varying topography seen in aerial photographs. The development of the faults in laharic material appears to have limited the development of brittle fractures and hence the degree of permeability associated with these faults.

2.3. Well NWS-4

NWS-4 (a top hole was not drilled next to NWS-3 because of the discouraging results from the NWS-3) was drilled between NWS-1 and NWS-3 at an elevation of 2487 m to test the mid-part of the resistivity anomaly. It was drilled to 2265 m as a directional well to the west. The familiar shallow sequence of Quaternary terrace deposits and Pliocene trachyandesitic volcanics was encountered. Beneath them lies a sequence of volcanics similar but not identical to the Eocene rocks encountered in NWS-1 and NWS-3. The laharic breccias found in NWS-3 could not be identified in NWS-4. The overall higher intensity of alteration in the well combined with blind drilling and a shallower TD has reduced the amount of stratigraphically useful information from the well and the volcanic sequence at depth has been lumped together as Early Tertiary volcanics. The bottom hole core is however a diorite porphyry dyke similar to that found in NWS-1 and a decrease in rate of penetration in the blind part of the hole has been interpreted to indicate that the well encountered a dyke-complex near its bottom.

Similarly to the previous wells earlier higher temperature relict alteration is present, which is best developed in the bottomhole core that contains abundant epidote, with rare remnant secondary amphibole and biotite. The current alteration includes a cap of smectitic clay responsible for the resistivity anomaly with deeper chlorite-calcite-quartz alteration with narrow zones of illite-quartz and-pyrite.

Material suitable for fluid inclusion analysis is limited in abundance. Quartz vein material from 1453 m contains secondary inclusions giving homogenisation temperatures of 230°C in agreement with temperatures anticipated from the wells heating trend.

Shallow losses of circulation with associated zones of strong silicification may possibly correlate with the shallow losses of circulation encountered in NWS-1. If this is the case the fact they were not encountered in NWS-5R (the shallow reinjection well drilled next to NWS-4) is suggestive of them having a NNW strike and westerly dip.

The well had a total loss of circulation at 1612 m and the well track turned to the right suggesting that it intersected the NW2 fault. However, it may have gained much of its permeability from the NNW2 fault as the well track continued to go down the NW2 fault, but didn't gain any additional permeability with depth and in fact partially regained circulation. At this stage, the well had potentially intersected the primary target objective and was starting to head away from the resistivity anomaly. There were therefore concerns with possible damage to permeability with continued drilling and it was terminated at a measured depth of 2265m.

3.SUMMARY AND CONCLUSIONS

An Eocene volcanic pile disconformably overlies the Paleozoic metasediments making up the area's basement. These rocks were intruded during the Miocene by a regional monzonite batholith. In the north the Eocene volcanic are overlain by Neogene to Pliocene andesitic and basaltic volcanics that are possibly an older part of the Mt Sabalan volcanic pile. These rocks are overlain by Pliocene trachyandesite volcanics of the Sabalan volcanic pile that are in turn overlain by Quaternary terrace deposits.

The rocks older than the terrace deposits have undergone a complex alteration history with the older rocks being affected by at least three alteration events. Generally where there is agreement between fluid inclusion homogenisation temperatures and temperatures interpreted from clay mineralogy current alteration can be recognised and this takes the form of illite-calcite-quartz-pyrite as narrow zones. This is consistent with the measured temperatures of approximately 230°C and an apparent increase in temperature with depth towards the south. The drop in temperature to the north may be the result of decreased permeability in this area due to the presence of laharic breccias that are not capable of sustaining substantial open fracturing.

Some of the narrow current alteration zones can be related to the surficial fault pattern, but it is also apparent that the terrace deposits have obscured much of the faulting directly within the valley. Overall, the nature of the original lithologies and the long history of hydrothermal activity in the area mean that there is unlikely to be productive primary permeability in the reservoir and that permeability is of a structural origin where there are suitably competent rocks.

Targeting faults has thus generally proved to be an effective means to gain permeability, although the low temperatures encountered in NWS-3 and the absence of competent rocks around the fault intersections has meant that they are not productive in this well. The results of this initial round of exploratory drilling have allowed for the identification of further drilling targets off the current pads and indicate that future drilling should also be undertaken further south where additional targets have been identified.

NWS-1 has been successfully discharged as a commercial well and NWS-4 shows good indications of being able to sustain a commercial output. These results therefore represent the first successful exploration drilling programme of an intraplate trachyandesite volcano thereby raising the prospectiveness of similar prospects, both in Iran and elsewhere, most notably in Turkey.

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