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STRUCTURAL FLOWPATHS OF REINJECTED FLUIDS BASED ON TRACER TESTS - PALINPINON I, PHILIPPINES

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ABSTRACT

Tracer tests using organic dye sodium fluorescein and radioactive isotope Iodine-131 were conducted in Palinpinon-I, Southern Negros Geothermal Field to quantify the rate and extent of communication between the reinjection and production sectors. The results established tracer recoveries of up to 45% and mean aerial flow velocities of 3.0 to 7.1 m/hr between the two sectors. The rapid and strong returns of the tracer indicated direct flowpaths between the re-injection and production wells provided: by faults which have been observed at the surface and subsurface.

The results of the tracer tests have greatly aided in prioritizing the reinjection wells according to the degree of communication with the production sector. As significantly, the results have established the need to reinject much farther from the producing area and to reinject along structures not directly connected to the production wells. Towards this goal, alternative reinjection sites or wells are now being considered to reduce reinjection returns.

INTRODUCTION

The Southern Negros Geothermal Field (Fig. 1) lies on the southern tip of Negros Island, Philippines. The field is divided into two sectors - Puhagan and Nasuji, as shown in Fig. 2. The Puhagan sector, which is the concern of this study, provides the steam that runs the 112.5-MWe Palinpinon I power plant.

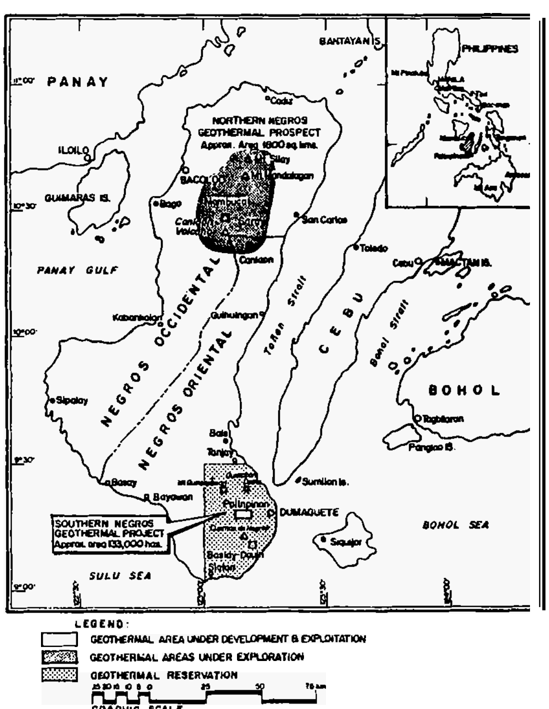


Figure 1. LOCATION MAP OF PALINPINON GEOTHERMAL FIELD
SOUTHERN NEGROS GEOTHERMAL PROJECT

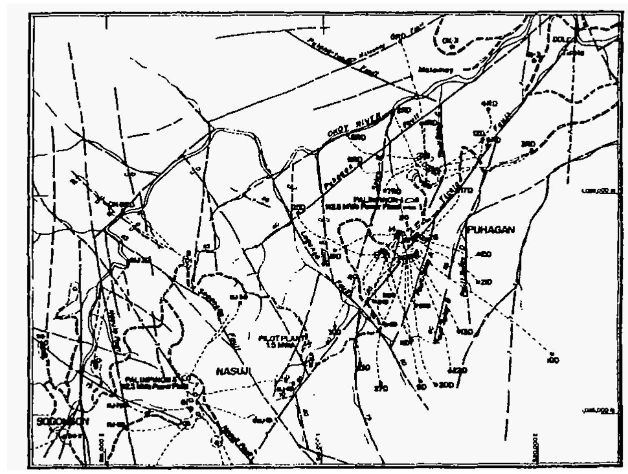


Figure 2. STRUCTURAL MAP
SOUTHERN NEGROS GEOTHERMAL PROJECT

The surface reticulation system, as well as the production and injection sectors are shown in Fig. 3. Twenty-one production wells are hooked up to the plant and ten reinjection wells, which accept wastewater by gravity flow, were drilled to the eastern, northern, and western sections of the field. Most production wells, drilled to depths ranging from 2774 to 3467 mMD, produce from multiple zones and discharge two-phase fluid from a single-phase liquid reservoir.

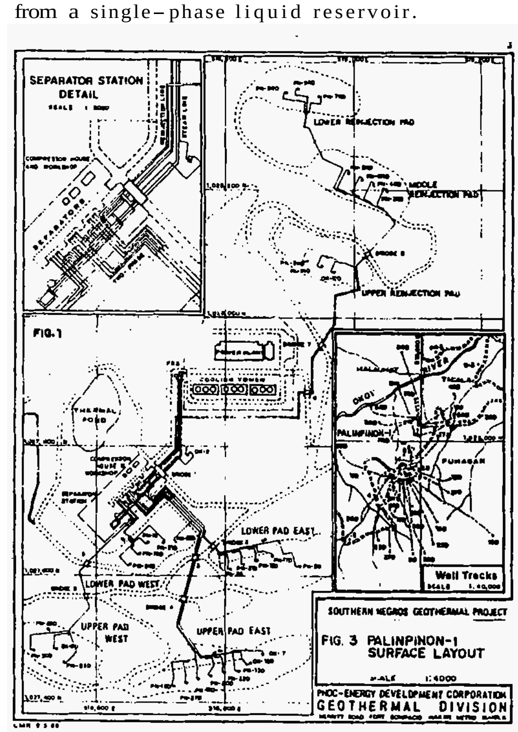


TABLE 1. TRACER TESTS IN PALINPINON-I. SOUTHERN NEGROS GEOTHERMAL PROJECT

TRACER AMOUNT	INCLUSIVE DATES	RECIPIENT WELL	OBJECTIVE	MONITORING WELLS SPRINGS, RIVERS	RESULTS Positive Return	Transit Time	% Return
I-131 18.5 GBq (0.50 Ci)	15 Aug - 06 Sep 81	OK-2	To investigate the transport of fluid reinjected into a shallow well to adjacent but much deeper wells	OK-7, OK-12D, PN-13D, PN-16D, OK-9D, OK-10D Ticala and Buahayan Springs	OK-7 OK-12D PN-13D	16.0 D 16.4 D 16.2 D	0.23 0.05 0.10
Na-Fluorescein 0.5 kg/test	30 Jul - 02 Aug 83	OK-12RD	To confirm transport of reinjected fluid to PN-6RD from OK-12RD	PN-6RD at different flowing conditions	PN-6RD	0.75-2.08 H	8-55
I-131 20.2 GBo (.545 Ci)	03 Aug - 29 Aug 83	OK-12RD	To establish and quantify movement of RI water in the Palinpinon-I Reservoir	OK-7, OK-10D, PN-15D, PN-17D, PN-21D, PN-26, PN-29D, PN-3RD, PN-4RD, PN-6RD	OK-7 OK-10D PN-15D PN-17D m-18	1Y.6 D 13.8 D 1.3 D 3.9 D 7.1 D 10.5 D 6.0 D	1.28 1.35 0.35 8.12 2.32 2.52 0.58
					PN-21D	Traces on 4th and 9th day after tracer injection	
					PN-26	Traces on 5th and 7th day after tracer injection	
					PN-3RD PN-4RD	Very low traces	
Na-Fluorescein 2.0 kg	28 Aug - 11 Sep 84	PN-1RD	To determine communication between PN-1RD and the production sector of Palinpinon-I	OK-7, OK-PD, OK-10D, PN-15D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-24D, PN-26, PN-27D, PN-28, PN-29D, PN-30D, PN-31D, N-3, OK-2, RI 317/318, PN-3RD, PN-6RD, PN-9RD	PN-26 m-18 a-7 a-1	40.0 H (1.67 D) 60.0 H (2.50 D) 80.0 H (3.33 D) 90.0 H (3.75 D)	
					PN-3RD	On downhole sample 27 hours (1.13D) after injection	
					PN-6RD	On downhole samples 95 (4.0 D) and 146 hours (6.1 D) after injection	
					PN-9RD	On downhole samples 168 hours (7.0D) after injection.	

NOTE: D - days
H - hours

Initial observations of the reservoir response and performance of both production and reinjection wells showed significant changes in a short period of time. These necessitated programmes to provide improved guidelines for the safe and efficient management of the Palinpinon I reservoir. One major policy was to minimize, if not avoid, rapid return of reinjected fluids by appropriate utilization of production and reinjection wells. On this basis, tracer tests were implemented to determine interaction among the various sectors of Palinpinon I production and reinjection blocks.

The purpose of this paper is to show how tracer tests can be used not only to establish the rate and extent of communication between reinjection and production sectors but also to determine the preferred flowpaths of the reinjected fluids. Discussion will center on the results and interpretation of the different tracer tests conducted in Palinpinon I. PNOC-EDC (1986) details the methodologies applied in the tests.

TRACER TESTS

Tracer tests in Palinpinon I employed the use of the organic dye sodium fluorescein and the radioactive isotope Iodine-131, which were introduced in 1981 and 1983, respectively. A few months after the plant started commercial operation, Iodine-131 of activity 20.2 Gigabecquerel (.545 Ci) was injected at OK-12RD to determine possible connections between the easterly injection sector and the producing wells. This possibility has been manifested by geochemical monitoring of the wells. One year later, in August 1984, a slug of 2.0 kgs of sodium fluorescein was introduced into the northeasterly injection well PN-1RD. The latest tests in PN-9RD, using both tracers, aimed principally to determine comunication between the western injection block and the producing wells.

OK-12RD

The results (Table 1) of the radioactive tracer test indicate that the eastern reinjection well OK-12RD communicates well with the eastern and central Puhagan wells. The tracer was detected first at PN-17D in less than one day. Total tracer recovery from five production wells (PN-17D, PN-15D, PN-28, OK-7, OK-10D) was 16.6% within four weeks, 79% of which was recovered from PN-17D. Traces were also detected in wells PN-26 and PN-21D and the easterly injection wells PN-3RD and PN-4RD. Mean transit times of the tracer ranged from 3.9 to 14.6 days, equivalent to average aerial flow velocities of 1.7 to 4.6 m/hr.

PN-1RD

Visual examination of the samples from the PN-1RD sodium fluorescein test was not sufficient to detect returns of the dye. Hence, an ultraviolet (UV) spectrophotometer was used to detect traces of active fluorescein. Positive returns were obtained from the central Puhagan wells PN-26, PN-28 and OK-7, as well as from the shallow reserve well OK-2. Well PN-26 exhibited the strongest and fastest response. The first arrival of the dye in these wells were registered at 40, 60, 80 and 90 hours, respectively, which translate to breakthrough velocities of 5.6 to 16.5 m/hr.

Tracer return was confirmed in only four wells due to: a) deterioration of sodium fluorescein with time at high temperatures; and b) interference of silica and sulfur with the detection process causing some samples to show visible coloured precipitate but no fluorescence under UV light.

PN-9RD

Test Description

Before the radioactive tracer test, a precursory test using sodium fluorescein was conducted to obtain initial information regarding well interaction for monitoring and sampling purposes. Ten kilograms of the chemical dye sodium fluorescein was introduced into reinjection well PN-9RD, and hourly cumulative. discharge samples (500-ml) from ten production wells were withdrawn from the 'two-phase lines using mini-silencers. Samples were analyzed for fluorescent emission using UV radiation.

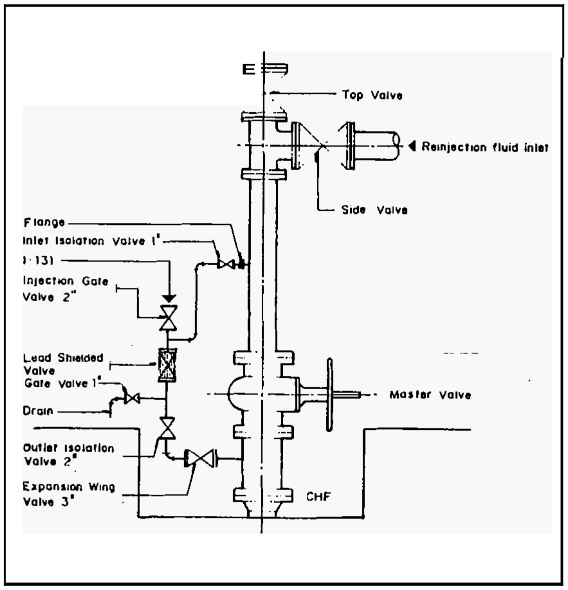


Figure 4. I-131 TRACER INJECTION SYSTEM

For the radioactive tracer test, 1–131 of activity 67 GBql (1.81 Ci) was introduced via a by–pass system shown in Fig. 4. For wells on production, five–liter samples were collected from the two–phase lines. For wells on bleed like PN–26 and PN–28, cooling coils attached to the side valve of the respective wellheads were utilized to collect the same volume of samples. The samples were then counted for radioactivity using NaI (Tl) detector, and field counts were cross–checked using a multi–channel analyzer (MCA).

The PN-9RD tracer test utilized for the first time the chemical recovery of radioactive Iodine–131 as iodide. This method was introduced by the Institute of Nuclear Sciences, New Zealand. It removes sulfides, sulfates, and silica interferences; and precipitates silver iodide from the 2–liter sample. The precipitate is analyzed for radioactivity using the MCA.

Results

Table 2 lists the breakthrough times of the chemical dye, as well as the mean transit times and percentage recovery of the radioactive tracer. The sodium fluorescein appeared immediately in one day at OK–7. Arrival times for the other wells ranged from 5.5 to 6.0 days, while for the more distant production wells PN-16D, PN-23D, and PN-30D, the chemical tracer was first detected in 7.5 to 9.8 days. With approximate aerial separation of .84 to 1.4 km of these wells from PN-9RD, breakthrough velocities were calculated to be as high as 35 m/hr from PN-9RD to OK-7, and from 4.7 to 7.8 m/hr from PN-9RD to the other production wells.

Table 2.
PN-9RD TRACER TEST RESULTS

WELL	Return	1-131 TRACER Average Transit Time DAYS	SODIUM FLUORESCEIN Breakthrough Time DAYS
OK-7	29.2	5.7	1.08
PN-29D	6.0	14.0	6.0
PN-26*	3.9	11.0	5.5
PN-28*	1.1	10.3	6.0
PN-18D	0.8	15.6	Not Monitored
PN-30D	0.8	15.7	8.3
PN-23D	0.4	15.8	7.5
PN-31D	0.4	16.0	5.5
PN-16D	Tracer found in samples after 8-19 days		9.8
PN-19D	Tracer found in samples after 15-19 days		6.0
PN-17D	No response		6.0
OK-9D	No response		No response detected

*Wells on heavy bleed. Tracer return values believed to be erroneous due to inaccurate mass flowrates used.

The radioactive tracer test confirmed the fast and strong returns of the reinjected fluid from PN-9RD to OK–7 with a mean transit time of 5.7 and about 30% tracer recovery. The mean transit time represents the time it would take half of the recovered tracer return to reach the production well. The rest of the wells had average transit times of 10 to 16 days with a cumulative tracer recovery of 15%. The radioactive tracer test has affirmed the communication between PN-9RD and the central, western, and southwestern production wells.

TRACER CURVES ANALYSIS

A tracer breakthrough curve shows the concentration of a tracer with time and is an expression of the fluid and chemical transport mechanism between an injection and a production well. To obtain physical parameters from tracer breakthrough curves, the two–well pulse transport model of Lenda and Zuber (1974) was used. This model involves an instantaneous injection of tracer in one well and the observation of its transit time to a discharging well. Their solution for the dispersion equation is used in the theoretical description of the concentration curve measured in the pumping well. Using the FORTRAN program TRIGR, which incorporates this model, the porosity, the mean tran–sit times, and the tracer recoveries are determined from the tracer curves. Aside from these, a measure of the dispersion D/vx, (where D is the dispersion constant, x the distance between the injection and producing wells, and v the mean velocity of flow), is obtained. As important as these numerical output, the program fits the experimental data by a single theoretical curve or by a sum of such curves.

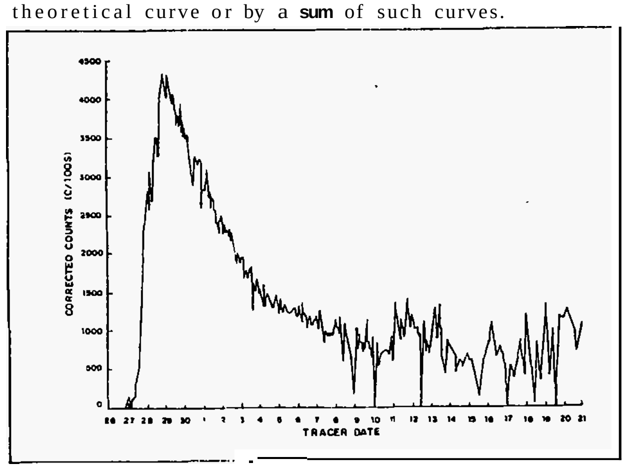
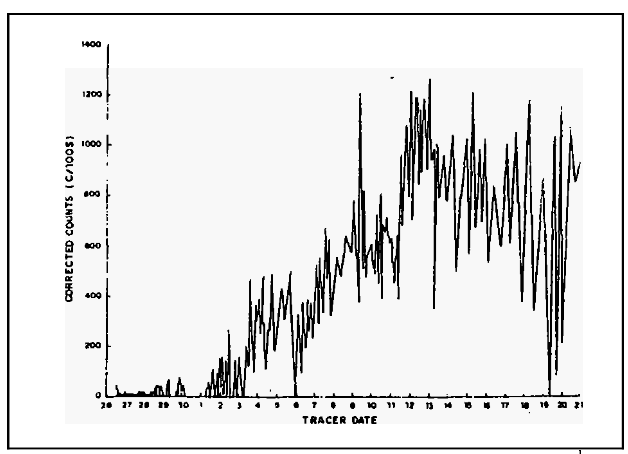


Figure 5 TRACER BREAKTHROUGH CURVE OF WELL *OK-7* 26 SEW1985 - X/OCT 1985

Figs 5 and 6 are examples of the experimental tracer curves of OK–7 and PN-29D, and Figs. 7 and 8 show the results of the interpreted curves for OK–7. It is interesting to note that, for OK–7, the breakthrough curve has been recognized by the program as a sum of two theoretical curves. Two different options for the flowpaths are, however, presented.



jure 6. TRACER BREAKTHROUGH CURVE OF WELL PN-29D 26 SEPT 1985 - 20 OCT 1985

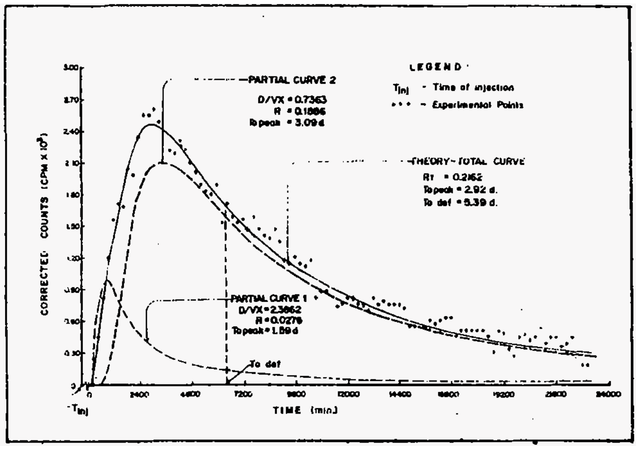


Figure 7 BREAKTHROUGH CURVE FOR WELL OK-7 (FIELD DATA) INTERPRETED BY TWO SUBCURVES USING TRIGR PROGRAM

Fig. 7 shows that through the first flowpath (Curve 1), the tracer return is rapid (1.6 days) and small (3%). It is the other component of the flow (Curve 2), with its peak at the third day, that accounts for the greater return of the tracer (19%). Figure 8, on the other hand, shows that it is the first component (Curve 1), recovering 21% of the tracer, which has a peak arrival of 3 days as contrasted to the second sub-curve which contributes only 1% of the tracer injected. The first flowpath of Fig. 8, by itself, could account for the fast and strong returns in OK-7, while the second component could represent longer travel paths (~7 days). This is supported by the higher D/vx of Curve 1, which implies that the primary flowpath has larger aperture, faster flow, and minimum fracture branching (Fossum, 1982).

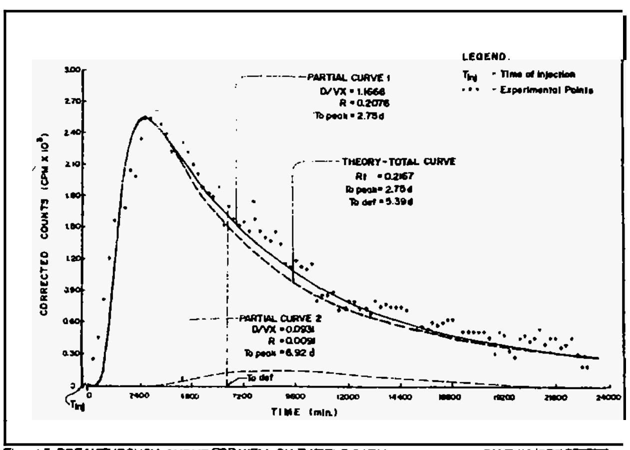


Figure 8. BREAKTHROUGH CURVE FOR WELL OK-7 (FIELD DATA) INTERPRETED BY TWO SUBCURVE USING TRIGR PROGRAM

For the other wells, the result shows that a single peak profile may be better modelled assuming multiple flowpaths. Since the quality of the fit does not improve appreciably with three or more curves, prudence dictates that a model with the least number of parameters be chosen. Nevertheless, this feature of the computer interpretation indicates that the tracer had taken more than a single flowpath to the producing wells. The tabulated results (Table 3) show that for the other wells, the first sub-curves have peak arrivals of six to twelve days, while the second component curves have a range of thirteen to twenty days. The mean transit times calculated (5.4 days for OK-7, 12.5 to 18.2 days for the other wells) are considerably closer to the secondary peaks and differ by at most two days from the values given in Table 2. Total tracer recovery was about 35%. The porosity-thickness product which range from .0060 to .0255 is comparable to the results obtained from pressure monitoring and interference tests. Of course, in the final analysis, although the computer interpretation is faster, more efficient, and probably more objective, critical judgment of the interpreter must be based on and supported by geological and hydrological evidences.

Table 3. COMPUTER INTERPRETATION OF TRACER BREAKTHROUGH CURVES

WELL NAME		OK-7	OK-7	PN-29D	PN-31D	PN-26	PN-28	PN-18D
Data		Field	Field	AgI	Field	AgI	AgI	AgI
Peak Countrate, (cpm)	Curve 1	0.99×10^4	2.55×10^3	0.93×10^3	0.56×10^2	1.20×10^3	0.37×10^3	4.32×10^2
	Curve 2	2.10×10^3	1.13×10^3	2.67×10^2	3.60×10^2	1.34×10^3	1.18×10^3	3.60×10^2
Peak Arrival (days)	Curve 1	1.59	2.75	9.64	12.1	7.42	6.21	15.89
	Curve 2	3.09	5.92	15.80	19.5	13.56	12.98	22.42
% Recovery	Curve 1	2.76	20.76	0.69	0.08	0.12	0.04	0.96
	Curve 2	18.86	0.91	3.90	1.56	0.34	0.29	0.67
D/Vx	Curve 1	2.3862	1.1666	0.1632	0.0548	0.2622	0.2873	0.7542
	Curve 2	0.7363	0.0931	0.0794	0.0820	0.1926	0.1474	0.0848
TOTAL TRACER % RETURN		21.62	21.67	4.59	1.64	0.46	0.33	1.63
MEAN TRANSIT TIME, days		5.39	5.39	15.64	1820	12.95	12.50	17.20
ϕh		0.0177	0.0213	0.0121	0.0060	0.0021	0.0024	0.0133

GEOLOGICAL STUDIES

To delineate the flowpaths taken by the tracer, detailed subsurface petrographic analysis of all reinjection and production wells was undertaken. The possible sources of production and permeability in the Puhagan sector were determined. Hence, for each well, the lithologic/stratigraphic units encountered, as well as the occurrence of dike intrusions, were noted. Likewise, possible fault intersections based on the occurrence of mylonites and drusy veins were marked. Mylonites are faulted rocks characterized by extreme granulation or grain-size reduction, strong foliation in the matrix defined by fibrous and opaque minerals, and ductile deformation exhibited by phenocrysts.

The results of the study showed that all permeable zones delineated by well tests coincide with fault intersections. No permeability was attributed either to stratigraphic contacts or to dike intrusions since by themselves they do not correlate with any permeable zone. They were coincident with permeable zones only when accompanied by faulting.

Since permeability and production are primarily controlled by structures, then the chief mechanism for the return of reinjection fluid to the production area is provided by faults. In order to delineate which faults acted as preferred channels for the reinjection fluid, the subsurface fault intersections were correlated to the surface traces of structures. Through graphical projections and numerical calculations, all faults mapped on the surface (Fig. 2, Pornuevo and Obusan, 1983) were satisfactorily correlated with the mylonite/vein zones in the different wells. However, some mylonite/vein zones could not be attributed to any of the faults identified on the surface. Instead, they relate to the lineaments identified from an independent photogeological study of the area (Panem , 1986). Some of these lineaments which coincide well with the mylonite zones are Fault F, Fault J, and Fault G (Fig. 9).

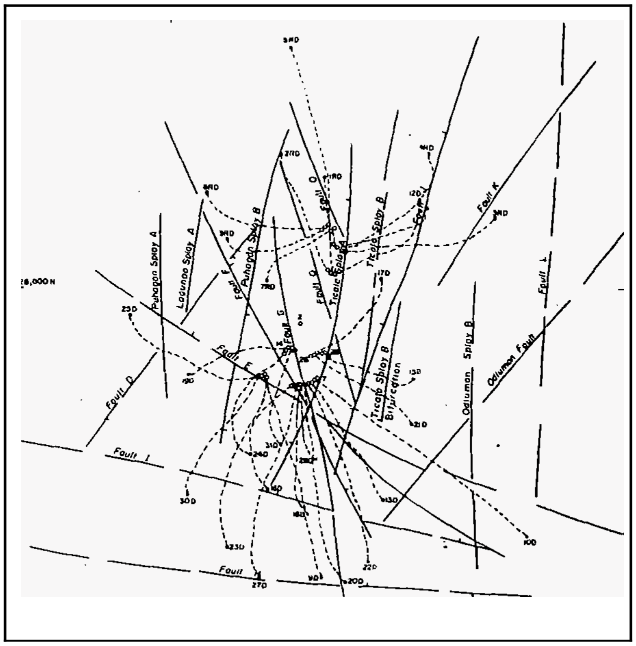


Figure 9. LINEAR FEATURES IDENTIFIED BY AIRPHOTO ANALYSIS

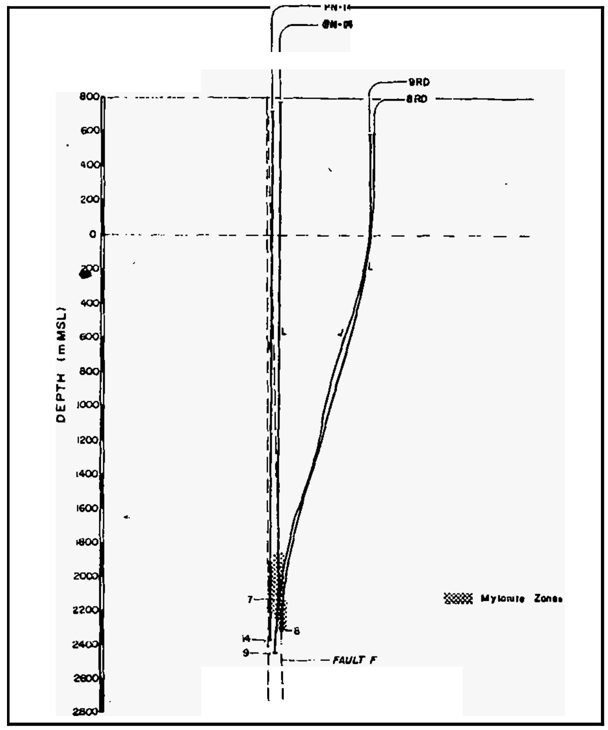


Figure IO FAULT F WELL INTERSECTIONS SOUTHERN NEGROS GEOTHERMAL PROJECT

Flowpaths Analysis and Interpretation

Analysis and correlation of the results of the tracer tests . and structural study indicate that there are preferred flowpaths for the return of reinjection fluid to the production sector.

Production wells which intersect and feed from Ticala Splay B and Fault J are bound to be affected by reinjection fluid return from OK-12RD. Some of these wells include the central Puhagan wells OK–7, PN–26, PN–28 and the easterly production wells PN-17D, PN-15D, PN–21D and OK-10D, in addition to the easterly reinjection wells PN-3RD, PN–4RD and PN-6RD.

Direct connection between PN-1RD and PN–26, as shown by the sodium fluorescein test, is provided by Ticala Splay A. PN–29D which produces from its intersection with this fault, is believed to be pumping injection fluid, too, from PN-1RD but which was not observed from the test due to deterioration of the chemical dye. Another structure which acts as conduit for the reinjection fluid from PN-1RD to the production wells is Ticala Splay B. Therefore, wells which feed from these two faults, such as PN–28 and OK–7 would be reached by fluid injected to PN-1RD.

The rapid and strong return of the tracer from PN–9RD to OK–7 is provided by Fault F (Fig. 10) which intersected the bottom main loss zone of PN-9RD and the bottom main feed zone of OK–7. This fault would be the direct pathway from PN–7RD to PN-9RD, PN–14 and OK–7, which results to strong pressure responses among the four wells. In addition, downhole samples taken from PN–14 and OK–7 confirmed reinjection returns in these wells. Other faults which have intersected PN–9RD such as Fault G , Puhagan Splay A and Puhagan Splay B are the channels for the return of reinjection fluid to the other production wells. In particular, the flowpath to the more distant production wells in the south and southwest is provided by Puhagan Splay A. Average flow velocities were approximately 7.1 m/hr through Fault F and 3.0 m/hr through Puhagan Splay A.

In summary, the study shows that the central Puhagan wells (OK–7, PN–26, PN–28, PN-29D) are rapidly and greatly affected by reinjection from the east, and northeast (OK-12RD, PN-1RD), and from the west (PN-7RD, PN-9RD) due to their proximity and intersection with the NW-SE trending faults such as Ticala Splay A, Ticala Splay B, and Fault J and the NE-SW trending faults like Puhagan Splay B, Fault F and Fault G. Other production wells which are situated farther away from the reinjection wells, but which have nevertheless intersected the above–mentioned faults, have also been the recipient of reinjection fluid returns although to a lesser degree. A graphical summary of these discussions, together with the approximate mean flow velocities through the structural flowpaths are given in Fig. 11.

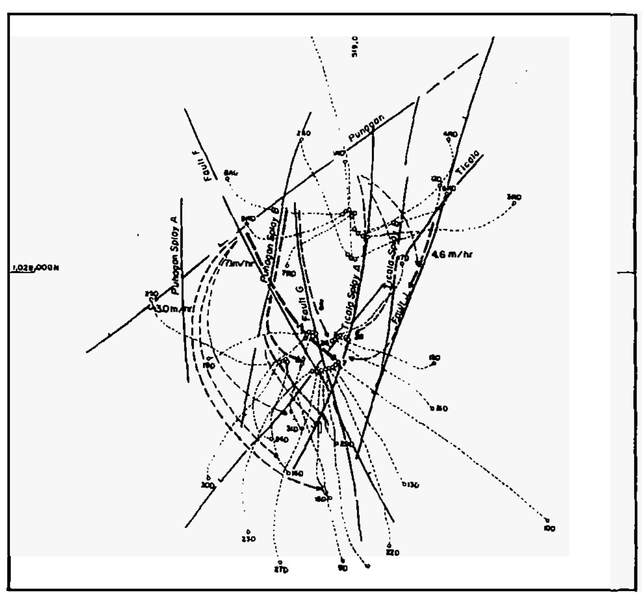


Figure 11. GRAPHICAL SUMMARY OF PALINPINON-I TRACER TESTS

CONCLUSION

The tracer test results, in alliance with geological study confirm that permeability and production in the Puhagan area are primarily controlled by structures. The results of the study showed that reinjection fluids are returning to the production area through faults. The major structural pathways for the return of injected fluid are Fault J, Ticala Splays A and B, Puhagan Splays A and B, Fault F and Fault G. Through these structures, average flow velocities of 3.0 to 7.1 m/hr have been determined.

The results of the tracer tests have helped in the proper management of the field such as in prioritizing the reinjection wells according to the degree of comunication with the producing area. The study strongly suggests that reinjection returns and their detrimental effects to the producing wells would increase in rate and extent not only due to a rise in station load but also due to the interconnection of these geologic structures. Therefore, there is the need to reinject even much farther from the producing area and to reinject along structures not directly connected to the production wells. Towards this objective, alternative reinjection sites or wells are now being studied to reduce reinjection fluid returns.

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