EVALUATION OF INITIAL INVESTIGATIONS

DIENG GEOTHERMAL AREA, CENTRAL JAVA, INDONESIA

by

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SUMMARY AND RECOMMENDATIONS

Evaluation of the geophysical, geochemical, and geological studies carried out in 1970 in the Dieng Mountains has been completed. On the basis of the evaluation, it is recommended that exploratory drilling of the Dieng geothermal field be undertaken following the general program outlined by Muffler (1970).

It is recommended that six exploratory holes be drilled, each to a depth of approximately 200 m. Proposed sites are:

1. Pagerkandang Crater
2. Just west of Telaga Terus
3. Just north of Pawuhan
4. 3/4 km east of Sekunang
5. Just southeast of Sidolok
6. Just west of Dieng Wetan

After completion of the 200 m holes, two holes should be drilled to a depth of approximately 650 m.

INTRODUCTION

Interest in possible utilization of the geothermal resources of the Dieng Mountains dates back to 1928, when the Dienst Van Den Mijbouw drilled several exploratory holes, the deepest to 80 m (Purbo-Hadiwidjojo, 1968; Hoesni, Arismunandar, and Radja, 1971). Although temperatures up to 145°C were found, there was no follow up to this limited exploratory drilling.

Renewed interest in the area was stimulated by the UNESCO Volcanological Mission (Tazieff, Marinelli, and Gorshkov, 1966), and was furthered by a geothermal mission sponsored by the French government in 1968. Both missions recommended further investigations and development of the geothermal resources of the Dieng area.

At the request of the Indonesian government and under the auspices of the United States Agency for International Development (USAID), a report recommending steps to evaluate and (if warranted) to develop the geothermal potential of the Dieng Mountains was prepared by the United States Geological Survey (Muffler, 1970). This report was based on a study of the available literature and a brief visit to the Dieng Mountains. The report concluded that the Dieng probably contained significant reserves of geothermal energy, and recommended a three step program with initiation of each successive step to be conditional upon favorable indications from the preceeding step. Recommended steps were:

1) a resistivity survey, with supplementary photogeology and geochemistry, 2) exploratory drilling, with supplementary geochemistry and production testing, and 3) development drilling.

The aims of steps 1 and 2 were to determine: a) whether the fumaroles are indeed the surface manifestations of a large, deep geothermal system, b) the optimum siting of exploration and development wells, c) the size of the geothermal system, and d) the characteristics of the reservoir (dry steam vs hot water; acid vs neutral; temperature; transmissibility; etc.).

Geophysical, geological, and geochemical investigations recommended as step 1 in the USGS report were carried out during the dry season of 1970 as follows:

a. An electrical geophysical survey was conducted by Group Seven Inc. (Jacobson and Pritchard, 1970; Jacobson, Pritchard, and Keller, 1970) under contract with USAID with strong counterpart support from the Geological Survey of Indonesia (GSI) and the Power Research Institute (PRI).

b. Fumaroles, hot springs, and rivers of the Dieng Mountains and surrounding areas were sampled and chemically analysed by the USGS and the GSI. The data are summarized and interpreted in a preliminary geochemistry report (Truesdell, 1970) and in a final geochemistry report (Truesdell, 1971).

c. Excellent aerial photographs of the Dieng Mountains and surrounding terrain were provided by Geotronics (processed by P.N. Aerial Surveys) under contract to USAID.

d. Using these photographs, a photogeologic map of the Dieng area was prepared by the GSI (Pardyanto, 1970).

Additionally, four topographic maps at 1:5,000 scale of about 21 km^2 of the Dieng and Batur areas were prepared from surveying data by the Indonesian Power Research Institute (PRI). Contour interval is 5 meters.

EVALUATION PROCEDURE

The results of the initial investigations have been reviewed and evaluated by a team composed of the following persons:

L.J.P. Muffler, Geologist, USGS, Chairman
Djajadi Hadikusumo, Chief, Volcanological Survey, GSI
H. L. Ong, Lecturer, Institute Technology of Bandung (ITB)
Vincent Radja, Chief of Operation, Electric Power Survey Project, PRI
M. T. Zen, Senior Lecturer, ITB

The evaluation team had the following goals:

1. To review and evaluate the initial investigations completed in 1970.
2. To recommend whether or not to proceed with exploratory drilling.
3. If exploratory drilling was recommended, to indicate the number, approximate location, and depth of holes required to adequately assess the potential of the geothermal system.

The evaluation team (excluding Ong) visited the Dieng Mountains on January 14 and 15, 1971, with M. R. Klepper (USGS), D. D. Fowler (USAID), Sutardono (PRI), and I. Sjamsu (PRI). Blessed by relatively dry weather, the group evaluated the thermal features and their geologic setting, inspected possible drilling sites and considered problems of road access, site preparation, and sources of drilling water.

Evaluation of the initial investigations was carried out at the GSI in Bandung on January 18-21 and at USAID in Djakarta January 22. A preliminary evaluation report, dated January 22, 1971, was written by Muffler, with the counsel and assistance of the other members of the evaluation team and with the invaluable assistance of M. R. Klepper. The final evaluation report was prepared by Muffler at the USGS in Menlo Park, California, February 1-10, 1971, and supersedes the preliminary report.

SUMMARY AND ANALYSIS OF INITIAL INVESTIGATIONS

Electrical Geophysical Survey

An electrical geophysical survey using several techniques was conducted in the Dieng Mountains in July and August, 1970 by Group Seven, Inc. under contract AID/ea-123. Assistance and location surveying were provided by GSI. Results of the electrical survey are contained in a preliminary report dated August 27, 1970 (Jacobson and Pritchard, 1970) and in a final report dated November 1, 1970 (Jacobson, Pritchard, and Keller, 1970). At the request of USAID, Group Seven subsequently prepared a revised Plate I showing metric coordinates.

These reports contain useful data and interpretative information, and are valuable aids in evaluating the geothermal potential of the Dieng Mountains and in recommending sites for exploration drill holes. Efficient use of the reports, however, is impaired by several deficiencies in coverage and in format of data presentation:

1. The dipole survey did not extend sufficiently far out from the low resistivity anomalies to give a reliable indication of background resistivity values in non-thermal ground. A dipole source near Batur, for example, would have been very useful.

2. Both dipole sources were sited in thermal ground, whereas at least one should have been sited in non-thermal ground, as outlined by preliminary Schlumberger surveys.

3. Additional Schlumberger profiling would have been useful, particularly along the roads that connect Kawah Sikidang with the Dieng-Batur road.

4. The maps accompanying the final report are very difficult to use, primarily because of inadequate geographical control. The three plates accompanying the final report show no coordinates, bench marks, or triangulation points, and the Dieng-Batur road is so generalized that it is difficult to use as a reference. These deficiencies occurred despite the availability of published topographic maps. Also, Plate II for some inexplicable reason was drafted with north to the bottom.

5. There are several discrepancies between illustrations. For example, figure 2 of the final report is misleading, in that there should be a gap of 2-1/2 km between locations 3 and 4 (cf. figure 1 of the final report and figure 5 of the preliminary report).

6. The tables accompanying the final report are very difficult to use because there is no explanation of the tabular format, and because the column headings of table 2 are incompletely labeled.

Three electrical techniques were used by the Group Seven field party: dipole survey, modified Schlumberger profiling, and Schlumberger soundings. In addition, two audio-magneto-telluric traverses were made, as well as one electromagnetic sounding.

Dipole Survey

The dipole results are presented by Jacobson, Pritchard, and Keller (1970) as two apparent resistivity maps (Plates I and II) contoured in ohm-meters. One map gives results from a source dipole located south of Dieng Kulon (Source A), and the other gives results from a source northwest of Karangengah (Source B). These maps have been redrafted at 1:25,000 and are shown on figure 1 of this report*/. Resistivity varies inversely with temperature, salinity,

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*/ There are significant discrepancies between the topographic map (based on the published 1:50,000 Batur sheet) and the sketchy base maps used for Plates I and II of Jacobson, Pritchard and Keller (1970). The discrepancies are particularly bad in the vicinity of dipole source B and could not be satisfactorily resolved on figure 1 of this report.

porosity, and the content of clay and zeolite minerals. Elevated values of these parameters are commonly characteristic of geothermal systems; accordingly, areas of low resistivity are likely to be underlain by a geothermal system at depth.

Plate I shows a prominent belt of low resistivity extending from Siglagah on the north to beyond Sikidang in the south. Plate II shows a similar belt, plus a smaller resistivity low near Tjandradimuka. The anomaly centered on the Dieng Plateau has a different shape on Plate I than on Plate II. This discrepancy is caused by the fact that effective probing depth of a dipole array varies with the position and orientation of the source array relative to the receiving array*/. The gross discrepancy between Plates I and II south of Dieng Kulon is due to the fact that source dipole "A" is located directly over a center of low resistivity, and measurements made near this source do not provide enough penetration to show the presence of conductive rocks at depth (Jacobson, Pritchard, and Keller, 1970, p. 8-10). Information from dipole "B" is more meaningful in this area.

The aggregate of the two dipole surveys defines a low resistivity region of approximately 9 square kilometers (the area within the 5 ohm-meter contours of figure 4 of Jacobson, Pritchard, and Keller, 1970). Within this area one might reasonably expect to find hot water and rock at depths less than 1 to 2 km. Within the 5 ohm-meter contour are 3 areas of lower resistivity (Pagerkandang, Sikidang, and an area 3/4 km south of Dieng Kulon). These areas are inferred to be centers of upwelling hot water, and indeed at Pagerkangdang and at Sikidang there are fumaroles.

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*/ The "effective probing depth" of a resistivity array is defined as the depth at which a boundary can be detected by any given spacing (Risk, Macdonald, and Dawson, 1970). For a dipole array the effective probing depth is $\frac{\tan^2 a + 2}{\tan^2 a + 4} R$ where R is the length of a line joining the midpoint of the source array and the center of the receiving array and $\underline{a}$ is the angle between this line and the polar axis of the source dipole. Angle $\underline{a}$ can vary through 360°, $\tan^2 a$ from 0 to ∞, and the effective probing depth from $\frac{1}{2}$R (polar dipole) to R (equatorial dipole). Thus the effective probing depth for any receiving station in the Dieng Mountains depends on which dipole source is used.

The boundary of the geothermal system cannot be defined precisely from the resistivity data, for data points outside the anomalous area are insufficient to reliably determine the apparent resistivity of the non-thermal volcanic rocks. The 5 ohm-meter contour chosen by Jacobson, Pritchard, and Keller (1970) is a reasonable guess, but there is no a priori reason why the boundary of the system should correspond to this particular contour. The absolute value of resistivity within a geothermal system is a complex function of temperature, salinity, porosity, and clay and zeolite mineral content, and the aggregate effect these factors have on resistivity varies from one geothermal system to another, depending on the relative importance of the factors.

The second area of low resistivity, at Tjandradimuka, is incompletely defined, but appears to have an extent of at least 1 km^2. The dipole data indicate that there is no apparent connection between the Tjandradimuka geothermal system and the much larger Dieng geothermal system, at least at depths shallower than several kilometers.

Modified Schlumberger profile

A resistivity profile along the road from Dieng Kulon to Batur was constructed from modified Schlumberger arrays about five source array locations. The resistivity contrast on the profile is good, and two areas of low resistivity are defined (just west of Dieng Kulon and to the northwest of Karantengah). These zones of low resistivity were emphasized in the preliminary Group Seven report, but deprecated in the final report. There seems to be no good reason for this downgrading of the data, and the anomalies shown on figure 5 of Jacobson and Pritchard (1970) and which can easily be contoured on figure 2 of Jacobson, Pritchard, and Keller (1970) appear to be valid. It should be noted that dipole survey A shows a lobe of resistivity less than 10 ohm-meters covering the area northwest of Karantengah. No resistivity low is shown on Plate II, but the data near source dipole "B" is suspect for the same reasons that applied to source dipole A (discussed above).

Schlumberger soundings

Four Schlumberger soundings to spacings (AB/2) of 200 meters were made over areas that showed very low resistivity in the dipole survey. These show that ground of very low resistivity at Kawah Sikidang and Kawah Sileri fumaroles extends downward to at least a depth of approximately 200 m. A sounding within Pagerkandang crater showed that resistive rock overlies material of low resistivity that can readily be interpreted as hot. The fourth sounding, on the south rim of Pagerkandang crater, probably is not meaningful owing to steep topography. At most, it reflects the highly resistive rock expected in a ridge 100 m above the bottom of Pagerkandang crater.

Audio-magneto-telluric measurements (AMT)

Two AMT traverses were made: one along the Dieng-Batur road, the other extending for 1 km NNE of Kawah Sikidang. Data are given only for the second traverse, although Jacobson, Pritchard, and Keller (1970, p. 27) state that both surveys yielded resistivity values which were similar in size to those measured by the more cumbersome profiling and sounding methods. The Dieng-Batur traverse showed low resistivity at Pawuhan, near Sidolok, and near Timbang. The traverse NNE of Sikidang showed a near-surface layer less than 60 m thick with a resistivity near 100 ohm-meters underlain by material of somewhat lower resistivity. Resistivities near Sikidang itself were quite low, as expected from the extensive fumarolic activity.

Geochemical Survey

A geochemical survey of the hot springs, fumaroles, and streams of the Dieng Mountains and neighboring areas was carried out in August, 1970 by A. H. Truesdell of the U.S. Geological Survey. A preliminary report on this work was submitted to USAID on August 24, 1970. The final geochemical report (Truesdell, 1971) was delayed pending receipt of geochemical analyses from USGS laboratories in Menlo Park.

Geothermal systems may produce either a mixture of hot-water and steam (a hot water system), or steam alone (a vapor-dominated or "dry steam" system). It is important in geothermal exploration to determine which type of system occurs in a given area. Upward transfer of H_2O and heat occurs by movement of liquid water in a hot water system, but by movement of steam in a vapor-dominated system. Since most chlorides are not appreciably soluble in steam below 300°C, a hot-water system can be predicted with a high degree of confidence if the surface springs have appreciable chloride, generally more than 50 mg/l.

In the Dieng Mountains the abundance of fumaroles, the scarcity of flowing springs, and the low chloride contents of most flowing springs would suggest a vapor-dominated system were it not for the high-chloride water at Kawah Sileri (173 mg/l) and at Pulosari (426 mg/l) springs. Inasmuch as high-chloride springs cannot be associated with a dry-steam system (White, Muffler, and Truesdell, 1971), the Dieng geothermal system is almost certainly a hot-water system, with a probable chloride content of 700 mg/l (Truesdell, 1971, p. 11). In this respect, the Dieng system is likely to be similar to Wairakei, New Zealand or Hengil, Iceland, but to differ from the two known commercial vapor-dominated systems of Lardarello, Italy, and The Geysers, California.

Samples from rivers draining the Dieng Mountains were taken to determine whether any high-chloride thermal water diluted by ground water is discharging directly into rivers. Many rivers draining the Dieng Mountains contained chloride in excess of background (10-25 mg/l), and in two rivers (Kali Tulis at 160-219 mg/l and Kali Dolok at 61 mg/l) the chloride content was quite high. These two rivers drain the Sikidang and Sileri areas, respectively, and the high chloride values are interpreted to reflect mixture of chloride-bearing thermal water with dilute meteoric water.

On the basis of the distribution of thermal activity, Truesdell (1970) concluded that in the Dieng Mountains at depths less than 200 m there are three geothermal systems, which may be interconnected at greater depths. Of these, the Pagerkandang system (including Sileri, Siglagah, and Bitingan) the largest, with an area of 2.5 km^2. Smaller systems are at Sikidang and Tjandradimuka. The chloride-rich water at Pulosari may represent outflow from either the Sikidang or Pagerkandang system.

Truesdell (1970, p. 13) notes that the elevation of Kawah Sileri is 1875 m, and he assumes that this level marks the top of chloride water in the Pagerkandang area. There is a 4% gradient between Sileri and Pulosari. If a similar gradient is assumed from Pulosari to Sikidang, the estimated elevation of chloride water under Kawah Sikidang (elevation 2035 m) is 1850 m. The floor of Pagerkandang crater is at about 2035 m. Therefore, both at Pagerkandang and Sikidang a hole of at least 200 m would be required to intercept chloride-bearing water.

Hot-spring fluid compositions, particularly the content of SiO_2 and the alkali and alkali-earth ratios, can be used to predict the subsurface temperatures of hot-water systems (Mahon, 1970; Fournier and Truesdell, 1970) Use of these chemical indicators, however, is based on a number of assumption (White, 1970):

1. Temperature-dependent reactions, with adequate supply of constituents in the local reservoir rocks,

2. Water-rock equilibration with specific mineral assemblages at high reservoir temperatures,

3. Rapid flow of water from reservoir to surface springs,

4. Negligible reaction in transit at lower temperatures,

5. Absence of dilution or mixing with other waters at intermediate levels.

White (1970) emphasizes that "depending on discrepancies that may exist between these assumptions and the actual conditions within a system, the indicated temperatures may be only slightly in error (generally indicating a minimum) or grossly incorrect, either high or low."

Two hot springs in the Dieng Mountains (Pulosari and Kawah Sileri) are considered on the basis of their appreciable chloride content to indicate the presence of deep geothermal water (p. 7). However, both these springs probably have been greatly diluted by meteoric water, and accordingly the chemical indices of subsurface temperature are of uncertain, but probably low, reliability.

Only Pulosari spring is suitable for SiO_2 geothermometry (Truesdell, 1971, p. 8-9). Using the measured silica content of 177 ppm (analysis 22, Table 2 of Truesdell, 1971), assuming cooling of deep water to 93°C by steam separation, and further assuming mixing with 15°C surface water containing 15 ppm SiO_2 to a final temperature of 55°C, Truesdell (1971, p. 8-9) infers a subsurface temperature of 203°C, using the experimental silica solubility data of Fournier and Rowe (1966).

The use of alkali ratios to estimate the underground temperature of the Dieng geothermal system is even less satisfactory. Comparison of Na/K ratios of Dieng waters with published curves (e.g., White, 1970, fig. 3) gives temperatures that are unrealistically and unreasonably high (>450°C). The failure of this index is due to the presence of abundant Ca in the waters. Curves that relate various functions of Ca, Na, and K to temperature are currently being developed by R. O. Fournier and A. H. Truesdell. Comparison of the Dieng data with these preliminary curves suggests that underground temperatures are in the vicinity of 200°C.

Given the extensive dilution of the deep geothermal fluid and the large number of assumptions upon which the calculations are based, one must view these temperature estimates with considerable skepticism. Temperatures are certainly elevated at depth, probably in excess of 200°C, but a reliable estimation will have to await better samples of the deep fluid, hopefully to be obtained in the 200-meter drilling proposed in this report.

Truesdell (1971, p. 10) concludes from the low Cl values and the only slightly acid pH values of condensates from the Dieng Mountains fumaroles that the hot water at depth is not acid, and should, therefore, present no corrosion problems during drilling or exploitation. He also concludes (p. 11) that attack by H_2S of electrical contacts should be minimal.

Pollution by boron in the geothermal effluent is considered briefly by Truesdell (1971, p. 11). He expects few problems from the 4-17 mg/l boron content of the waters because considerable dilution by rain water and ground water of low salinity will occur.

Geologic Interpretation

Aerial photographs were made in August, 1970 by Geotronics Surveys under contract AID-477-25-T from USAID. Approximately 125 km^2 over the Dieng Mountains was flown at 1:20,000, and an area of 3,500 km^2 extending from Gunung Slamet east to the Dieng Mountains and thence southeast to Gunung Sumbing was flown at 1:35,000. The photography is of superb quality, and the contractor should be commended for doing an excellent job.

Based on these photographs, a photogeologic map at 1:25,000 was prepared by GSI (Pardyanto, 1970). Geologic features of particular significance shown on the map are (a) the numerous young flows that radiate from the volcanoes around Gunung Pakuwadja, (b) the major phreatic explosion craters, (c) a zone of volcanic lineaments[*/] extending northwest from Gunung Butak to Pagerkandang crater, (d) conspicuous east-west structural lineaments south of Batur, and (e) N.10 W. structural lineaments in the vicinity of the Dieng-Batur road between Batur and Gunung Nagasari.

The 1:50,000 geologic map accompanying the thesis of Gunawan (1968, Plate II) is the most detailed geologic map seen to date[‡/]. Although there appears to be no map legend, the units on the map can be correlated with the thesis text, which gives a detailed sequence of volcanic rocks, based on geomorphic criteria. The map shows in a general way the same volcanic and structural lineaments that Pardyanto (1970) presents, and in addition, the text, Plate X, and figure 2 give much detail on the N.10° W. and N.10° E. lineaments defined by the explosion craters at Timbang and Gua Djimat.

Petrologic data are contained in Gunawan's thesis (1968) and in a paper by Neumann van Padang (1936). Both writers suggest a sequence of magmatic differentiation that correlates well with the age sequence deduced from geomorphology. There are no analytical ages, and no fossil control. All of the volcanic rocks appear to be of Quaternary age (less than 3 million years). Although there have been numerous historic phreatic eruptions, only one truly volcanic (i.e., magmatic) eruption from the Dieng Mountains has been reported in historic time, that of Gunung Pakuwadja in 1826 (Gunawan, 1968, p. 89).

[*/] A volcanic lineament as used in this report is a linear array of discrete volcanic eruption points. A structural lineament is an alinement of topographic or vegetative features that reflect a fracture or fault in the earth. Both volcanic lineaments and structural lineaments are commonly interpreted to be surface expressions of deep zones of fracture or weakness in the earth.

[‡/] Regretably, Gunawan's map and thesis were not made available either to Pardyanto for use in his photogeologic evaluation, to Truesdell for use in locating fumaroles and hot springs, or to Muffler in 1970. Early access to Gunawan's work could have greatly simplified and expedited the work of all three scientists.

In summary of these three sources of geologic data, the Dieng Mountains comprise a complex of separate extrusions (lavas and pyroclastic cones) that range in composition through the Quaternary from early basalt (Gunung Prau) through olivine-bearing andesite, pyroxene andesite, hornblende andesite (Gunung Butak) to the young biotite andesites of the mountains around Gunung Pakuwadja. Laharic breccias, ash, and some lake sediments are complexly intercalated with the pyroclastic cones and lava flows. The Dieng Plateau itself is a tuff- and sediment-filled topographic depression between volcanic extrusions.

Two young volcanic lineaments are obvious: (a) a line of craters and flows trending east-west along the mountain crest east of Gunung Butak (fig. 1) and b) a zone of craters extending southeast from Pagerkandang crater to Gunung Pakuwadja and thence many miles southeast to Gunung Sundoro and Gunung Sumbing (see figure 2 of Muffler, 1970).

The geothermal systems of the Dieng Mountains are clearly related to the volcanic and structural lineaments. The resistivity data (fig. 1) show that the thermal areas of Pagerkandang and Sikidang are probably connected at depth to form a single geothermal system, here named the Dieng geothermal system. This geothermal system is coincident with the zone of volcanic lineaments that extends from Pagerkandang crater to Gunung Pakuwadja. The area of most intense surface thermal activity (in and around the Pagerkandang crater) is at the intersection of this northwest-trending zone and the east-west volcanic lineament along the crest of the mountains. The smaller and probably separate Tjandradimuka geothermal system falls on this same east-west volcanic lineament at its intersection with the N. 10°W. structural lineaments of Timbang, Gua Djimat, etc.

The association of the two geothermal systems with tectonic zones of weakness (characterized by fracturing and volcanic activity) suggests that effective permeability at depth in the geothermal systems will be due to interconnected fractures, as at The Geysers in California. There is no evidence in the Dieng Mountains for an extensive "cap-rock" overlying a clearly defined reservoir, as seems to be the case at Larderello, Italy, and in many oil fields. Tazieff, Marinelli, and Gorshkov (1966) appear to have placed excessive emphasis on the possibility that the basin-filling sediments of the Dieng Plateau could form a cap rock. Data acquired during the present investigations show that these sediments overlie only a small part of the Dieng geothermal system as defined by the resistivity low. There may well be layers of restricted permeability at depth in the Dieng Mountains, and indeed the existence of such layers may be important in determining field characteristics under exploitation. But one cannot predict the existence or location of such layers from available surface data, and thus the cap rock concept in the Dieng Mountains is of little practical use in geothermal exploration.

RECOMMENDATIONS

In view of the favorable findings from the initial investigations, it is recommended that exploratory drilling in the Dieng geothermal system be undertaken following the general procedure of step 2 of the program outlined by Muffler (1970, p. 11). Several slim core drill holes should be drilled to approximately 200 meters to determine temperature gradients, calibrate the geophysical data, and acquire fluid and rock samples. After completion of these 200-meter holes, two holes should be drilled to approximately 650 meters. The purposes of these 650-meter holes are to determine the base temperature of the geothermal system, to allow collection of fluid samples, and to allow testing of the production characteristics of the geothermal system.

It is my recommendation, and the recommendation of the other four members of the evaluation team, that the exploratory drilling program include six holes each 200 meters deep rather than the four originally suggested by Muffler (1970). The additional cost for the two extra holes should not exceed $50,000 and might be significantly less. The two additional holes are proposed to evaluate parts of the Dieng geothermal system that could not be adequately assessed by inference from only four holes.

Individual sites are shown on figure 1. Although the sites are shown as points, they are not to be interpreted as exact locations that cannot be changed by a few tens or even 100 meters. The supervising geologist or engineer should have latitude to shift precise locations to minimize logistic or engineering problems.

Individual sites, listed in order of decreasing priority are as follows, with metric coordinates referring to figure 1:

1. Within the Pagerkandang Crater (89,050 N; 37,850 E); exact location within the crater is not important. The site is suggested as a prime target by the geophysics, the geochemistry, and the geology. Access to the site will require road work, possibly including construction of a bridge over Kali Dolok. The consensus of the evaluation team and Messrs. Fowler, Sutardono, and Klepper was that upgrading of an existing broad trail up the southeast side of the crater for a distance of about 1 km would present fewest difficulties. A group of springs and seeps at the crater bottom would provide a source of drill water during the rainy season. These springs are reported to dry up during the dry season; if they do, water will be a problem.

2. A site southwest of Telaga Terus (86,500 N; 39,600 E) on the margin of the low resistivity area at Kawah Sikidang. The site indicated is at a sufficient distance from obvious, vigorous thermal activity to provide good ground for the shallow parts of the hole and to otherwise minimize likelihood of operational problems and hazards. No road construction should be necessary, although some strengthening of the bridge across Kali Tulis may be required. Water can be obtained from Kali Tulis, 100 m to the southeast.

3. This site (88,425 N; 38,600 E) on the bench just north of the village of Pawuhan is chosen to evaluate the southeastern part of the Pagerkandang 2.5 ohm-meter resistivity low at the lowest feasible drill collar elevation (2,025 m) and to see if the Pagerkandang center of thermal activity extends to the southeast at depth. Access could be via the road constructed to Pagerkandang crater. Drill water is available from Kali Dolok.

4. A site (85,300 N; 39,675 E) north of the road junction 750 m east of the village of Sekunang, is chosen to evaluate the southeastward extension of the resistivity anomaly and to see whether the geothermal reservoir is continuous at depth between Sikidang and the fumaroles at Telaga Tjebong. Access problems are minimal; the nearest water appears to be at Sekunang, a distance of about 800 meters.

5. A site (88,225 N; 37,000 E) southeast of the village of Sidolok on the Dieng-Batur road is chosen to test whether or not the low resistivity zone shown on the modified Schlumberger survey represents a deep thermal anomaly or merely near-surface outflow from Kawah Sileri. Access is no problem; water probably can be had from Kali Dolok or related irrigation canals within 200 meters of the site.

6. A site (87,625 N; 39,875 E) about 1/4 km west of Dieng Wetan and about 1/2 km south of Dieng Kulon is chosen to evaluate whether or not the geothermal anomaly extends to the northeast side of the Dieng Plateau. Access is easy, and water can be obtained from the immediately adjacent Kali Tulis.

The order of priority given is not necessarily the order in which the holes should be drilled. The Pagerkandang and Telaga Terus holes are likely to be in the hottest ground and to present greatest drilling problems. Accordingly, perhaps a hole such as Pawuhan or Sidolok should be drilled first, in order to allow the contractor to gain experience in local conditions and in the problems of geothermal drilling.

There should be sufficient latitude in the drilling contract for the supervising geologist or engineer to terminate a hole at depths shallower than 200 m or to drill onward for several tens of meters beyond 200 m should conditions warrant. There is nothing magic about the 200 m number; it was chosen as a figure which on the average should be deep enough to allow acquisition of information needed to more fully evaluate the geothermal system.

Drilling at Tjandradimuka is not recommended at present for four reasons:

1. The small size of the resistivity anomaly.

2. Difficult access.

3. History of violent phreatic eruptions at Timbang to the southwest and Gua Djimat to the southeast.

4. Presence of toxic gases at Timbang and Gua Djimat.

Sites for the 650-m holes should not be selected until most of the data from the 200-m holes are available. (This was Muffler's 1970 intent, although his report is not explicit in this respect.) The 650-m holes should be sited principally on the basis of thermal gradients determined from the 200-m holes, keeping in mind that the primary object of the 650-m holes is to determine the base temperature of the geothermal system.

It is obviously inappropriate to site any development holes until both the 200-meter and 650-meter exploratory holes are drilled and the results (including geochemical sampling and analysis of fluids) are available.

OBJECTIVES AND REQUIREMENTS OF DRILLING

Drilling should be conducted so as to achieve the objectives outlined on p. 11 of Muffler's report (1970). The 200-meter holes should be designed to:

a. Determine temperatures and temperature gradients,
b. Allow collection of water and gases from the holes after completion of drilling
c. Sample the rocks drilled
d. Test the geophysical, geochemical, and geological indicators.

An accurate determination of the temperature gradient from 100 to 200 meters is important. Recent USGS research drilling in Yellowstone National Park, Wyoming, USA, has shown that the only accurate method of determining pre-drilling ground temperatures in geothermal areas is to drill for no longer than eight hours, let the hole stand for 15 hours, and then take a bottom-hole temperature[*/]. Accordingly, at depths of 100 to 200 meters, drilling should progress at no more than 33 meters per day, so that four or more

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[*/] In the Yellowstone drilling, it was feasible to leave the rods in the drill hole overnight and take the bottomhole temperature through the rods and the drill bit. In caving ground, it may not be possible to leave the rods in the hole overnight without danger of them becoming stuck. If drill mud is used, it may prove impossible to lower a temperature probe to the hole bottom through the mud after it has settled for 15 hours. If so, it may be necessary to lower the probe just after the end of the drilling shift, and leave the probe at hole bottom overnight.

meaningful temperatures can be determined from 100 to 200 meters depth*/. Effort should also be made to determine bottomhole temperatures at depths less than 100 meters whenever feasible.

Samples of water and gases should be collected from the holes after completion of drilling and recovery of the hole from drill-water loss. If the hole shows a tendency to cave, slotted liner should be hung in the hole, so that there will be continuing access to all depths of the hole for fluid sampling. The minimum internal diameter of the liner should be at least 2-1/4 inches (5.72 cm) to allow 2-inch O.D. sampling devices to be lowered. Accordingly, holes should be drilled at a diameter sufficient to allow slotted liner of at least 2-1/4 inches I.D. to be inserted.

It would be ideal to have the holes cored throughout their total depth below 20 meters or so, but this may not be financially feasible. Some core, at least every 30 meters, is essential, however, to permit laboratory determinations of physical properties such as porosity, density, conductivity, etc. This obviously will require a diamond drill rig with coring capability. Assuming that the rig is equipped for wire-line recovery of core, it may not cost appreciably more to core continuously than to core only intermittantly. These alternatives should be explored with possible contractors.

There are two possible programs for interrelating the 200-meter and the 650-meter holes:

1. Drill the 200-meter holes at a diameter sufficiently great to allow a string of casing to be cemented in at 200-250 meters, retaining sufficient diameter within this casing to allow drilling to proceed safely and successfully to 650 meters.

2. Drill the 200-meter holes at small diameters, and drill completely new 650-meter holes after thorough evaluation of best diameters and casing program.

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*/ There are a number of ways of measuring temperatures at depth. Thermisters, thermocouples, resistance thermometers and other electrical devices are accurate and efficient <u>when they work</u>, but in a number of geothermal drilling projects (e.g., Yellowstone and Nicaragua) they have shown a distressing tendency to fail, owing to shorting of the cable or to breakdown of the potting compound under the high-temperature conditions and in the presence of an electrically conducting fluid. Maximum-recording thermometers (mercury in glass) do not have this potential for electrical failure, but care must be taken to insulate the thermometer when temperature reversals are suspected. If temperatures at depth in the Dieng Mountains are determined using electrical methods, great care must be taken to insure that the gear is reliable and will not fail; the Dieng Mountains are a long, long way from the nearest point where electronic gear can be repaired or replaced. At the very least, several maximum-reading thermometers (with insulating cases and tight restrictions so that the mercury column is not easily shaken down during withdrawal) should be on hand to back up the electrical gear in case of failure.

A choice between these alternatives requires cost and drilling equipment data not available to me, and should be made after preliminary consultation with prospective drilling contractors and after evaluation of the USAID-assisted 2,000-foot drilling program in Nicaragua.

The drilling and casing program should be designed to preclude any uncontrolled eruptions of steam and water, particularly any eruptions around (outside) the casing*/. Based on the nature of the surface activity in the Dieng area, it is anticipated that the geothermal water level will be at considerable depth, perhaps as much as 200 meters. If this is the case, pressures are unlikely to be high until that depth, and even at considerably greater depths pressures should be largely counter-balanced and controlled by the weight of water standing in the hole. However, at most depths there is some potential for a surprise eruption, and accordingly casing should be cemented in the hole so that any eruption will occur through the casing†/. If there is any indication of pressure, an appropriate valve and stuffing box should be mounted on the casing, and drilling should be done through the valve and stuffing box. If wireline is used, provision should be made to withdraw the core under positive pressure within the drill string.

With regard to appropriate drilling operations and casing program, it is important that the level of water standing in the hole be noted and recorded each day. Gradual rise of water level on successive days can give warning of increasing pressure and potential drilling or casing problems. Water level measurements are also very important scientific data essential to the interpretation and evaluation of the geothermal system.

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*/The "wild bores" at The Geysers, California and at Wairakei, New Zealand are apparently both due to insufficient depth of casing, with high-pressure steam coming up the open hole to the foot of the casing and then out into the formation to the surface.

†/It is not possible to give positive guidelines for casing depths and number of strings. In the USGS Yellowstone drilling, where the thermal water table was at the ground surface, and appreciable pressures over hydrostatic developed as drilling progressed, one string of 4-1/2 x 5-1/2 inch casing was generally set and cemented at 20 feet, and a second string of smaller diameter near 100 feet. A third string was set and cemented at about 500 feet if much greater depth and higher temperatures were anticipated. If the geothermal water table in the Dieng Mountains is near the predicted elevation (1875 m., Truesdell, 1971), the casing program need not be so thorough as at Yellowstone. Casing programs for developmental geothermal wells are discussed by Giovannoni (1970) and by Dench (1970), but their discussions related to deep (1,000-2,300 meter) production holes that require far more casing of far larger diameter than that needed for the 200-m exploratory holes in the Dieng Mountains.

VOLCANIC, EARTHQUAKE, AND LANDSLIDE HAZARDS

A geothermal system requires a potent heat source at depth. Although such a heat source has never been drilled or sampled, various lines of geologic reasoning point to the presence of a hot body of intrusive rock at depths of 3 km or greater. Meteoric water circulates to these depths, acquires heat from the hot body of rock, and buoyantly rises to the surface in the upwelling core of the geothermal system.

In most explored geothermal areas, igneous activity is not only inferred from the existence of the geothermal system, but is directly expressed at the earth's surface by Quaternary volcanic rocks. These rocks represent masses of molten rock (magma) that made their way to the surface rather than cooling and solidifying at depth. A number of geothermal areas are located in regions where there has been historic volcanic activity. For example, the Wairakei geothermal field in New Zealand is located only 10 km north of Lake Taupo, the locus of the 131 A.D. Taupo Pumice eruption, perhaps the world's largest volcanic eruption of the past 2,500 years. The Kawerau geothermal field in New Zealand is located 25 km northeast of Mt. Tarawera, which last erupted in 1886.

The Dieng geothermal system is also located in an area of very young and probably continuing volcanism. Although there are no radiometric dates in the region, the physiography of mountains such as Gunung Pakuwadja, Gunung Kendil, and Gunung Sundoro and of craters such as Pagerkandang, Dringo, Merdada, and Pangonen indicates that volcanic activity in the Dieng Mountains has persisted until very recent times. Indeed, Gunung Pakuwadja is reported to have erupted in 1826, although the precise nature of the eruption is not clear from the scanty reports (Gunawan, 1968).

Although there have been no true volcanic eruptions (i.e., those that involved eruption of molten rock) in the Dieng Mountains since 1826, there have been several phreatic eruptions or hydrothermal explosions*/; these have been described in detail by Gunawan (1968, p. 90-103), and are summarized in table 1 of this report.

It is apparent from table 1 that violent phreatic eruptions or hydrothermal explosions have occurred in recent years at Kawah Sileri, and that similar eruptions can be expected in the future. Accordingly, drilling at Kawah Sileri itself should be avoided, and any buildings or generating facilities

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*/ Phreatic eruptions and hydrothermal explosions are commonly confused. A phreatic eruption <u>sensu strictu</u> occurs when magma contacts ground water, vaporizing it to steam with consequent explosive expansion producing a crater. A hydrothermal explosion is produced when water contained in near-surface rocks at temperatures up to perhaps 250°C flashes into steam and violently disrupts the confining rocks; no magma is directly involved. It is not always possible to determine whether a given eruption is a phreatic eruption or a hydrothermal explosion, particularly when observational data are scanty or uncritical. Both types of activity seem to have taken place in the Dieng Mountains.

Table 1.--Historic phreatic eruptions and hydrothermal explosions in the Dieng Mountains (from Gunawan, 1968, p. 90-103).

Date	Location	Comments
1786(?)	Tjandradimuka (?) Gua Djimat (?)	No descriptions until 1826; associated earthquakes and landslides; Telega Sewiwi formed by landslide.
May 13, 1928	Timbang	3 craters (maximum size 60 x by 40 m); mud flow partly destroyed village; rocks thrown 750 m west; 1 death; toxic gas ($CO_2 + Cl_2$) expelled for many years after.
Oct. 13, 1939	Timbang	15 craters along N. 10° W. and N. 10° E. lines; maximum crater size 170 x 60 m. Associated mud flows; village of Timbang destroyed; 10 persons missing; associated earthquakes.
Dec. 4, 1944	Kawah Sileri	Villages of Kepakisan, Sekulan, Sidolok, Pagerkandang, Guadjahmungkur, and Kepakisan-Lor covered with fine debris (to depth of 1.5 to 2.0 meters in Guajahmungkur); blocks thrown 1 km; 59 deaths; 55 people missing, no associated earthquakes.
April 12, 1945	Kawah Tjandradimuka	Minor; change in fumarolic activity.
Dec. 6, 1954	?	Cloud 50 m high.
June 2, 1956	Kawah Sileri	Cloud 150 m high.
Dec. 13, 1964	Kawah Sileri	Mud and fine debris to estimated 500 m height for 2 to 3 minutes.

should be located away from Kawah Sileri, probably near Dieng Wetan. Any eruptions from Kawah Sileri are likely to be accompanied by some earthquake activity, of uncertain but probably rather low intensity. Planning for any plant construction should take into account this potential local seismicity, as well as any regional seismicity.

The last truly volcanic eruption in the Dieng Mountains took place at Gunung Pakuwadja in 1826(?). One cannot assume that volcanic activity has ceased, yet there is no way to predict if, when, and where, another volcanic eruption will occur. If a volcanic eruption should occur, one might expect its locus to be near Gunung Pakuwadja.

Landslides have been very common through historic time in the Dieng Mountains, and the village of Legetang was buried in 1955 by a landslide from Gunung Pengamun-amun (Gunawan, 1968, p. 63). Telaga Sewiwi (northwest of Karantengah) apparently was formed by a landslide in 1786 that may have been triggered by the phreatic eruptions at Tjandradimuka and Timbang. Landslides clearly present a hazard that must be considered in any generating plant location.

ORGANIZATION OF EXPLORATORY PROGRAM

To date there has been no specific organizational structure for the initial investigations of the Dieng Mountains, and no single operational and coordinating focus such as a project manager. This pattern, though generally satisfactory, has resulted in intermittent confusion and misunderstanding among the various institutions, contractors, and individuals involved as to their specific responsibilities and time schedules. There have been no major problems, however, and the Initial Investigations have been completed satisfactorily, in great part due to good will and sense of cooperation exhibited by all. In particular, the expediting efforts of Dr. Johannas of the GSI, Dr. Arismunandar of the PRI, Dr. Klepper of the USGS, and Mr. Kent and Mr. Fowler of USAID have been invaluable.

The evaluation team, however, unanimously feels that a formal, recognized project organization, probably headed by a project manager with clearly defined responsibility and authority, is essential for the exploratory drilling and any subsequent steps. The anticipated increase in cost, personnel and complexity greatly increases the potential for serious misunderstandings, lack of coordination, and omissions. In particular, long and short-range planning and timing of contracts, advisory personnel, and supporting services is essential.

It is beyond the scope of this report to suggest any specific organizational structure. However, attention should be drawn to the organization of the state-run geothermal enterprises in New Zealand, Italy, and Japan.

SUPPORTING GEOLOGICAL AND GEOPHYSICAL INVESTIGATIONS

Although not required for assessment of the geothermal resources of the Dieng Mountains, several lines of scientific investigation could well provide data useful in planning the development of the field. It is the hope of the evaluation team that these investigations might be investigated by the cooperating institutions during the coming year so that some results would be available in the event a decision is made to proceed with development of the field.

It is recommended that regional photogeologic analysis of the 3,500 km^2 covered by the 1:35,000 aerial photographs be completed. Preliminary assessment is currently being made by W. H. Condon, USGS.

Gravity studies in the Dieng Mountains may prove useful in determining the thickness of the inter-volcano sediments in the Dieng-Sikidang area and in the flat lands surrounding Batur. An initial gravity survey is currently being conducted along the Dieng-Batur road by the GSI. If the results of this survey are favorable, if may be appropriate to extend the survey throughout the Dieng Mountains.

It is also recommended that a microseismic monitoring system be installed in the Dieng Mountains. Such a monitoring system would serve three purposes:

1. To locate earthquake epicenter concentrations that may indicate deep geothermal targets (cf. Ward and Björnsson, 1971; Ward, Palmason, and Drake, 1969; Lange and Westphal, 1969).

2. To detect any increase in frequency of microearthquakes or change in location of epicenters, in order to anticipate possible volcanic (including phreatic) eruption.

3. If development of the geothermal field proceeds, to monitor any increase in number of microseismic events related to large-scale fluid withdrawal (Healy, Rubey, Griggs, and Raleigh, 1968).

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