添付資料

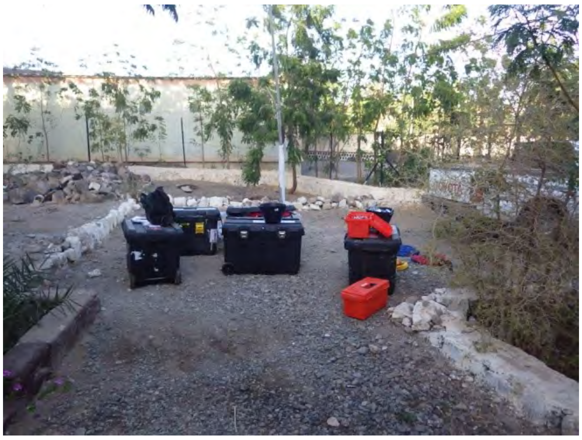
添付資料-1　　収集資料リスト

添付資料-1　収集資料リスト

No	資料名	著者	発行年
1	Projet pour l’evaluation des ressources geothermiques	Aquater	1981
2	Ressources geothermiques etudes effectuees par Aquater 1980 - 1982	Aquater	1982
3	Interpretation of gradient wells data – Hanle plain	Geotermica	1985
4	Geothermal exploration project Hanle-Gaggade republic of Djibouti – Hanle 1 report	Aquater	1987
5	Geothermal exploration project Hanle-Gaggade republic of Djibouti – Hanle 2 report	Aquater	1987
6	Carte geologique de la republique de Djibouti a 1:100,000 - Dikhil	ORSTOM	1987
7	Djibouti geothermal exploration project republic of Djibouti – draft final report	Aquater	1989
8	Data collection survey on geothermal development in the republic of Djibouti	JICA	2014
9	Decree 2011-029/PR/MHUEAT: procédure d’étude d’impact environnemental	Le president de la republique de Djibouti	2011
10	Projet d’évaluation des ressources géothermiques – Etude -Cadre d’Impact Environnemental et Social (ECIES) -	The World Bank/ FICHTNER	2012

添付資料-2　　写真集

添付資料-2　写真集

 ODDEG head office	 Inception meeting at ODDEG head office
 Survey team Office in ODDEG headoffice	 Outside view of ODDEG new head office (under construction)
 Inside of ODDEG new head office	 MT/TEM survey: luggage for MT/TEM survey

MT/TEM survey: unboxing/ preparation of survey equipment

MT/TEM survey: non-polarized electrode

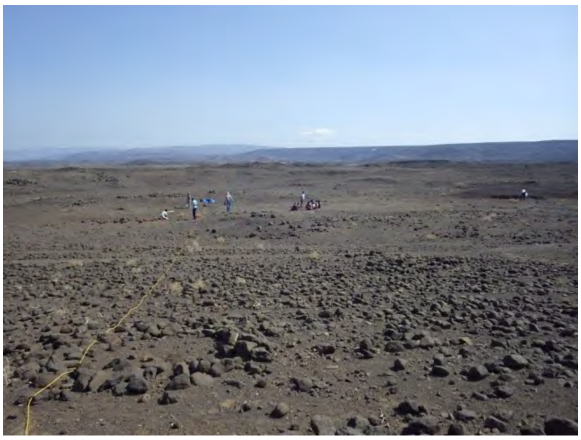

Access road to the site

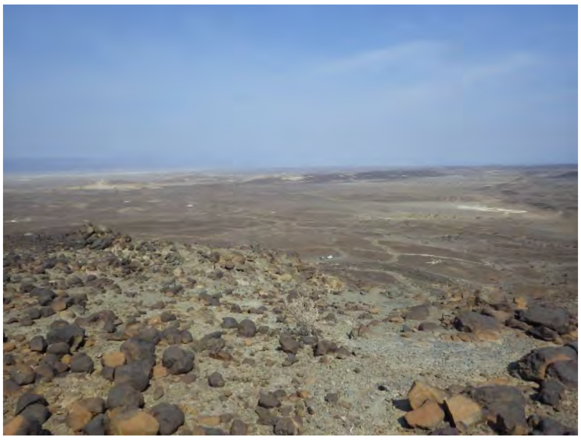

MT/TEM survey: mobilization of survey equipment at the site

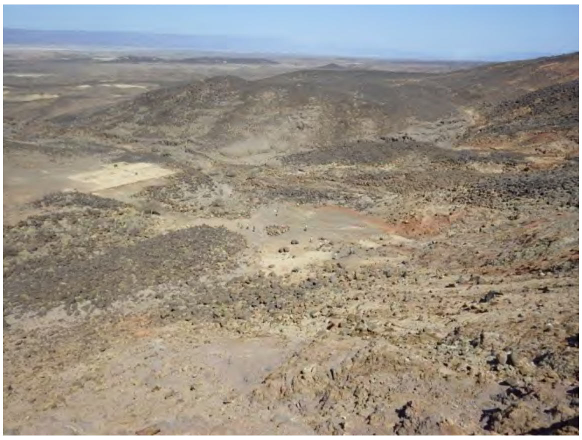

MT/TEM survey: preparation of survey equipment at the site


MT/TEM survey: preparation of survey equipment at the site (batteries and data loggers)

 MT/TEM Survey: preparation of induction coils	 MT/TEM survey: induction coils by Phoenix
 MT/TEM survey: unloading of loop coil for TEM Survey	 MT/TEM survey: setting of horizontal induction coil
 MT/TEM survey: setting of horizontal induction coil	 MT/TEM survey: setting of vertical induction coils

	
MT/TEM survey: preparation for setting of non-polarized electrode	MT/TEM survey: setting of non-polarized electrode
	
MT/TEM survey: arranging of survey equipment	MT/TEM survey: site measurement (data logger was covered by vinyl seat)
	
MT/TEM Survey: site measurement at the point (Center)	MT/TEM survey: data logging and analysis at the survey site

 MT/TEM survey: a set of survey equipment and members	 Overview of survey site: ground covered by basaltic boulders
 Overview of survey site: basaltic breccias	 Overview of survey site: hilly slope
 Overview of survey site: Some part of the surface is covered by basaltic rock.	 Overview of Hanle Plain from survey site

 Alluvial deposit in Hanle Plain	 Overview of Garabbayis fumaroles and well pad
 Closer view of drilling pad with existing borehole (Garabbayis-2)	 Fumaroles with alteration zone in Garabbayis
 Ground temperature measurement at Garabbayis fumaroles	 Gas sampling at Garabbayis fumaroles


Fumaroles at the north of survey area (center)


Altered clay at the fumarole point


Altered basalt at the Site


Altered rock at the Site: calcite vain are common


Existing test well in Garabbayis (Garabbayis-2)


Existing test well in Hanle

Plants at the site

Animals at the site

Outside view of the hotel in Dikhil (nearest accommodation from the site)

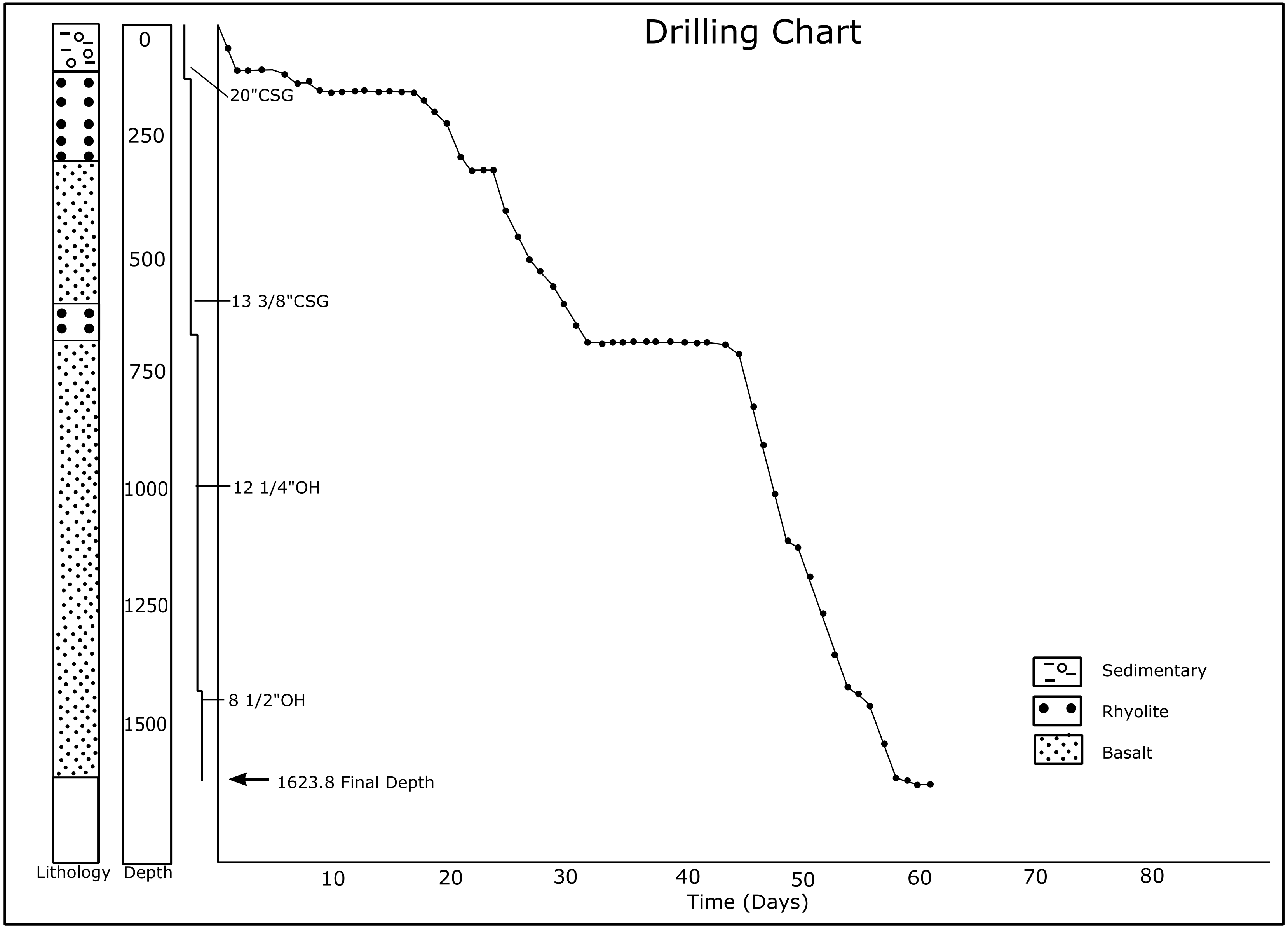
Meals at the hotel

Flash flood by heavy rain (on 5th May 2015)

Hanle Plain flooded by heavy rain (on 5th May 2015)

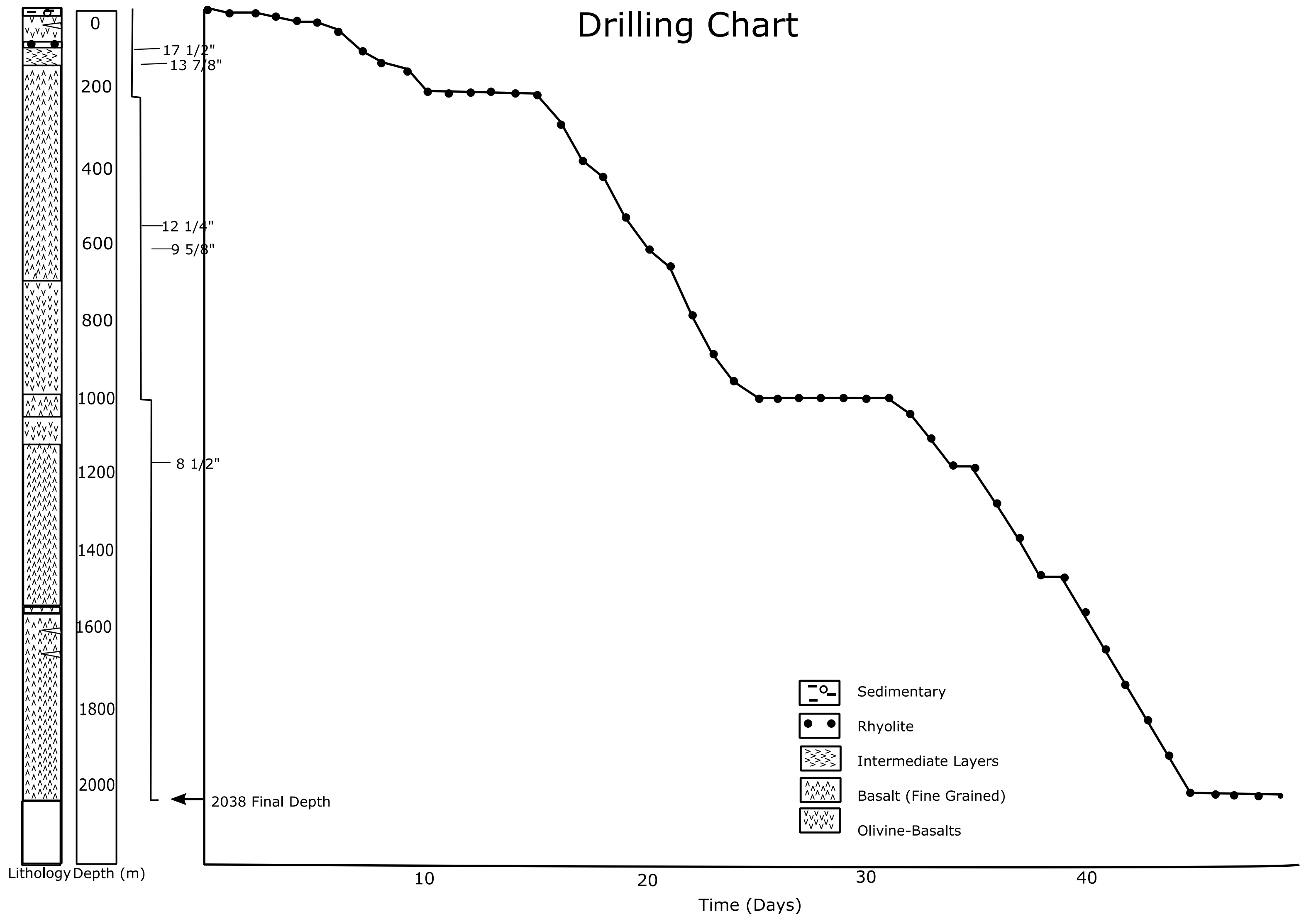
添付資料-3　　既存調査井データ

添付資料-3　既存調査井データ



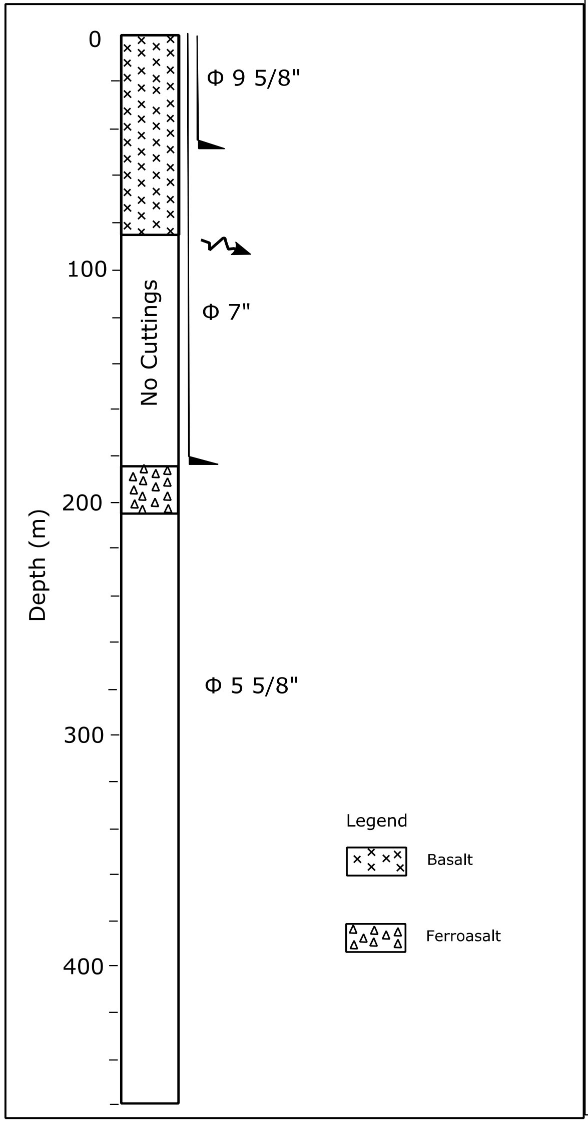
Aquate r (1987a)

Hanle-1



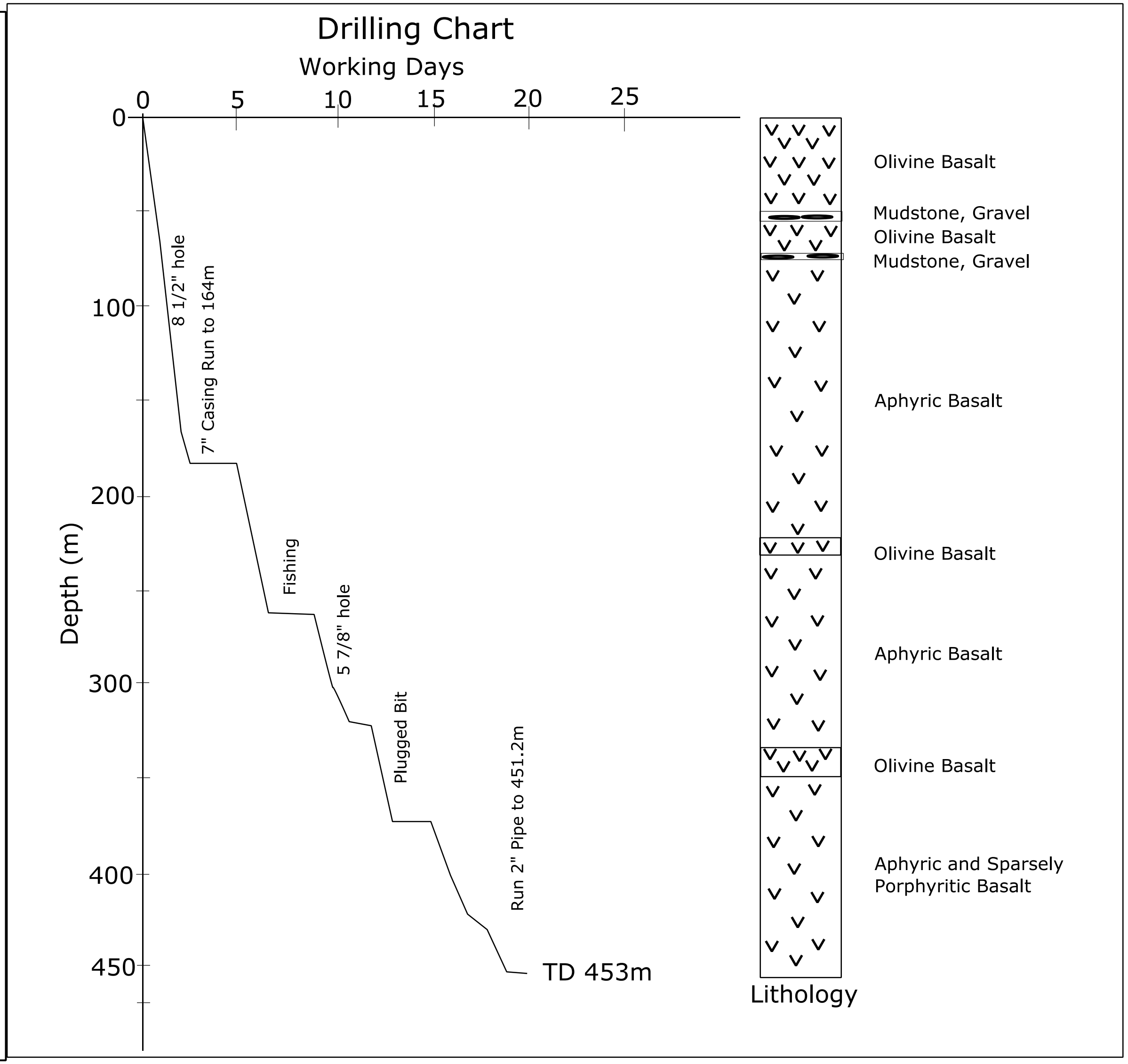
Aquate r (1987b)

Hanle-2



Aquater (1982)

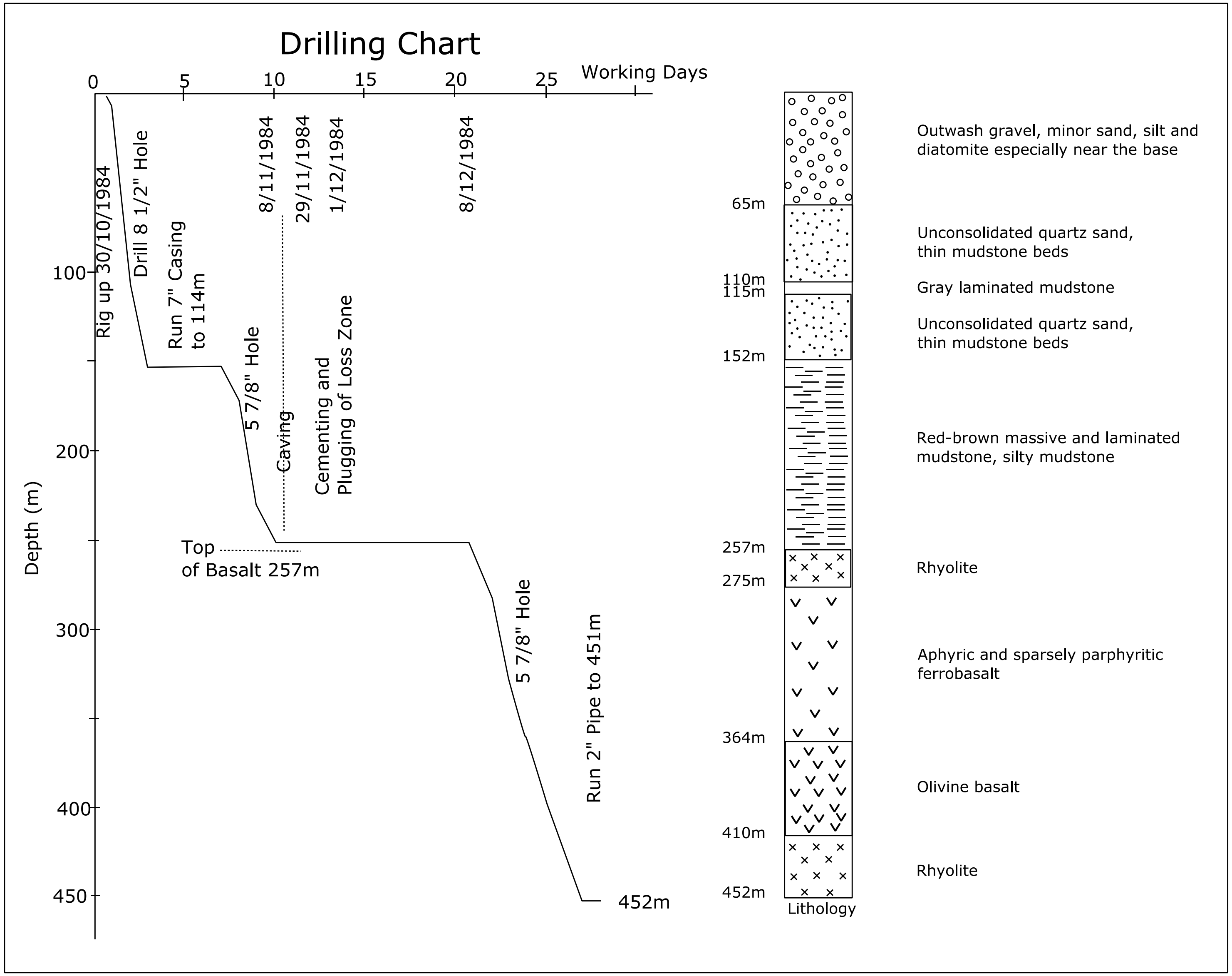
Garabbayis-1



Geotermica (1985)

Garabbayis-2

日本工営株式会社
住鉱資源開発株式会社
地熱エンジニアリング株式会社
国際協力機構



Geotermica (1985)

Teweo-1

添付資料-4　　物理探査

添付資料-4　物理探査

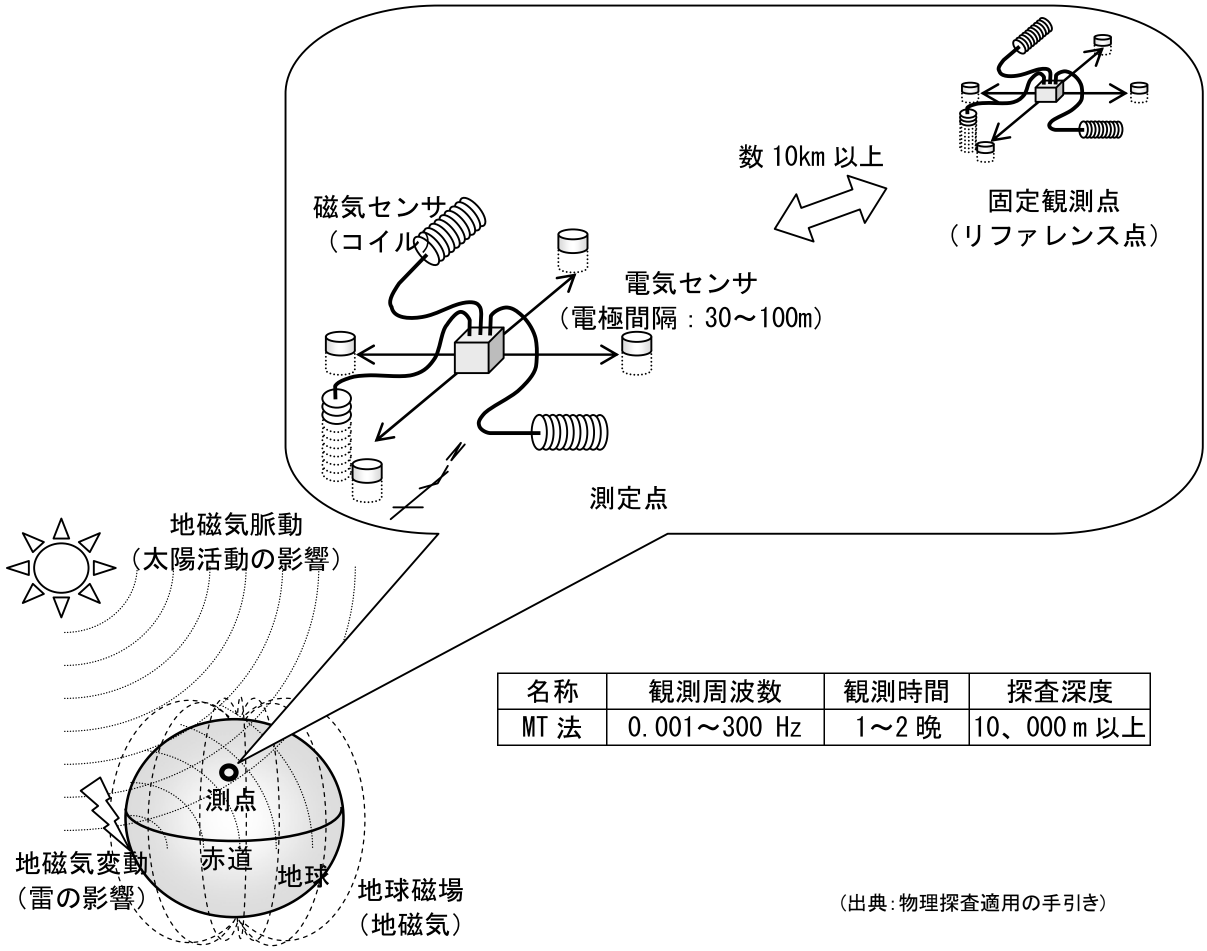
4.1　調査方法

4.1.1　**MT** 法探査

(1)　探査原理

MT(Magneto-Telluric)法は、磁気センサと電気センサで自然の地磁気と地電流を観測して地下深部の地下構造を探査する電磁探査法である。MT 法は深さ 10,000 m 以上の探査が可能である。

MT 法は地磁気-地電流法ともよばれ、地球の磁場(地磁気)の変化によって地中に生じる地電流を用いる探査法である(下図)。地磁気の変化は自然に生じているもので、太陽の活動に関連する 1 Hz 以下の地磁気脈動と、遠方の雷によって生じる 1Hz 以上の地磁気変動が原因と考えられている。MT 法では 0.001～1000 Hz 程度の周波数帯での観測を行う。ノイズレベルの低い夜間に 1 晩かけて観測を行うことが一般的である。調査範囲から 50 km 以上離れた場所の固定観測点(リファレンス点)の観測結果を用いて、測点周辺のノイズを除去する方法をリモートリファレンス方式とよぶ。



名称	観測周波数	観測時間	探査深度
MT 法	0.001～300 Hz	1～2 晩	10、000ｍ以上

（出典:物理探査適用の手引き）

MT 法の測定原理・測定模式図

電磁波が大地に入射し地下深部に浸透していくと、電磁波のエネルギーは減衰する．MT 法では、エネルギー強度が地表の 1/e（約 0.37 倍）になる表皮深度（m）を探査深度の目安とする．表皮深度 δ は大地の比抵抗 ρ （Ω・m）と電磁波の周波数 f（Hz）に依存し、次式によって表される。

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \cong 503 \sqrt{\frac{\rho}{f}}$$

ここで、μ は透磁率

上式より電磁場の周波数が低いほど、大地の比抵抗が高いほど MT 法の探査深度は大きくなることがわかる．300～0.001Hz 程度の周波数帯域を測定する MT 法では、大地の比抵抗が 10Ω・m であれば表皮深度は約 92m～約 50km となる。MT 法の探査深度は表皮深度の 2-1/2（≒0.707）倍程度といわれている。

MT 法は太陽活動の影響を受けた地磁気脈動とよばれる低い周波数帯の地磁気や地電流の変動を観測するため、人工ノイズが減少する夜間に少なくとも 1 晩以上の観測を行わなければならない。しかしながら、MT 法でも地磁気や地電流の変動は小さくノイズと識別が難しいので、図 3.2.1 に示したように、調査地から離れたノイズの少ない場所に固定観測点を設けて同時観測を行い、固定観測点での観測データと相関のある変動を信号とみなすことでノイズの影響を低減させる。この測定法をリモートリファレンス法、固定観測点を固定リファレンス点とよぶ。

MT 法を含めた電磁探査や電気探査で得られる電気的物性は比抵抗である。比抵抗は、単位断面を通る電流の単位長さあたりの電気抵抗である。層状の地層や大きな亀裂をもつ岩石では測定する方向によって比抵抗が異なる、すなわち異方性を示す。MT 法以外の電磁探査や電気探査は方向性を考慮した探査を行うことができないが、MT 法では方向性を考慮した探査を行うことができる。例えば大きな断層周辺で行う場合、断層に沿う方向の比抵抗を TE モード、直交する方向の比抵抗を TM モードとよぶ。

MT 法は、一般に南北方向（x 方向）の磁場 Hx と電場 Ex、東西方向（y 方向）の磁場 Hy と電場 Ey を観測する。磁場や電場の記号が太字となっているのは、複素数であることを意味している。磁場と電場の関係は、下式のようにインピーダンステンソル Z を定義して表すことができる。

$$\begin{pmatrix} \mathbf{E}_x \\ \mathbf{E}_y \end{pmatrix} = \mathbf{Z}\begin{pmatrix} \mathbf{H}_x \\ \mathbf{H}_y \end{pmatrix} = \begin{pmatrix} \mathbf{Z}_{xx} & \mathbf{Z}_{xy} \\ \mathbf{Z}_{yx} & \mathbf{Z}_{yy} \end{pmatrix}\begin{pmatrix} \mathbf{H}_x \\ \mathbf{H}_y \end{pmatrix}$$

比抵抗は互いに直交するインピーダンステンソル成分 Zxy、 Zyx に関連する。すなわち、MT 法では互いに直交する 2 方向の比抵抗が求まる。x 方向を南北方向から回転させると、インピーダンステンソル Z の各成分の数値が変化する。これは南北方向および東西方向の観測から求めたインピーダンステンソル Z を使って、任意の方向の比抵抗を求めることができることを意味している。

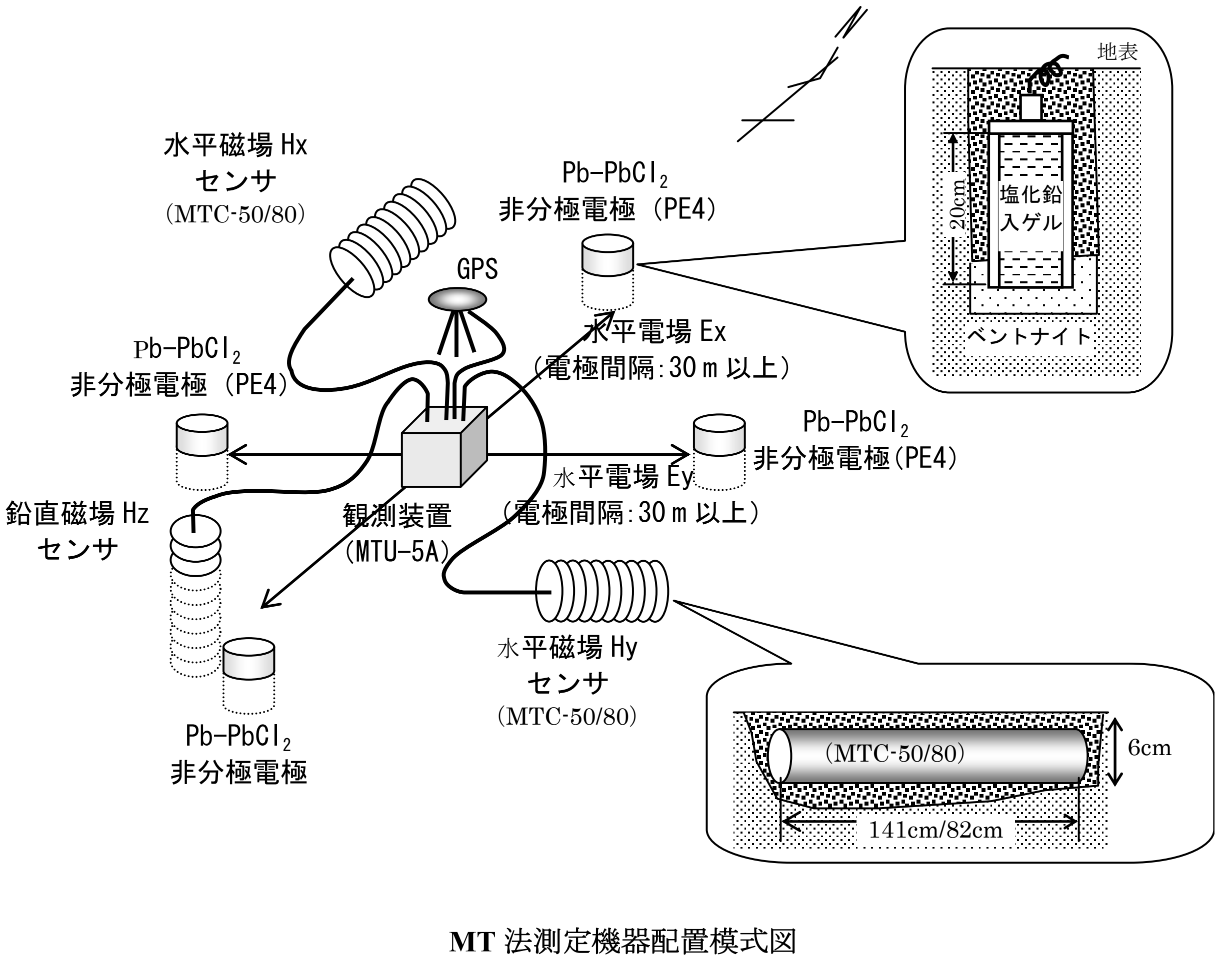
(2) 測定方法

本プロジェクトで行った MT 法の測定模式図を次ページの図に示す。測定には Phoenix 社製 MTU-5A システム（MT 法および AMT 法対応）を使用し、各測点で電場 2 成分、磁場 3 成分の時間変化を時系列データとして観測した。

電場の測定には、Phoenix 社製非分極性電位電極 PE4（鉛－塩化鉛電極）を使用し、測点の状況に応じて 50～100m 離した 2 個の電位電極を電線で結んだ電場ダイポールを用いた。電場ダイポールの方向は、磁北を基準とする南北および東西方向とした。電位電極は深さ 30cm 程度の穴底にベントナイトと水を入れて設置し、接地抵抗の低減に努めた。

磁場の測定には Phoenix 社製インダクションコイル MTC-50 および MTC-80 を使用し、南北および東西方向（磁北基準）の水平磁場に加えて、鉛直磁場を測定した。

本調査では、調査地域から 30km 以上離れた固定リファレス点を設置し、各測点では夜間に 14 時間以上、リファレンス点と同時測定を行い、昼間に撤収して次の測点に移動して準備を行った。なお、各探査対象地域での測定を開始する前には、磁気センサの動作と係数を確認するキャリブレーション測定を行った。



MT 法測定機器配置模式図

(3) データ処理方法

観測装置で取得した磁場 3 成分、電場 2 成分時系列データは、測定終了後すぐに現地でノートパソコンに転送した。各成分の時系列データはフーリエ変換を用いたスペクトル解析を行って各成分の周波数 f (Hz) 毎のスペクトルを求めた。スペクトル解析で求めた水平磁場成分 Hx(f)、Hy(f) および電場成分 Ex(f)、Ey(f)のスペクトル比が、周波数ごとのインピーダンステンソル Z(f)の各

成分となる。インピーダンステンソル Z(f)から次式を使って互い直交する 2 方向の比抵抗 ρxy(f)、ρyx(f)と位相差Δφxy(f)、Δφyx(f) を求めた。

$$\rho_{xy}(f)=\frac{1}{2\pi f\mu}\left|\mathbf{Z}_{xy}(f)\right|=\frac{1}{5f}\frac{\left|\mathbf{E}_x(f)\right|}{\left|\mathbf{H}_y(f)\right|},\quad \Delta\phi_{xy}(f)=\phi\{\mathbf{H}_y(f)\}-\phi\{\mathbf{E}_x(f)\}$$

$$\rho_{yx}(f)=\frac{1}{2\pi f\mu}\left|\mathbf{Z}_{yx}(f)\right|=\frac{1}{5f}\frac{\left|\mathbf{E}_y(f)\right|}{\left|\mathbf{H}_x(f)\right|},\quad \Delta\phi_{xy}(f)=\phi\{\mathbf{H}_y(f)\}-\phi\{\mathbf{E}_x(f)\}$$

ここで

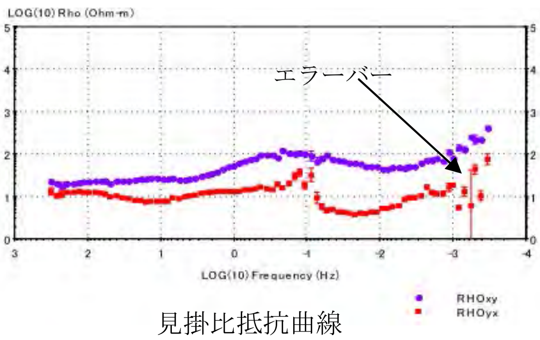
f: 周波数（Hz）、π: 円周率、μ: 透磁率

$|\mathbf{E}_x(f)|$、$|\mathbf{E}_y(f)|$: 電場強度（V/m）、$|\mathbf{H}_x(f)|$、$|\mathbf{H}_y(f)|$: 磁場強度（nT）

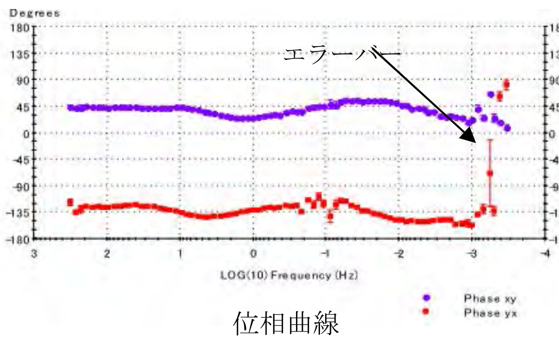
$\phi\{\mathbf{E}_x(f)\}$、$\phi\{\mathbf{E}_y(f)\}$: 電場位相（°）、$\phi\{\mathbf{H}_x(f)\}$、$\phi\{\mathbf{H}_y(f)\}$: 磁場位相（°）

求めた比抵抗ρxy(f)、ρyx(f)は大地の比抵抗が一様である場合にはその比抵抗を表すが、実際には一様ではないので近似的な比抵抗となるため、MT 法では見掛比抵抗とよぶ。位相差も、位相とよんでφxy(f)、φyx(f)と表す。下図に示すように周波数 f の常用対数を横軸にとり、縦軸に見掛比抵抗の常用対数をとった両対数グラフを見掛比抵抗曲線とよぶ。また、周波数 f の常用対数を横軸にとり、縦軸に位相をとった両対数グラフを位相曲線とよぶ。

本プロジェクトでは、測定した時系列データを 20 のセグメントに分割し、セグメント毎にデータ処理を行って見掛比抵抗や位相等を求めた。周波数毎に 20 個ずつのデータ処理値が求まるが、それらを統計処理し、ばらつきをエラーバーの形式で見掛比抵抗曲線や位相曲線上に表示した。一般に、見掛比抵抗曲線や位相曲線に表示されるエラーバーが小さく、滑らかな曲線となっているほどデータ品質がよい。測定点での観測データのみを用いてデータ処理を行うことをローカル処理とよぶが、本プロジェクトでは、ノートパソコンへのデータ転送後にローカル処理を行い、ノートパソコンのディスプレイ上に表示した見掛比抵抗曲線、位相曲線から観測データの品質チェックを行った。



見掛比抵抗曲線

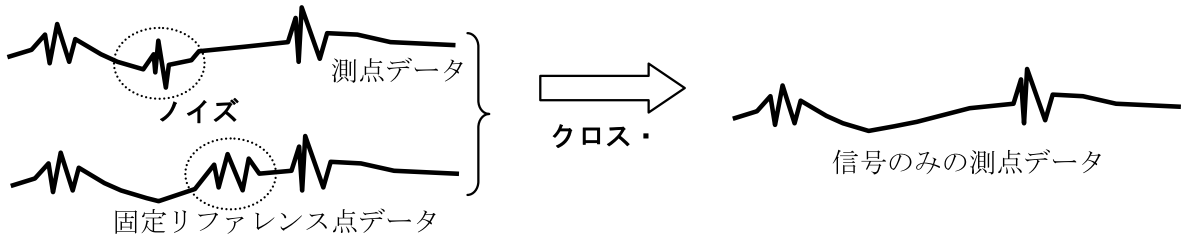


位相曲線

見掛比抵抗曲線・位相曲線例

本調査のデータ処理では、MT 法に関しては 320Hz～0.00034Hz の範囲の 80 周波数で、それぞれインピーダンステンソル Z(f)を求めた。

現地調査終了後、固定リファレンス点の時系列データを用いてリモートリファレンス処理を行い、局所ノイズの除去を行った。リモートリファレンス処理を模式的に示すと、下図に示すようになる。測点データにも固定リファレンス点にも、信号の他に丸で囲んだような送電線、商用電線、人家、車両の通行などに関連する電磁ノイズが含まれている。測点と固定リファレンス点が十分離れていれば、信号の相関は良いのに対し、ノイズの相関は低くなるはずである。したがって、クロス・コリレーションとよばれる相互相関処理を行うと測点データではノイズが除去されて信号のみのデータとなる。



リモートリファレンス処理模式図

リモートリファレンス処理に至るまでの一連のデータ処理には Phoenix 社製 SSMT2000 を使用した。データはリファレンス処理後に測点ごとにエラーバーが小さく、滑らかな見掛比抵抗曲線や位相曲線が得られるよう、各周波数毎に S/N の高いセグメントのスペクトルを取捨選択するエディット処理を行った。エディット処理には Phoenix 社製 MT editor を使用した。

(4) 解析方法

上述のデータ処理によって得られる見掛比抵抗 ρxy(f)、ρyx(f)は周波数に対応する探査深度（表皮深度の約 0.707 倍程度）付近までの平均的な比抵抗を表しているにすぎない。見掛比抵抗曲線や位相曲線を基に地下の比抵抗分布を推定するために 2 次元解析を実施した。

解析に際しては、調査地域の大局的な走向を考慮して設定した測線の測線方向が y 方向、それに直交する方向が x 方向となるように、インピーダンステンソルを回転させ、x 方向の電場と y 方向の磁場から求められる見掛比抵抗を TE モードの見掛比抵抗（構造に平行)、y 方向の電場と x 方向の磁場から求められる見掛比抵抗を TM モードの見掛比抵抗（構造に直交）とみなし、2 次元解析の入力値として使用した。

２次元解析は、測線と直交する方向には比抵抗構造が変化せず、無限に連続するという仮定の下で、観測されたインピーダンスを最もよく説明する比抵抗モデルを自動解析によっても求めるものである。解析セルの比抵抗は断面上の全測点の見掛比抵抗から非線形最小二乗法を使って決定する。隣接する測点の見掛比抵抗および隣接する解析セルの比抵抗も考慮するため、比較的連続性のよい合理的な解析結果が得られる。

本プロジェクトでは Schlumberger 社製 WinGLink の２次元インバージョン解析ソフトウェアを使用して、２次元解析を行った。まず、各測線下の地下断面をモデル計算に用いる差分法の要素と、要素を組み合わせた比抵抗モデル用解析セルに分割する。要素や解析セルの大きさは解析対象範囲となる浅部の中央部ほど細かく、端部や深部に近づくにつれて大きくなるように分割する。

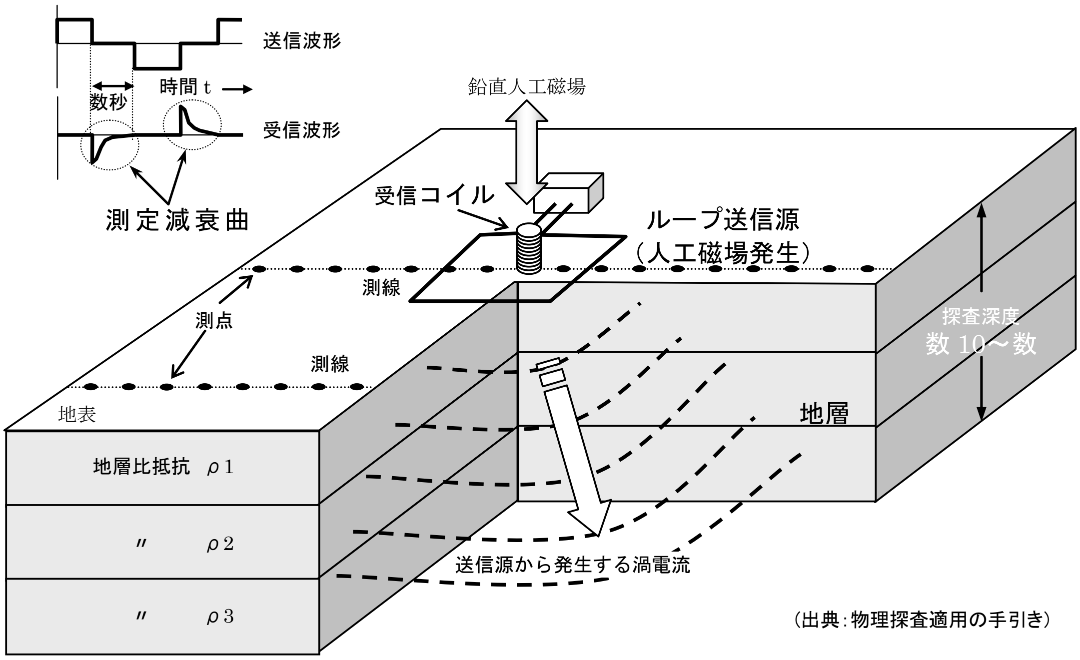
次に、初期比抵抗モデルとして 100Ω･m の均質モデルを適用し、この比抵抗モデルに誘導される電磁場を差分法で計算し、各測点の計算見掛比抵抗を求めた．この計算見掛比抵抗と該当する観測見掛比抵抗を比較し、RMS（Root Mean Square の略：平均二乗）誤差が許容値以下になるまで、比抵抗モデルの修正を繰り返す反復修正法を用いた。

4.1.2 TEM 法探査

(1) 探査原理

TEM 法は Transient Electromagnetic（過渡現象電磁）法の略称で、人工的に送信した磁場を切った時の磁場の時間変化を観測する探査法という意味である（下図参照）。

地面上を正方形（長方形や円形でも良い）に一周させた電線（送信ループ）に電流を流すと鉛直方向に人工的な磁場が発生する。電線に流した電流を切る（カットオフする）と、人工磁場を維持しようとするように地面にループ状の電流が発生する。この電流は次第に地下に深く広がっていく。この電流はその形状から渦電流とよばれ、葉巻の煙環のようなスモークリングとよばれることもある。それに応じて人工磁場は減衰していくが、比抵抗が低いほど減衰する割合が小さい。この人工磁場の減衰状況を受信用のコイルで観測して、地下の比抵抗を求める。電流切断の瞬間から早い時間帯（アーリータイム）は浅部の比抵抗を表し、遅い時間帯（レイトタイム）は深部の比抵抗を表す。



TEM 法の測定原理・測定模式図

TEM 法は、特に、探査対象が地下水、粘土層、深層風化帯、変質帯等の低比抵抗を示す（電気を通しやすい）地下構造には最も有効である。

TEM 法の探査深度 δ (m)は拡散深度とよばれる次式を目安とする。

$$\delta = \sqrt{\frac{2t\rho}{\mu}}$$

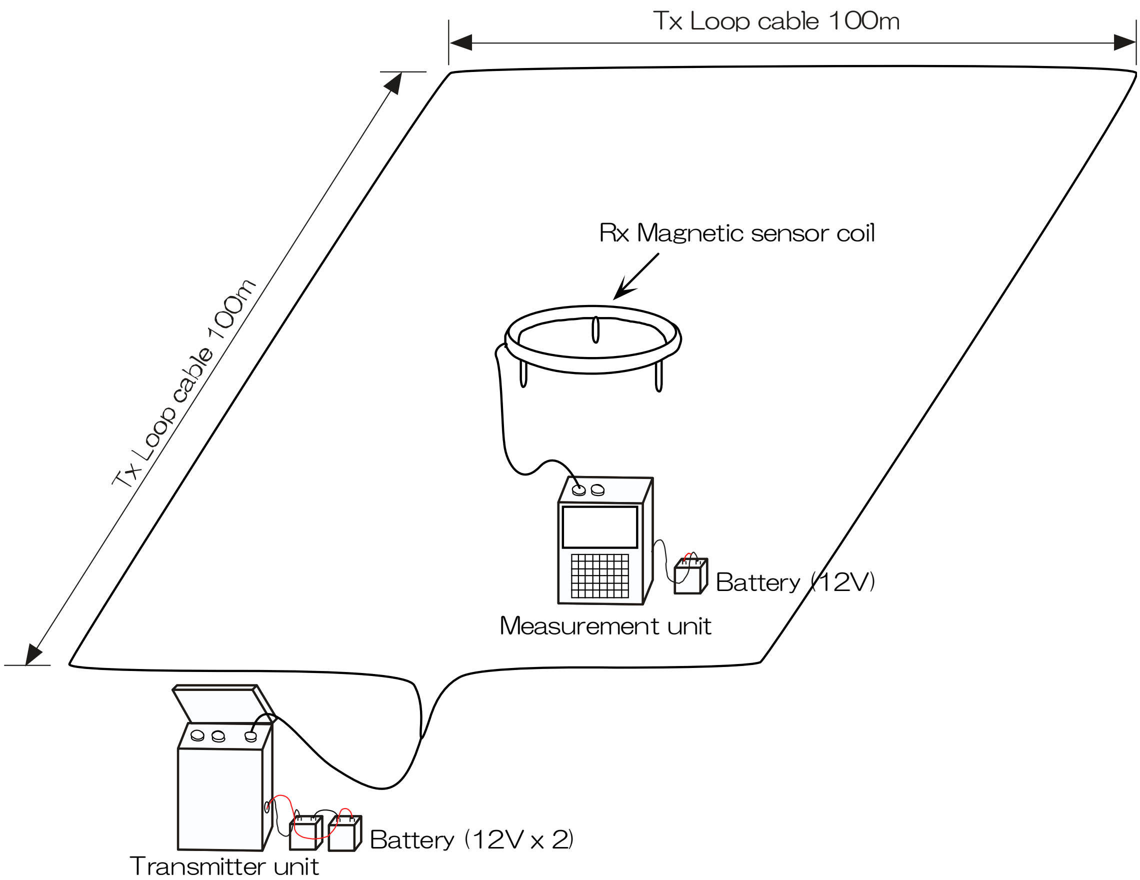
ここで、ρ：地盤の比抵抗(Ω･m)、t：時間(sec)、μ：透磁率

この式は、地盤の比抵抗が高いほど探査深度は深くなり、長い時間まで測定できるほど探査深度は深くなることを示唆している。

また、地下浅部に粘土層や変質帯のような低比抵抗の地層が分布する地域で電気探査を適用すると、低比抵抗の地層より深い地層の探査が困難になるが、TEM 法では深い地層まで探査できる。特に、表層付近に粘土層が分布したり、塩分濃度の高い地下水が分布したりする地域に TEM 法の適用が適している。

(2) 測定方法

本プロジェクトでは、TEM 法探査は MT 法データのスタティック補正を目的としている。そのため探査深度としては 100m 程度が必要であるため、100m x 100m の正方形ループ状に電線を地面に這わせ、これに小型送信機で電流を流して磁場を発生させて、電線に流した電流を切った後の磁場の時間的変化を正方形ループの中心に置いた受信コイルで数分間測定するインループ配置での測定を実施した。本調査で行った TEM 法の測定模式図を下図に示す。測定には Phoenix 社製 V8 送受信システムを使用し、各測点で鉛直方向の磁場 1 成分の過渡応答現象を測定した。測定においては、送信電流は 3.5A 程度、時間ウィンドウ数 20、スタック回数は 10 回以上、リピートレート 25Hz、2.5Hz の主に 2 周波数を用いた。



MT 法測定機器配置模式図

(3) データ処理および解析方法

TEM 法で取得された測定データを用いて 1 次元層構造解析を行った。本調査の 1 次元解析には、Schlumberger 社製 WinGLink を使用した。各測定点において 5~6 層の層構造を仮定し、観測された磁場の減衰曲線を最もよく説明するような水平多層構造モデルの各層の比抵抗と層厚をインバージョン解析で求めた。下図に測定データと 1 次元インバージョン層構造解析結果の例を示す。

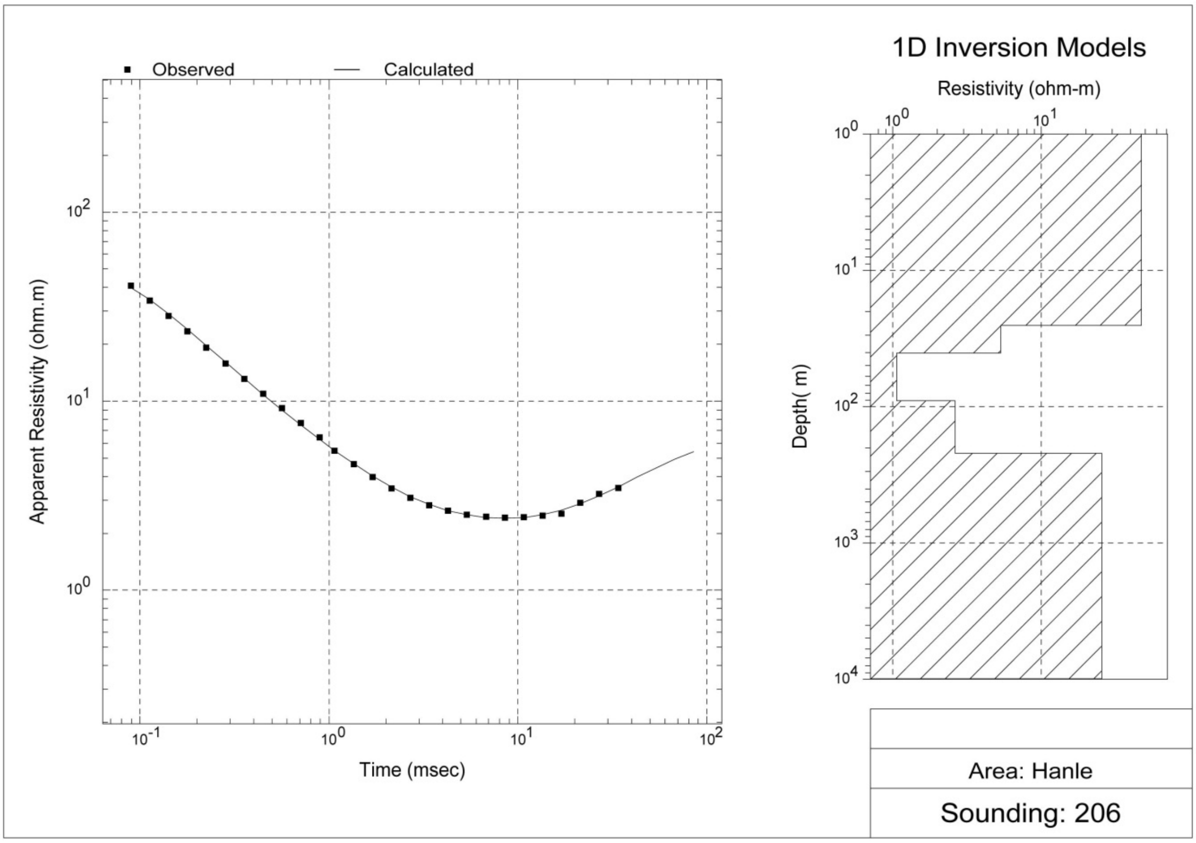
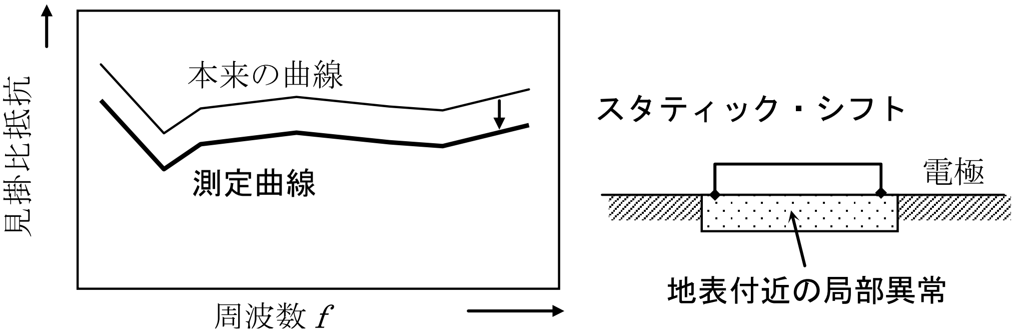


図　**TEM 法探査の測定データ例**

(4) MT 法データのスタティック補正

MT 法のデータ処理で重要なもののひとつにスタティック補正がある。下図に示すように、測点近傍の浅所にのみ局所的な比抵抗異常がある場合、見掛比抵抗曲線が全体的に移動した結果が得られる。解析を行う前に、局所的な異常が無い時の見掛比抵抗曲線に戻す処理が必要である。電気探査や TEM 法などの他の電磁探査法による地下浅部の比抵抗情報を利用したり、高周波数における 2 組の見掛比抵抗の違いを利用したりして、定性的な処理を行うことが多い。



（出典：物理探査適用の手引き）

スタティック・シフト概念模式図

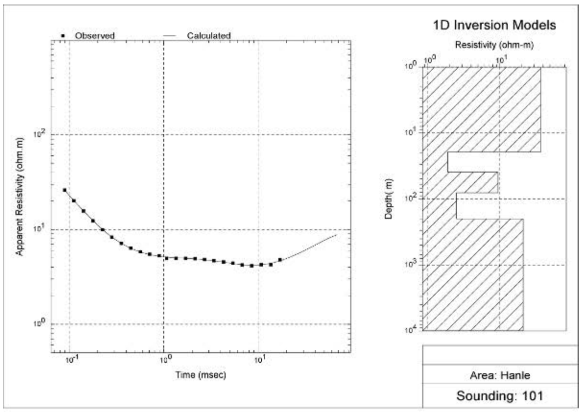
本プロジェクトでは MT 法探査測定点と同一の点で TEM 法探査を実施し、データの解析から求められた 1 次元比抵抗構造を基に MT 法データのスタティック補正を行った。得られた比抵抗構造を用いて MT 法の見掛比抵抗・位相のレスポンスを算出する。MT 法の最も高い周波数の測定データを TEM 法探査の結果から算出された見掛比抵抗曲線に合うようにシフトさせた。

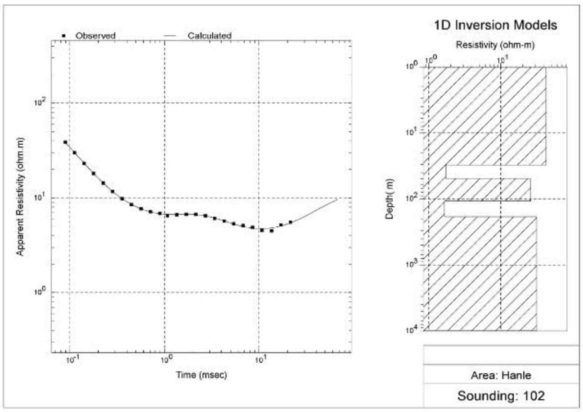
測点位置座標一覧表

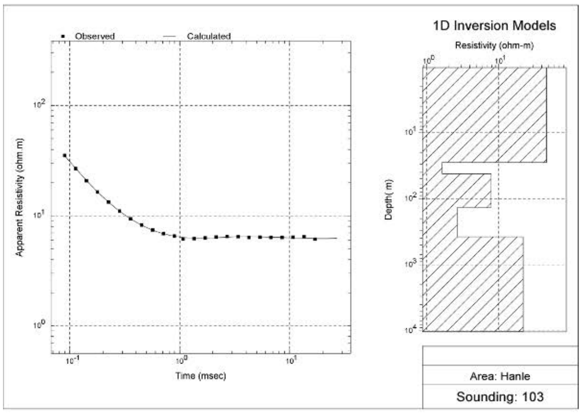
Station	Coordinate (WGS84)		Elevation (m)
	Latitude	Longitude	
HNL-101	11°22'42.8"	42°10'36.8"	301
HNL-102	11°23'2.3"	42°10'59.5"	349
HNL-103	11°23'17.9"	42°11'30.6"	356
HNL-104	11°23'40.0"	42°11'55.1"	379
HNL-105	11°23'58.6"	42°12'22.9"	378
HNL-106	11°24'17.0"	42°12'50.0"	393
HNL-201	11°23'16.8"	42°10'7.9"	243
HNL-202	11°23'42.1"	42°10'35.6"	346
HNL-203	11°23'54.0"	42°11'5.4"	364
HNL-204	11°24'12.4"	42°11'32.7"	394
HNL-205	11°24'33.0"	42°11'59.0"	413
HNL-206	11°24'48.1"	42°12'25.6"	413
HNL-301	11°23'53.4"	42°9'49.2"	240
HNL-302	11°24'9.4"	42°10'13.4"	250
HNL-303	11°24'27.3"	42°10'45.7"	298
HNL-304	11°24'47.0"	42°11'8.6"	400
HNL-305	11°25'6.0"	42°11'34.4"	439
HNL-306	11°25'22.4"	42°12'2.7"	431
HNL-401	11°24'26.2"	42°9'20.8"	230
HNL-402	11°24'44.7"	42°9'52.0"	247
HNL-403	11°25'0.1"	42°10'13.6"	267
HNL-404	11°25'19.5"	42°10'45.0"	408
HNL-405	11°25'38.3"	42°11'12.0"	451
HNL-406	11°25'53.8"	42°11'38.0"	454
HNL-501	11°24'57.8"	42°8'55.3"	224
HNL-502	11°25'16.7"	42°9'25.4"	228
HNL-503	11°25'32.5"	42°9'53.4"	272
HNL-504	11°25'47.6"	42°10'18.8"	315
HNL-505	11°26'10.8"	42°10'49.1"	458
HNL-506	11°26'29.4"	42°11'16.2"	476
HNL-900 (MT-Ref: Dikhil)	11° 8'12.2"	42° 19'8.57"	391

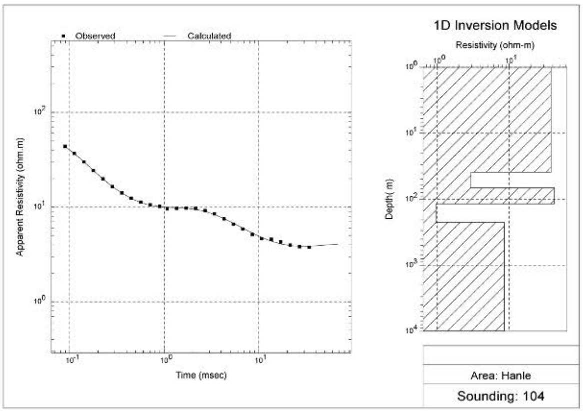
スタティックシフト補正値一覧表

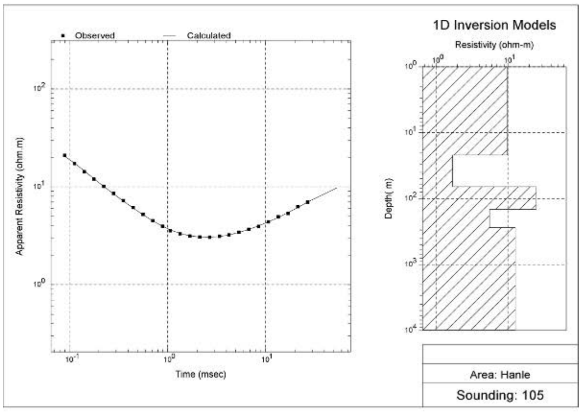
Station	Static Shift (TE)	Static Shift (TM)	Station	Static Shift (TE)	Static Shift (TM)
HNL-101	1.000	1.000	HNL-304	1.079	1.382
HNL-102	1.085	1.464	HNL-305	1.000	1.130
HNL-103	0.914	1.253	HNL-306	1.126	1.000
HNL-104	0.779	1.299	HNL-401	1.000	1.000
HNL-105	1.247	1.000	HNL-402	1.146	1.132
HNL-106	1.211	1.348	HNL-403	1.000	0.230
HNL-201	1.196	0.880	HNL-404	1.162	1.301
HNL-202	1.378	0.928	HNL-405	1.000	1.209
HNL-203	0.918	1.000	HNL-406	1.185	1.000
HNL-204	1.000	1.000	HNL-501	1.044	1.869
HNL-205	1.123	1.072	HNL-502	1.454	1.000
HNL-206	1.117	1.000	HNL-503	1.190	1.785
HNL-301	1.000	1.060	HNL-504	0.437	0.790
HNL-302	1.099	1.163	HNL-505	1.000	1.000
HNL-303	1.000	0.316	HNL-506	1.344	0.759

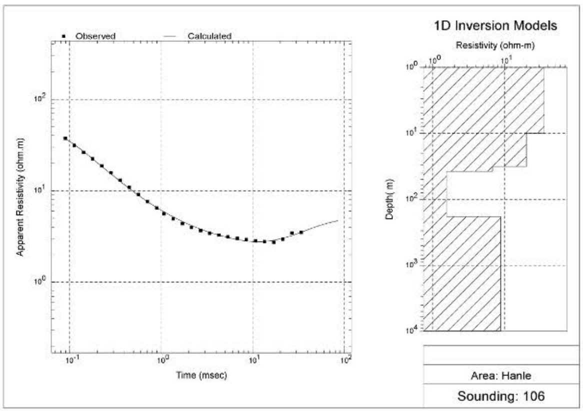




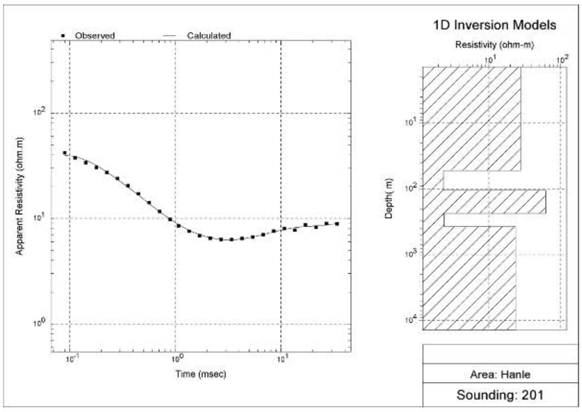


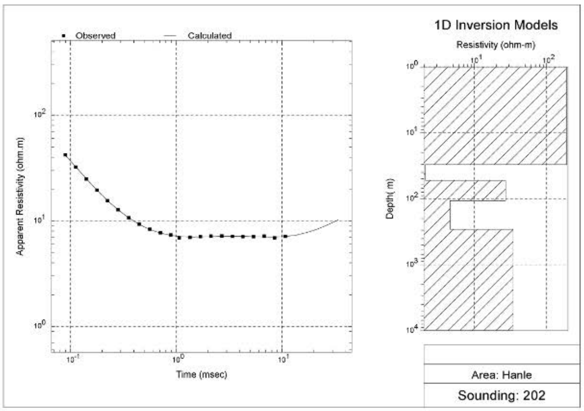


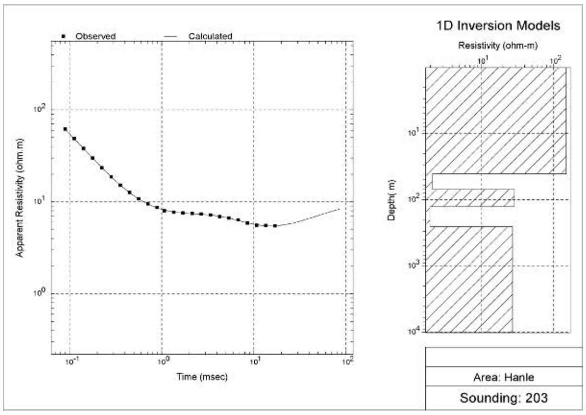


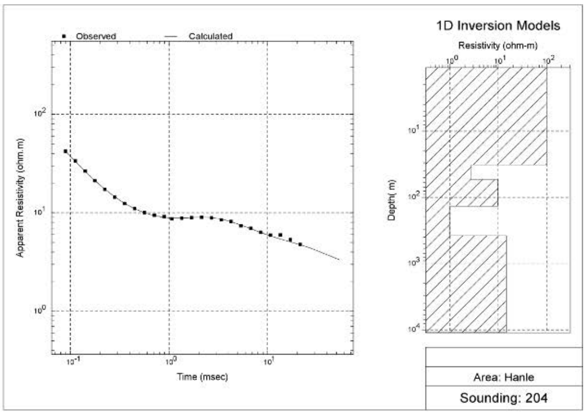


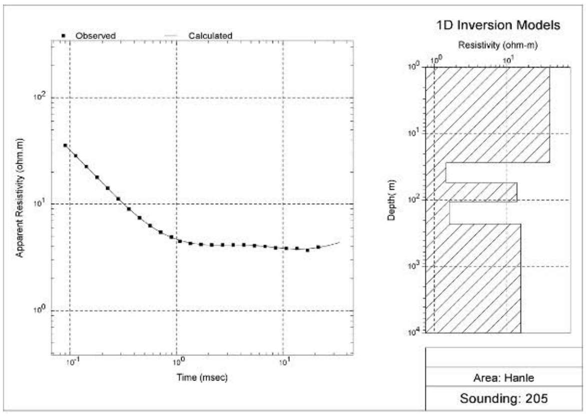
TEM法探査 1次元層構造解析結果 (HNL100)

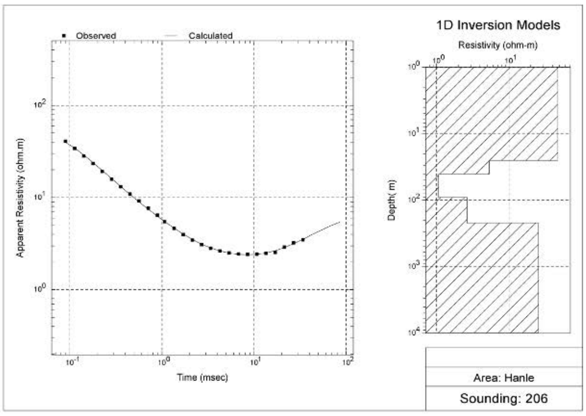




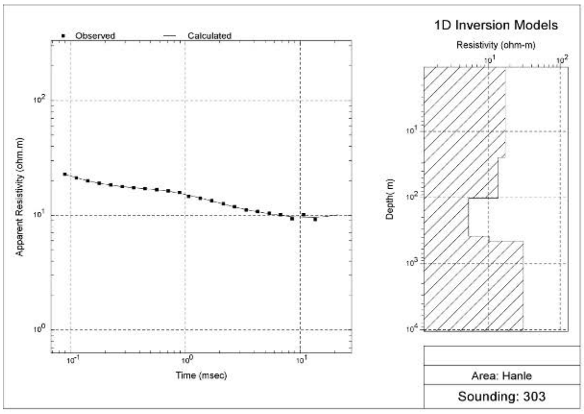


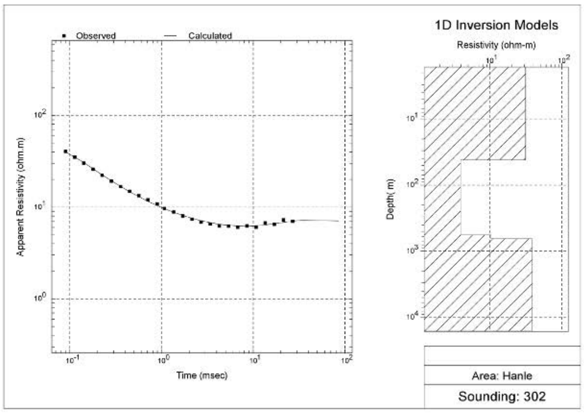


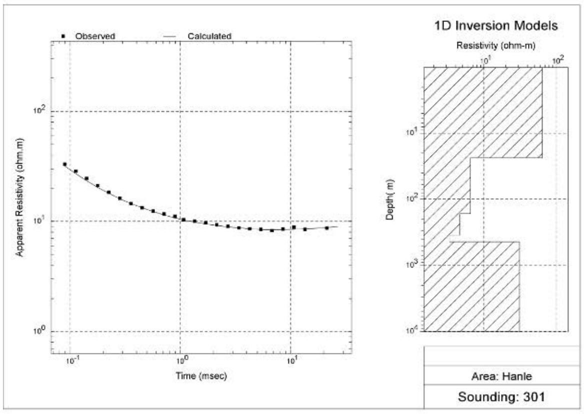


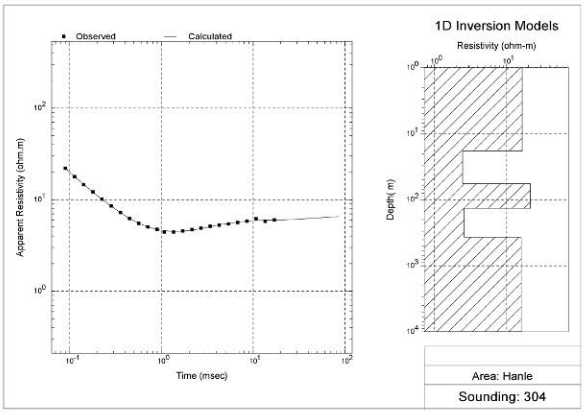


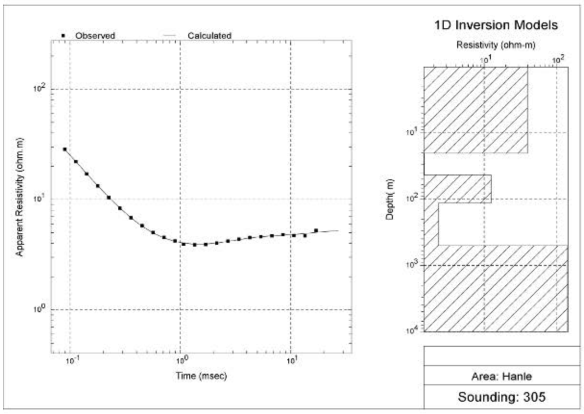
TEM法探査 1次元層構造解析結果 (HNL200)

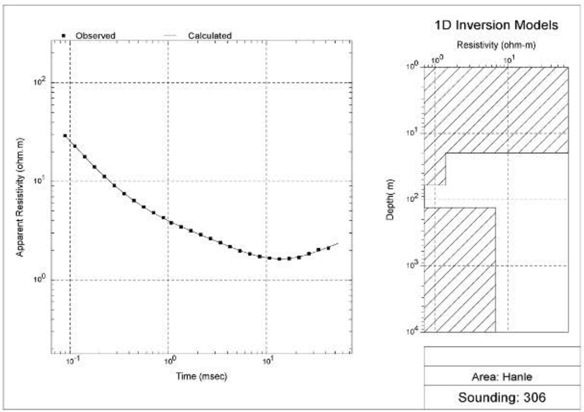




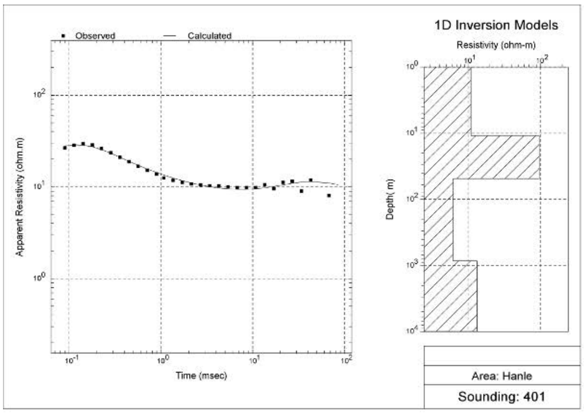


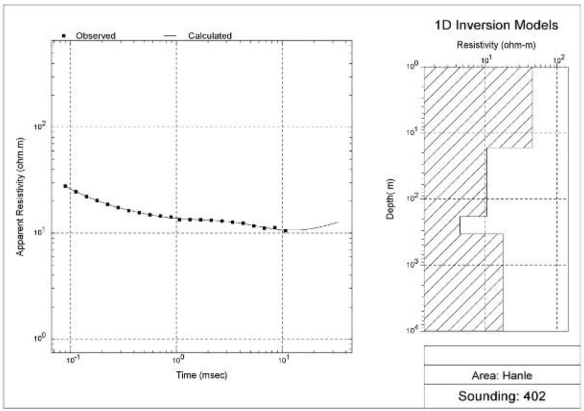


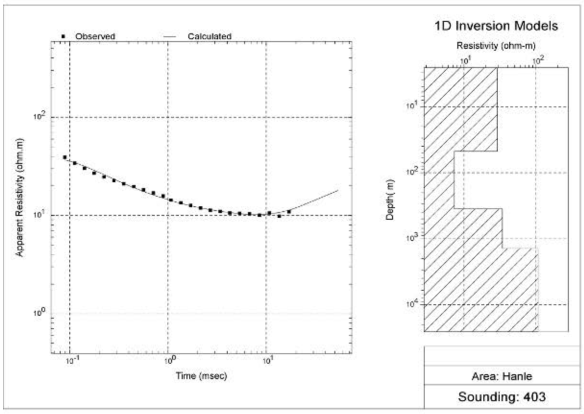


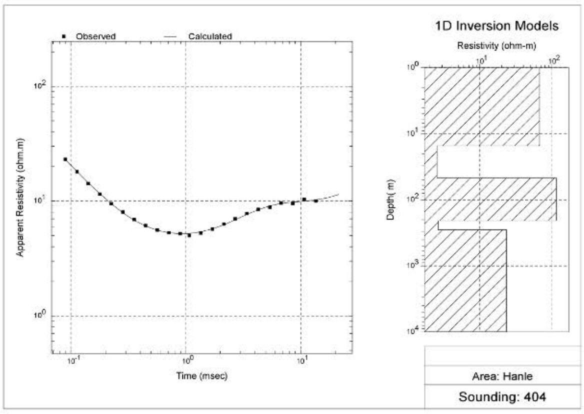


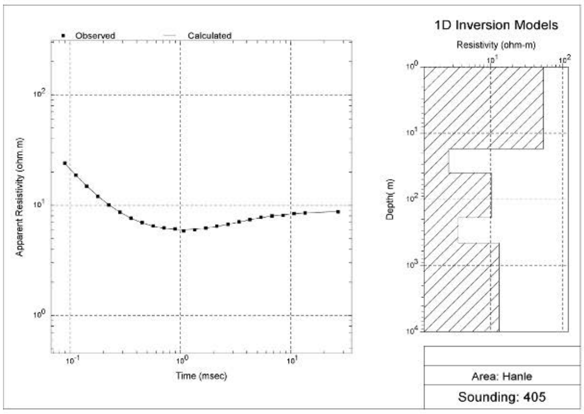
TEM法探査 1次元層構造解析結果 (HNL300)

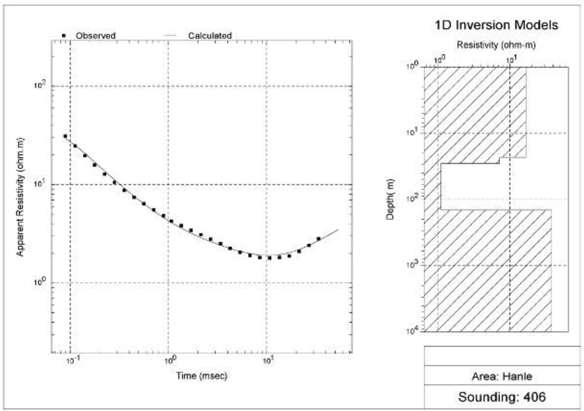




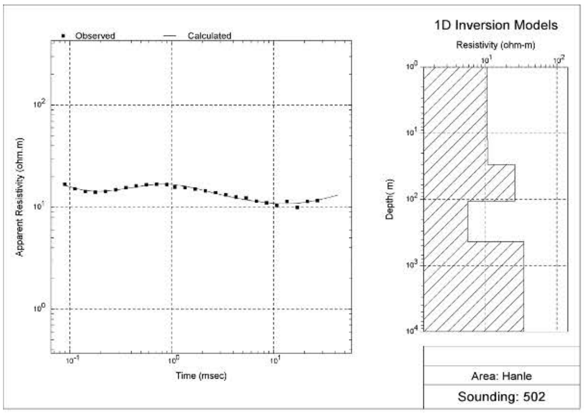


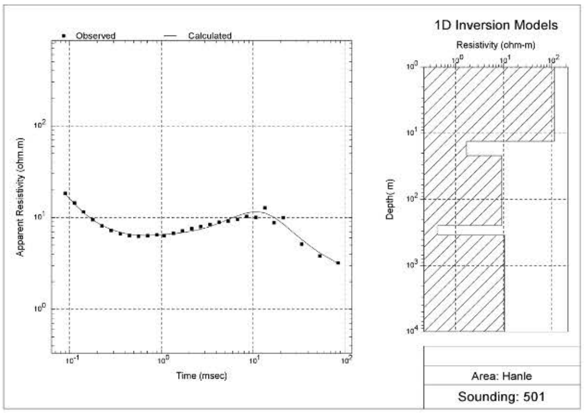


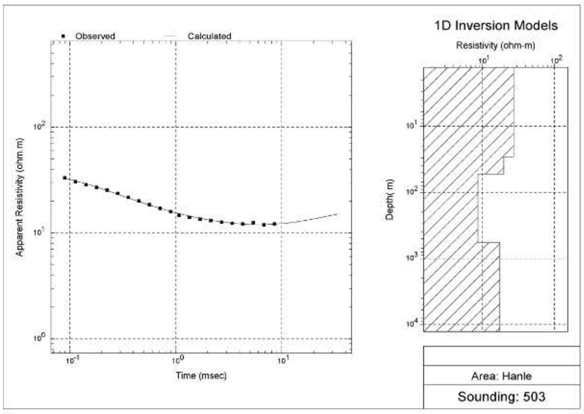


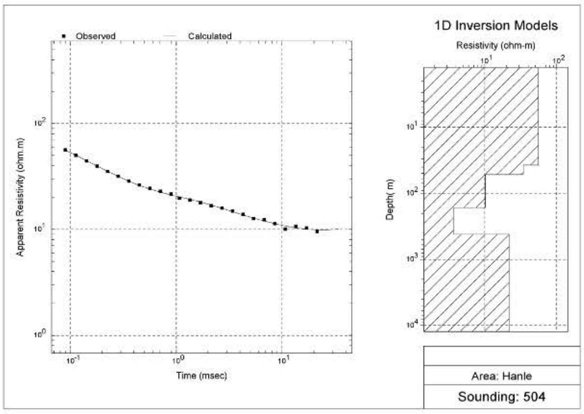


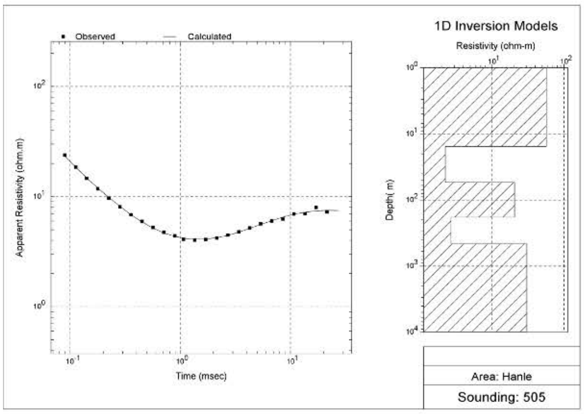
TEM法探査 1次元層構造解析結果 (HNL400)

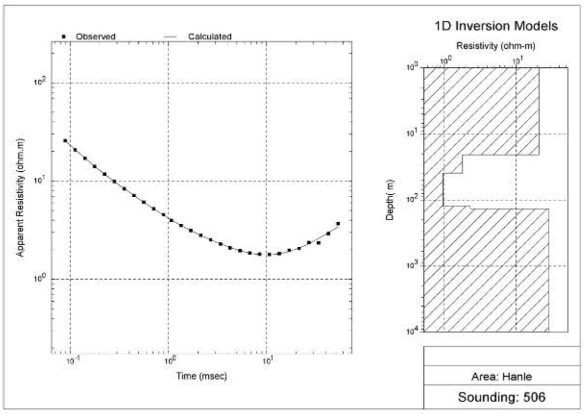




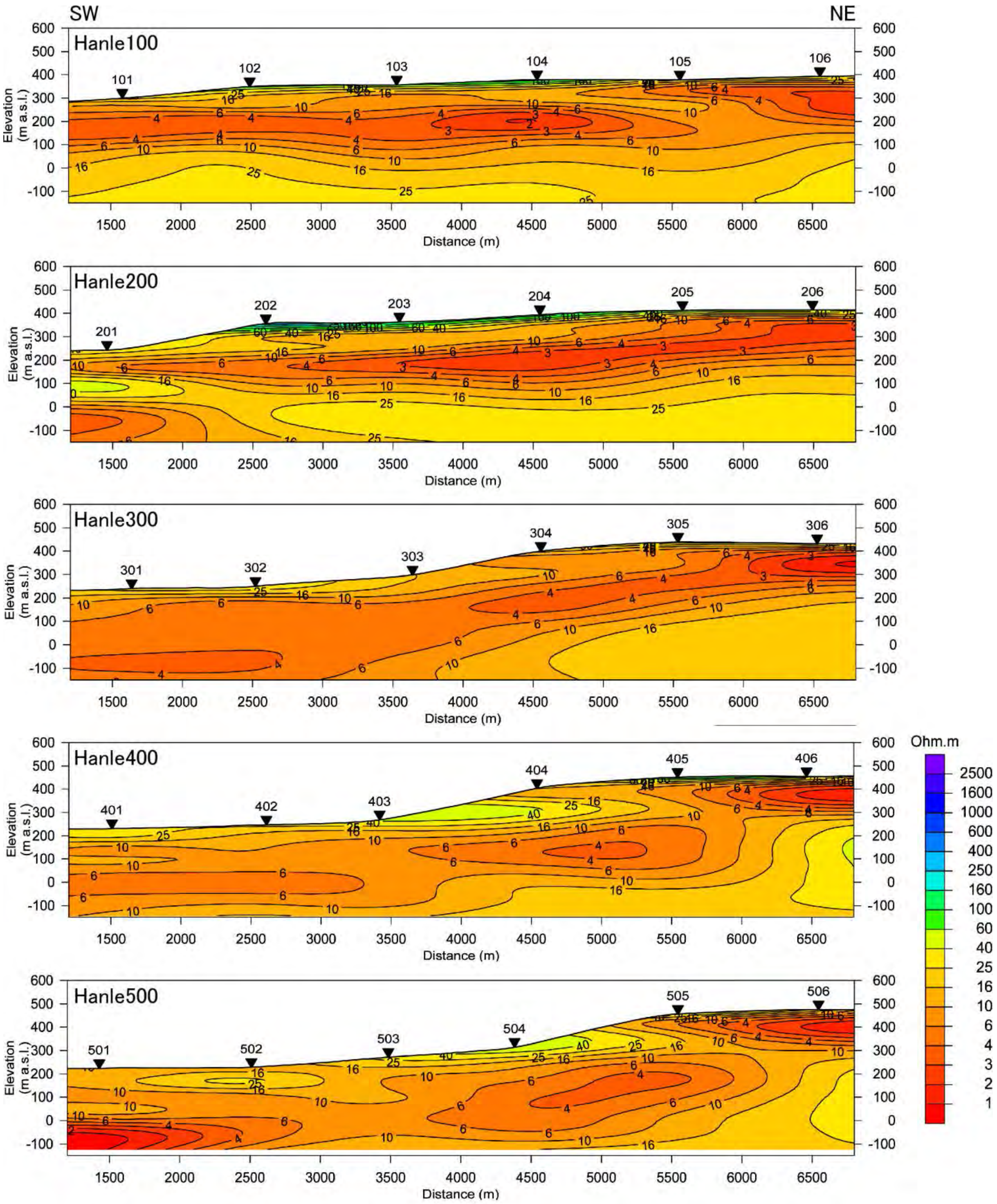






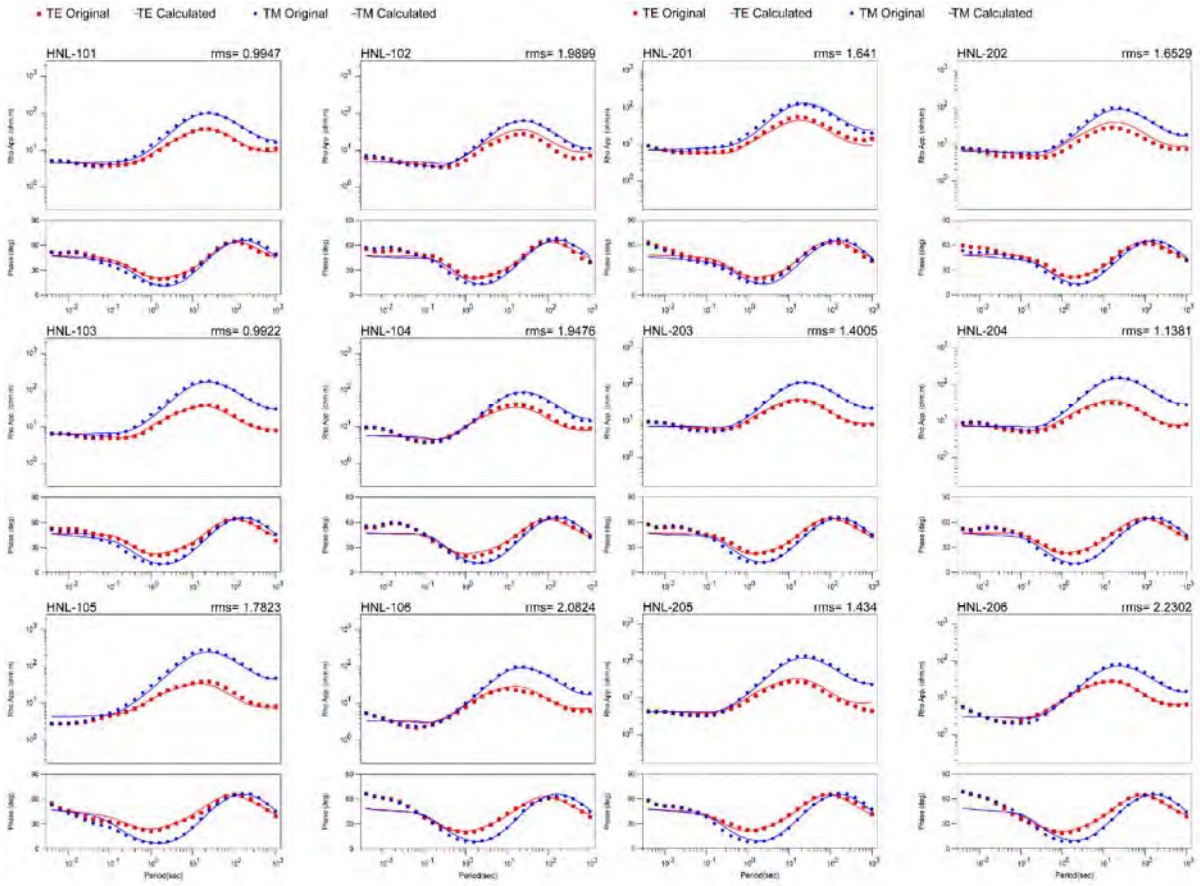


TEM法探査 1次元層構造解析結果 (HNL500)

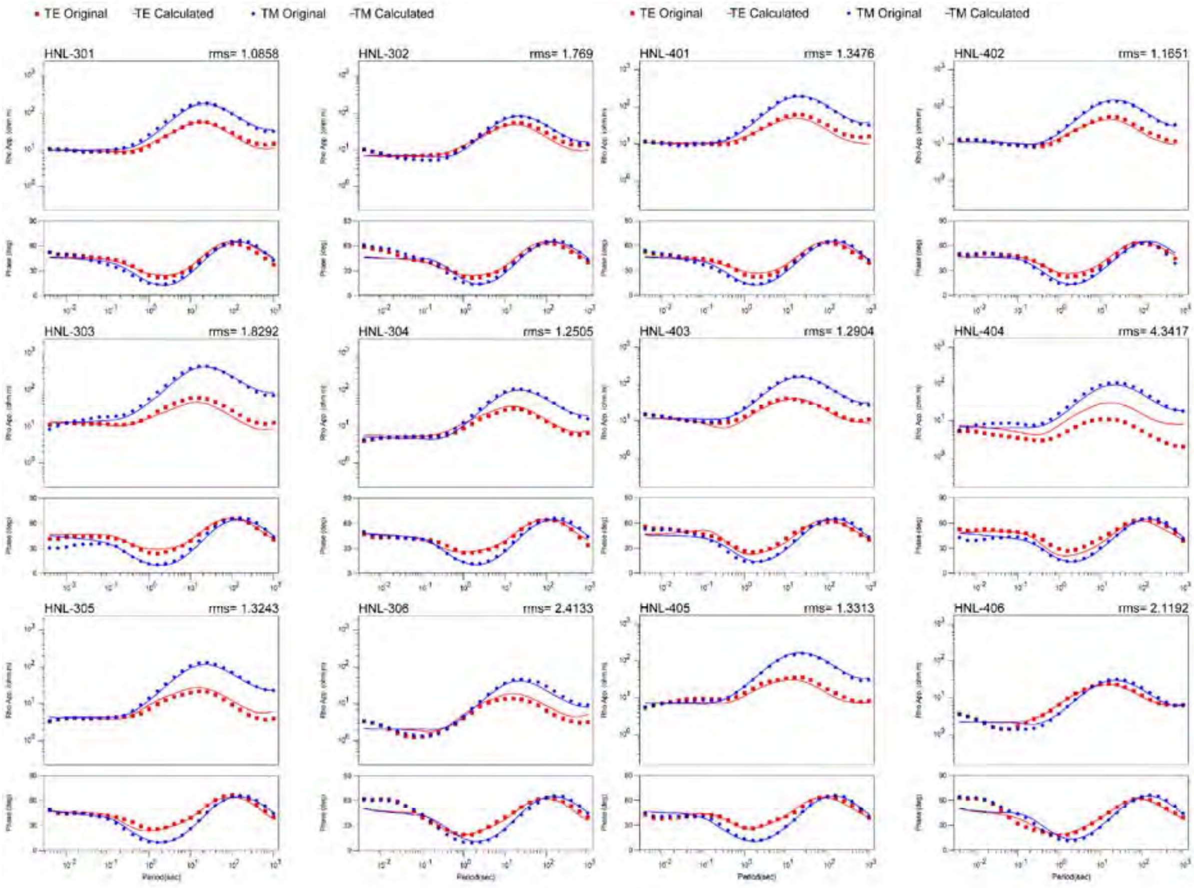


The resistivity cross sections of the very shallow zone from the results of TEM 1D inversion analysis

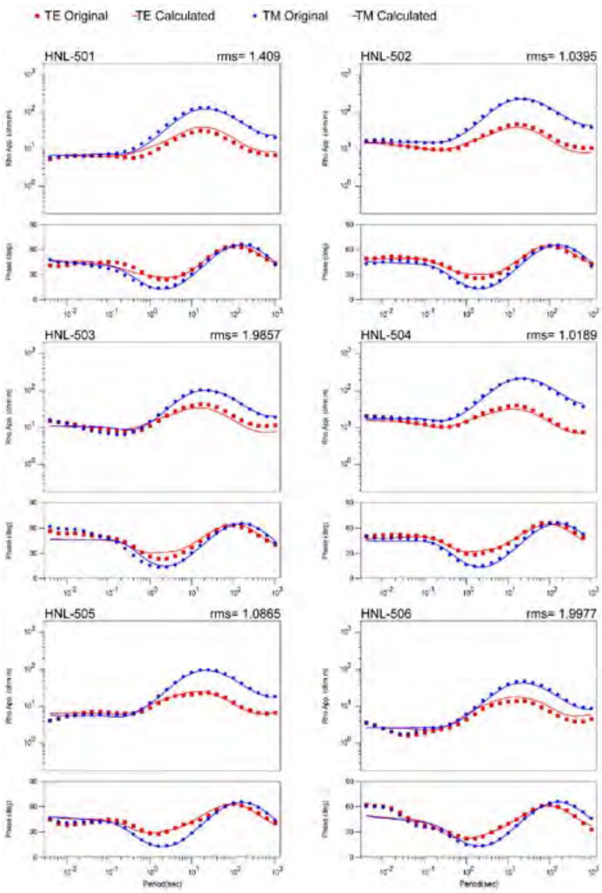
TEMデータの1Dインバージョン解析から求められた極浅部の比抵抗構造断面図



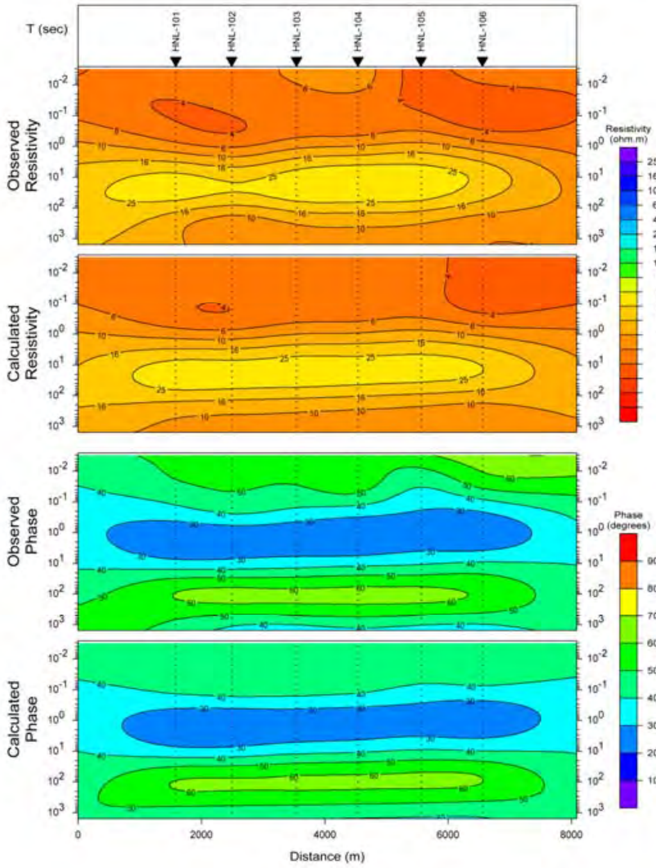
見掛比抵抗・位相曲線（HNL100, HNL200）

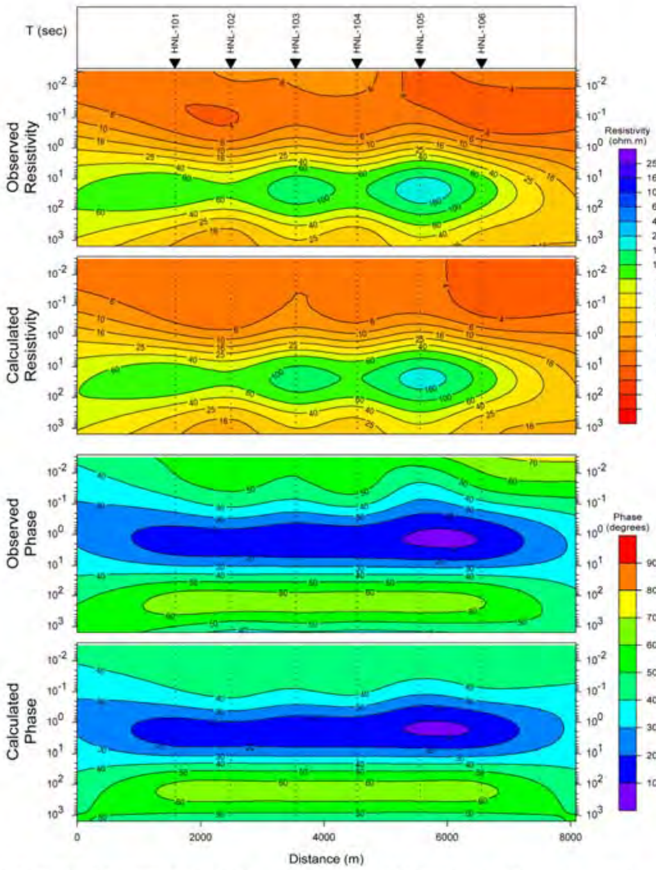


見掛比抵抗・位相曲線（HNL300, HNL400）

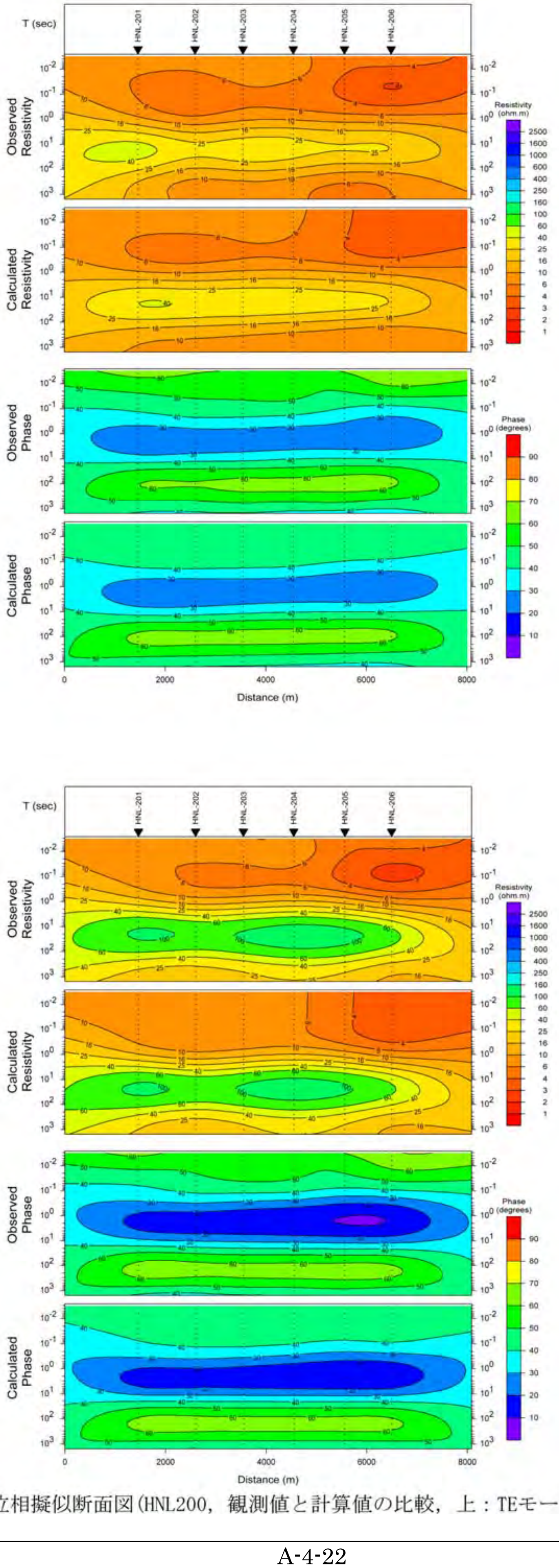


見掛比抵抗・位相曲線（HNL500）

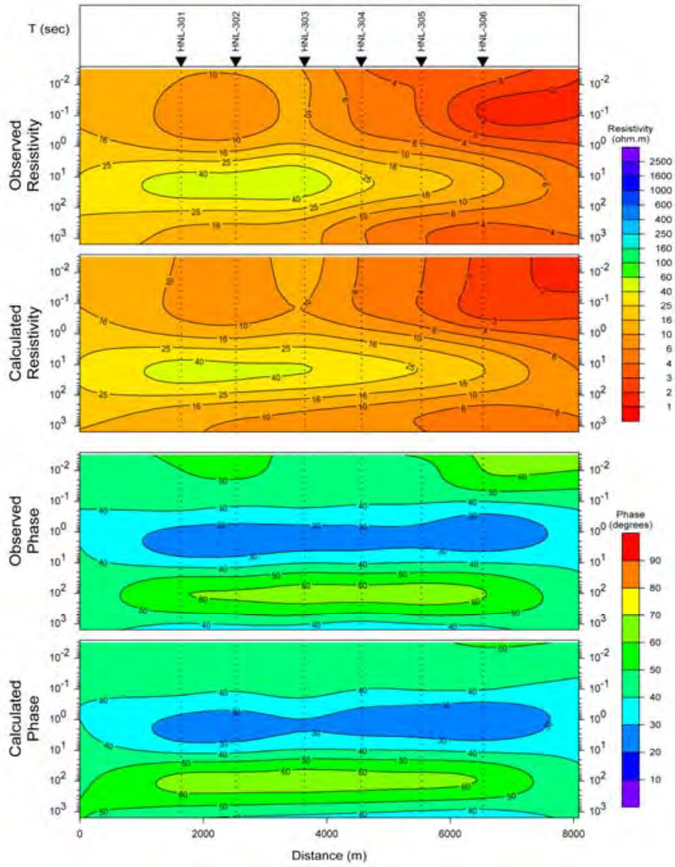


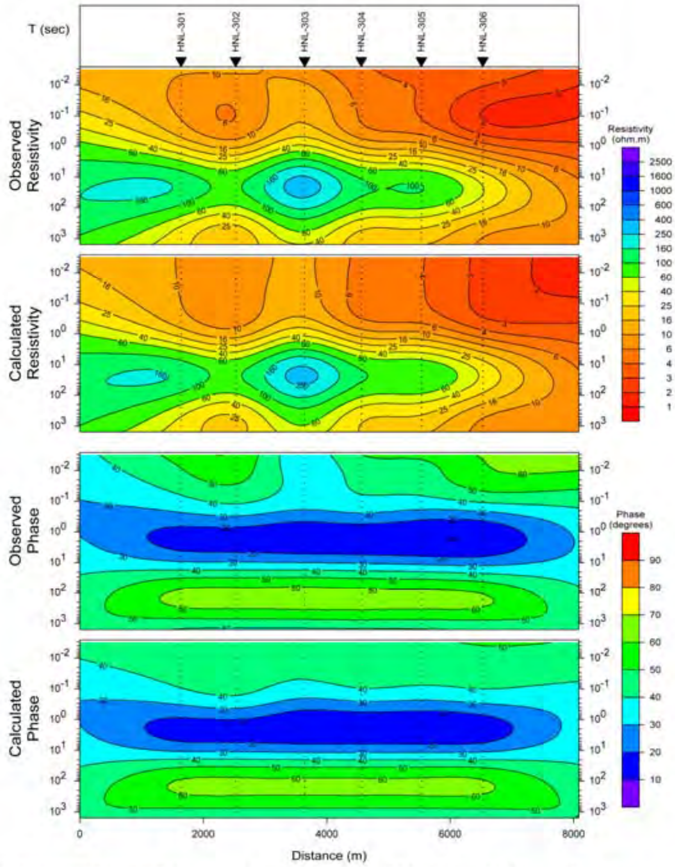


比抵抗・位相擬似断面図（HNL100，観測値と計算値の比較，上：TEモード，下：TMモード）

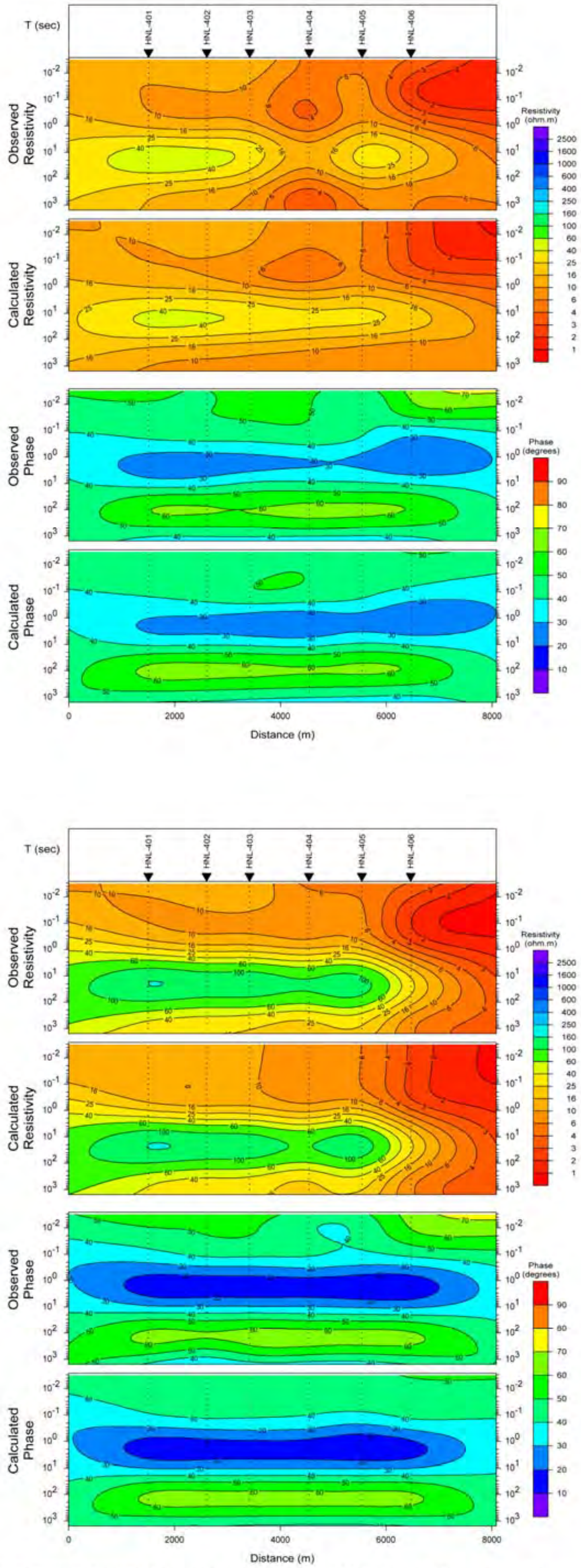


比抵抗・位相擬似断面図（HNL200，観測値と計算値の比較，上：TEモード，下：TMモード）

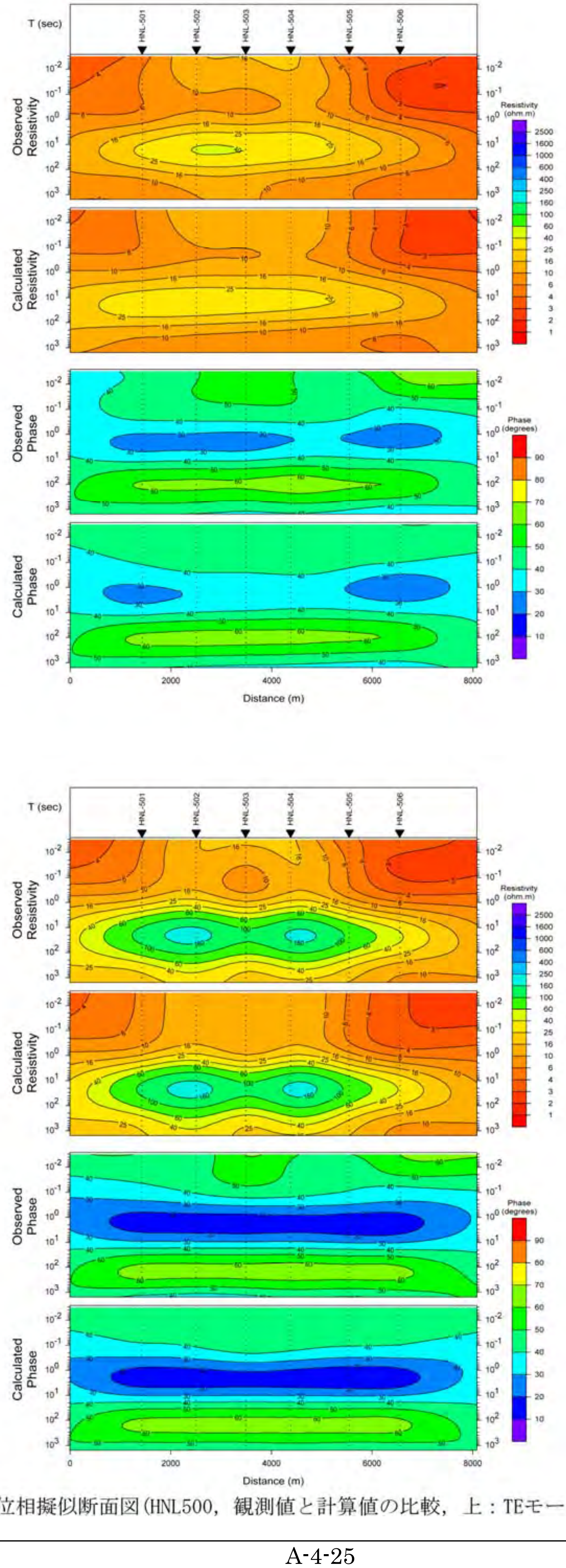




比抵抗・位相擬似断面図（HNL300，観測値と計算値の比較，上：TEモード，下：TMモード）



比抵抗・位相擬似断面図（HNL400，観測値と計算値の比較，上：TEモード，下：TMモード）



比抵抗・位相擬似断面図（HNL500，観測値と計算値の比較，上：TEモード，下：TMモード）

添付資料-5　　損益分岐発送電価格計算シート

A. Case-1: Plant Factor 80%, Well successful rate 60%

A.1 Investment schedule

Investment Schedule

Project Description							
Name	Hanle GPP						
Installed capacity	15	MW					
Plant factor	80	%					
Station use	9	%					
Generated energy	105.1	GWh					
Saled energy	95.7	GWh					
Costruction cost	104.5	M$	(2015 price)				
Construction period	5	years	(2016-2020)				
Operating period	30	years	(2021-2050)				

Captital cost disbursement schedule (2015 price, in US$ million)

Period	1	2	3	4	5	Total
Year	2016	2017	2018	2019	2020	
1. Test drilling	4.2	4.2				8.4
2. Preparatory works		2.5				2.5
3. Main works						
Consulting fees (design)		2.4				2.4
Production well drilling			15.0	20.0	15.0	49.9
Steam gathering system (FCRC)			1.8	2.4	1.8	6.0
Plant costruction			7.4	9.9	7.4	24.8
Consulting fees (supervision)			1.0	1.3	1.0	3.2
Administration & management			1.0	1.3	1.0	3.2
Physical contingencies			1.2	1.6	1.2	4.0
Total	4.2	9.1	27.4	36.5	27.4	104.5

		1	2	3	4	5
Inflation	US$ inflation	2%	2%	2%	2%	2%
	Inflation factor (base is 2015)	1.020	1.040	1.061	1.082	1.104

Captital cost disbursement schedule (nominal price, in US$ million)

Period	1	2	3	4	5	Total
Year	2016	2017	2018	2019	2020	
1. Test drilling	4.3	4.4				8.7
2. Preparatory works		2.6				2.6
3. Main works						
Consulting fees (design)		2.5				2.5
Production well drilling			15.9	21.6	16.5	54.0
Steam gathering system (FCRC)			1.9	2.6	2.0	6.5
Plant costruction			7.9	10.7	8.2	26.8
Consulting fees (supervision)			1.0	1.4	1.1	3.5
Administration & management			1.0	1.4	1.1	3.5
Physical contingencies			1.3	1.7	1.3	4.4
Total	4.3	9.5	29.0	39.5	30.2	112.5

A.2 Financing plan

Financing Plan

Funding Sources and Financing Terms

Source	Interest	Repayment period (yr)	Grace period (yr)	Commitment fee	Front-end fee
Equity capital (Equity)					
ODA grant fund (grant)					
Government budget (GoD)					
ODA loan-mulitlateral (ODA-Mul)	5.0%	20	5	1.0%	1.0%
ODA loan-bilateral (ODA-Bi)	2.5%	30	10	0.5%	0.0%
Commercial bank loan (CB)	6.0%	10	3	1.0%	1.0%

Breakdown of Base Costs and Financing Plan (in US$ million)

Year	Grant	GoE	ODA-Mul	ODA-Bi	CB	Equity	Total
1. Test drilling	4.3	4.4					8.7
2. Preparatory works		2.6					2.6
3. Main works							
Consulting fees (design)		2.5					2.5
Production well drilling					41.6	12.4	54.0
Steam gathering system (FCRC)					5.0	1.5	6.5
Plant costruction					20.7	6.2	26.8
Consulting fees (supervision)						3.5	3.5
Administration & management						3.5	3.5
Physical contingencies						4.4	4.4
Total	4.3	9.5			67.3	31.5	112.5

Financial Costs during Construction (in US$ million)

Year	2016	2017	2018	2019	2020	Total
1. ODA grant fund	4.3	4.4				8.7
2. Government budget		5.1				5.1
3. Equity capital			9.2	12.6	9.6	31.5
4. ODA loan-multilateral						
Disbursement						
Interest						
Sub-total						
5. ODA loan-bilateral						
Disbursement						
Interest						
Sub-total						
6. Commercial bank loan						
Disbursement			19.8	26.9	20.6	67.3
Interest				1.2	2.8	4.0
Sub-total			19.8	28.1	23.4	71.3
Total of 1 through 6	4.3	9.5	29.0	40.7	33.0	116.5
7. Front-end fee						
ODA loan-multilateral						
ODA loan-bilateral						
Commercial bank loan		0.7				0.7
Total		0.7				0.7
8. Commitment fee						
ODA loan-multilateral						
ODA loan-bilateral						
Commercial bank loan			0.5	0.2	0.0	0.7
Total			0.5	0.2	0.0	0.7
Total of 1 through 8	4.3	10.2	29.5	40.9	33.0	117.9
					Loan ratio	69.8%

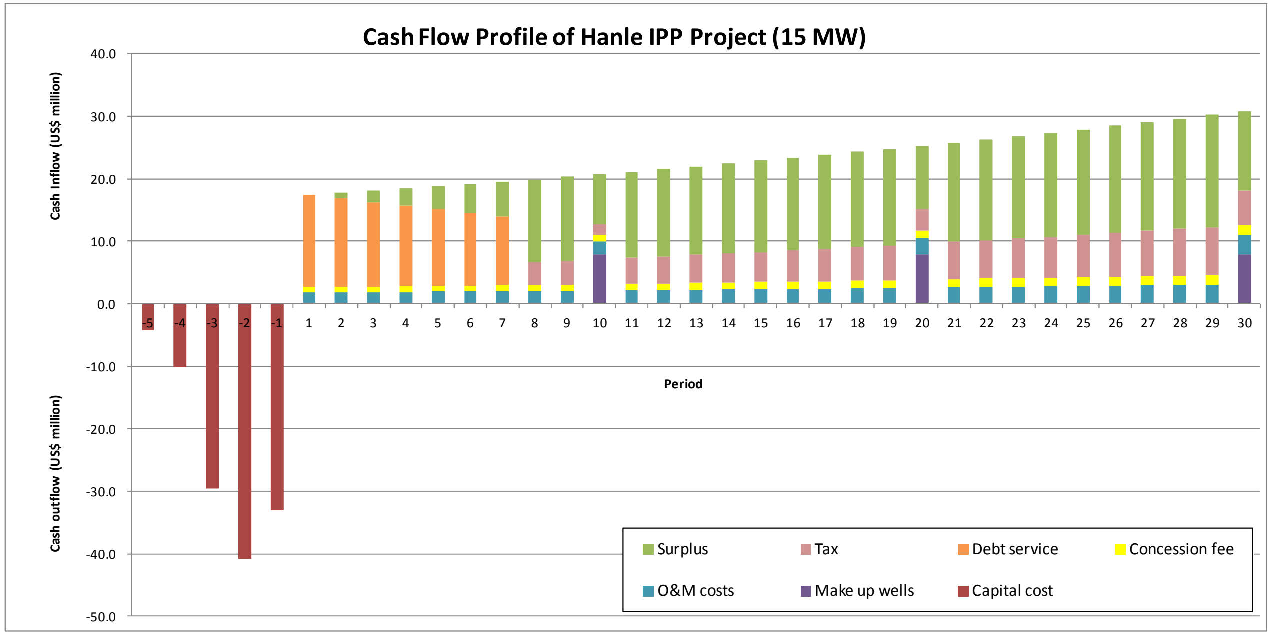
A.3 Assumptions on Financial Analysis

Assumptions on Financial Analysis					
Loan profile	Loan amount (M$)	Interest	Loan repay period (yr)	Grace period (yr)	Principal repay period (yr)
ODA loan - multilateral	0.0	5.0%	20	5	15
ODA loan - bilateral	0.0	2.5%	30	10	20
Commercial bank (CB)	72.7	6.0%	10	3	7
Total	72.7				
Equity capital	31.5	M$			
Fixed assets					
GoD	13.8	M$	(to be transferred to IPP)		
IPP	104.2	M$			
Energy sale					
Saled energy	95.7	GWh			
Sales price (2015 price)	16.10	¢/kWh			
Sales price (in 2021)	18.13	¢/kWh			
Escalation rate (/yr)	2.0%				
Operation & maintenance cost					
O&M cost (2015 price)	1.6	M$ (1.5% of capital cost)			
O&M cost (in 2021)	1.8	M$ (1.5% of capital cost)			
Escalation rate (/yr)	2.0%				
Depreciation					
Asset value (US$ million)	117.9	(including GoE assets)			
Useful life (in year)	30				
Residual value	0%				
Method	Straight line				
Concession fee	5.0%	of sales revenue			
Escrow account (for CB loan)	50.0%	of annual debt service			
Cash required	2.0%	of sales revenue			
Accounts receivable	12.5%	1.5 month of sales revenue			
Accounts payable	8.0%	1 month of O&M cost			
Deposite rate	3.0%				
Income tax	30.0%	from 8th year of operation			
Dividend rate	70.0%	of net profit			
Exchanger rate					

A.4 Graphs

Period	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12
Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Capital cost	-4.3	-10.2	-29.5	-40.9	-33.0												
Revenue						17.3	17.7	18.0	18.4	18.8	19.1	19.5	19.9	20.3	20.7	21.1	21.6
Make up wells						0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9	0.0	0.0
O&M costs						1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.2
Concession fee						0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.1	1.1
Debt service						14.8	14.1	13.5	12.9	12.3	11.6	11.0	0.0	0.0	0.0	0.0	0.0
Tax						0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	3.8	1.6	4.1	4.3
Surplus						▲ 0.0	0.9	1.8	2.7	3.7	4.6	5.6	13.2	13.4	8.1	13.8	14.0

Period	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Year	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Capital cost																		
Revenue	22.0	22.4	22.9	23.3	23.8	24.3	24.8	25.3	25.8	26.3	26.8	27.4	27.9	28.5	29.0	29.6	30.2	30.8
Make up wells	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9
O&M costs	2.2	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.7	2.7	2.8	2.8	2.9	3.0	3.0	3.1	3.1
Concession fee	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.5	1.5	1.5	1.5
Debt service	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tax	4.5	4.7	4.8	5.0	5.2	5.4	5.6	3.4	6.0	6.2	6.4	6.6	6.8	7.0	7.2	7.5	7.7	5.6
Surplus	14.2	14.4	14.6	14.8	15.0	15.2	15.4	10.1	15.9	16.1	16.4	16.6	16.9	17.1	17.4	17.6	17.9	12.6



B. Case-2: Plant Factor 80%, Well successful rate 70%

B.1 Investment schedule

Investment Schedule

Project Description								
Name	Hanle GPP							
Installed capacity	15	MW						
Plant factor	80	%						
Station use	9	%						
Generated energy	105.1	GWh						
Saled energy	95.7	GWh						
Costruction cost	98.4	M$	(2015 price)					
Construction period	5	years	(2016-2020)					
Operating period	30	years	(2021-2050)					

Captital cost disbursement schedule (2015 price, in US$ million)

Period	1	2	3	4	5	Total
Year	2016	2017	2018	2019	2020	
1. Test drilling	4.2	4.2				8.4
2. Preparatory works		2.5				2.5
3. Main works						
Consulting fees (design)		2.3				2.3
Production well drilling			13.4	17.8	13.4	44.6
Steam gathering system (FCRC)			1.8	2.4	1.8	6.0
Plant costruction			7.4	9.9	7.4	24.8
Consulting fees (supervision)			0.9	1.2	0.9	3.0
Administration & management			0.9	1.2	0.9	3.0
Physical contingencies			1.1	1.5	1.1	3.8
Total	4.2	9.0	25.6	34.1	25.6	98.4

Inflation	US$ inflation	2%	2%	2%	2%	2%
	Inflation factor (base is 2015)	1.020	1.040	1.061	1.082	1.104

Captital cost disbursement schedule (nominal price, in US$ million)

Period	1	2	3	4	5	Total
Year	2016	2017	2018	2019	2020	
1. Test drilling	4.3	4.4				8.7
2. Preparatory works		2.6				2.6
3. Main works						
Consulting fees (design)		2.4				2.4
Production well drilling			14.2	19.3	14.8	48.3
Steam gathering system (FCRC)			1.9	2.6	2.0	6.5
Plant costruction			7.9	10.7	8.2	26.8
Consulting fees (supervision)			1.0	1.3	1.0	3.3
Administration & management			1.0	1.3	1.0	3.3
Physical contingencies			1.2	1.6	1.2	4.1
Total	4.3	9.3	27.1	36.9	28.2	105.8

B.2 Financing plan

Financing Plan

Funding Sources and Financing Terms

Source	Interest	Repayment period (yr)	Grace period (yr)	Commitment fee	Front-end fee
Equity capital (Equity)					
ODA grant fund (grant)					
Government budget (GoD)					
ODA loan-mulitlateral (ODA-Mul)	5.0%	20	5	1.0%	1.0%
ODA loan-bilateral (ODA-Bi)	2.5%	30	10	0.5%	0.0%
Commercial bank loan (CB)	6.0%	10	3	1.0%	1.0%

Breakdown of Base Costs and Financing Plan (in US$ million)

Year	Grant	GoE	ODA-Mul	ODA-Bi	CB	Equity	Total
1. Test drilling	4.3	4.4					8.7
2. Preparatory works		2.6					2.6
3. Main works							
Consulting fees (design)		2.4					2.4
Production well drilling					37.2	11.1	48.3
Steam gathering system (FCRC)					5.0	1.5	6.5
Plant costruction					20.7	6.2	26.8
Consulting fees (supervision)						3.3	3.3
Administration & management						3.3	3.3
Physical contingencies						4.1	4.1
Total	4.3	9.3			62.9	29.4	105.8

Financial Costs during Construction (in US$ million)

Year	2016	2017	2018	2019	2020	Total
1. ODA grant fund	4.3	4.4				8.7
2. Government budget		5.0				5.0
3. Equity capital			8.6	11.8	9.0	29.4
4. ODA loan-multilateral						
Disbursement						
Interest						
Sub-total						
5. ODA loan-bilateral						
Disbursement						
Interest						
Sub-total						
6. Commercial bank loan						
Disbursement			18.5	25.1	19.2	62.9
Interest				1.1	2.6	3.7
Sub-total			18.5	26.2	21.8	66.6
Total of 1 through 6	4.3	9.3	27.1	38.0	30.8	109.6
7. Front-end fee						
ODA loan-multilateral						
ODA loan-bilateral						
Commercial bank loan		0.7				0.7
Total		0.7				0.7
8. Commitment fee						
ODA loan-multilateral						
ODA loan-bilateral						
Commercial bank loan			0.5	0.2	0.0	0.7
Total			0.5	0.2	0.0	0.7
Total of 1 through 8	4.3	10.0	27.6	38.2	30.8	110.9
					Loan ratio	69.8%

B.3 Assumptions on Financial Analysis

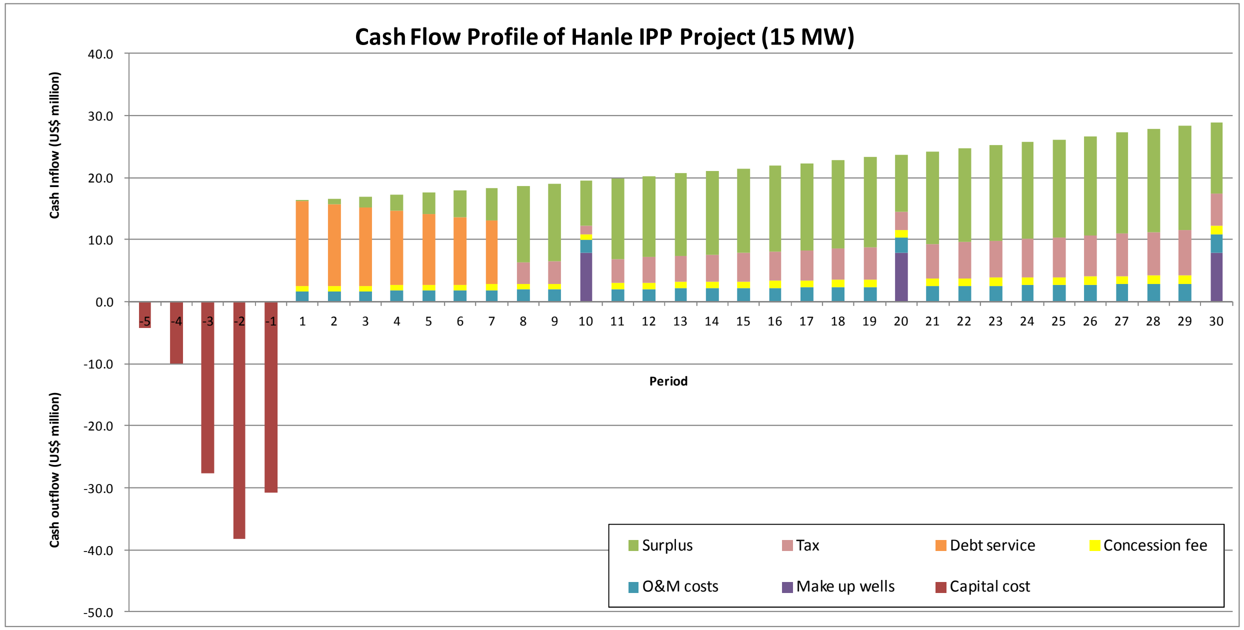
Assumptions on Financial Analysis

Loan profile	Loan amount (M$)	Interest	Loan repay period (yr)	Grace period (yr)	Principal repay period (yr)
ODA loan - multilateral	0.0	5.0%	20	5	15
ODA loan - bilateral	0.0	2.5%	30	10	20
Commercial bank (CB)	67.9	6.0%	10	3	7
Total	67.9				
Equity capital	29.4	M$			
Fixed assets					
GoD	13.6	M$	(to be transferred to IPP)		
IPP	97.3	M$			
Energy sale					
Saled energy	95.7	GWh			
Sales price (2015 price)	15.10	¢/kWh			
Sales price (in 2021)	17.01	¢/kWh			
Escalation rate (/yr)	2.0%				
Operation & maintenance cost					
O&M cost (2015 price)	1.5	M$ (1.5% of capital cost)			
O&M cost (in 2021)	1.7	M$ (1.5% of capital cost)			
Escalation rate (/yr)	2.0%				
Depreciation					
Asset value (US$ million)	110.9	(including GoE assets)			
Useful life (in year)	30				
Residual value	0%				
Method	Straight line				
Concession fee	5.0%	of sales revenue			
Escrow account (for CB loan)	50.0%	of annual debt service			
Cash required	2.0%	of sales revenue			
Accounts receivable	12.5%	1.5 month of sales revenue			
Accounts payable	8.0%	1 month of O&M cost			
Deposite rate	3.0%				
Income tax	30.0%	from 8th year of operation			
Dividend rate	70.0%	of net profit			
Exchanger rate					

B.4 Graphs

Period	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12
Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Capital cost	-4.3	-10.0	-27.6	-38.2	-30.8												
Revenue						16.3	16.6	16.9	17.3	17.6	18.0	18.3	18.7	19.1	19.4	19.8	20.2
Make up wells						0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9	0.0	0.0
O&M costs						1.7	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0	2.1
Concession fee						0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0
Debt service						13.8	13.2	12.6	12.0	11.5	10.9	10.3	0.0	0.0	0.0	0.0	0.0
Tax						0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	3.6	1.4	3.9	4.0
Surplus						0.0	0.9	1.7	2.6	3.5	4.4	5.2	12.4	12.6	7.2	12.9	13.1

Period	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Year	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Capital cost																		
Revenue	20.6	21.0	21.5	21.9	22.3	22.8	23.2	23.7	24.2	24.7	25.1	25.7	26.2	26.7	27.2	27.8	28.3	28.9
Make up wells	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9
O&M costs	2.1	2.1	2.2	2.2	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.7	2.7	2.8	2.8	2.9	3.0
Concession fee	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4
Debt service	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tax	4.2	4.4	4.5	4.7	4.9	5.1	5.2	3.1	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.0	7.2	5.1
Surplus	13.3	13.5	13.7	13.9	14.1	14.3	14.5	9.1	14.9	15.1	15.3	15.6	15.8	16.0	16.3	16.5	16.8	11.5



C. Transmission Cost per kWh

plant factor	80%	15.0 MW	8760		
New Transmission Line Length	70	km			
Construction Cost	17.5	mil $	Interest Rate	10	%
Capital Recovery Factor (10%, 30 years)	10.6	%	Economic Life	30	year
Annualized Capital Cost	1.9	mil $/year			
Produced Energy (Plant)	105.12	GWh			
Station Use	9.0	%	95.659		
Transmission Loss	8.6	%	87.433		
Energy Sales	87.4	GWh			
Transmission Cost	**0.021**	¢/kWh			

添付資料-6　　容積法計算方法

PROCEEDINGS, Thirty-Ninth Workshop on Geothermal energy Reservoir Engineering
Stanford University, Stanford, California, January 26-28, 2015
SGP-TR-204

A Rational and Practical Calculation Approach for Volumetric Method

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Keywords: volumetric method, typical power cycle process, steam-liquid separation process, adiabatic heat drop, exergy efficiency, available thermal energy function

ABSTRACT

The USGS volumetric method together with Monte Carlo simulations is widely used for assessing the electrical capacity of a geothermal reservoir. However, the USGS method appears not to be easily usable with the probabilistic method. On the other hand, some of prevailing references practice the volumetric method calculations differently from the USGS method; in many cases rational explanations are not necessarily provided. Instead, we herein propose a rational and practical calculation method by reflecting both the steam-liquid separation process at separator and the adiabatic heat-drop process at turbine, together with a rational temperature at condenser; that can be used with Monte Carlo method also. The proposed method enables us to assess electrical capacity by clearly and rationally defined parameters for the equations; resulting in clearer understandings of the electrical capacity estimation of a geothermal reservoir. The proposed method shows an approximate agreement with the USGS method, but gives larger estimation results than the ones given by the prevailing calculation method. This might be attributed to how underground-related parameters should be estimated.

1. INTRODUCTION

USGS (Muffler, L.J.P, Editor 1978) introduced the stored heat method for assessing the electrical capacity of a geothermal reservoir. The equations for the methods are as follows.

$$q_r = \rho C V (T_r - T_{ref}) \quad \text{[kJ]} \quad (1)$$

$$R_g = q_{WH} / q_r \quad \text{[-]} \quad (2)$$

$$q_{WH} = m_{WH} (h_{WH} - h_{ref}) \quad \text{[kJ]} \quad (3)$$

$$W_A = m_{WH} \left[h_{WH} - h_0 - T_0 (s_{WH} - s_0) \right] \quad \text{[kJ] or [kW]} \quad (4)$$

(for a geothermal reservoir temperature > 150°C)

$$E = W_A \eta_u / (FL) \quad \text{[kJ/s] or [kW]} \quad (5)$$

Where q_r is reservoir geothermal energy, q_{WH} is geothermal energy recovered at wellhead, T_r is reservoir temperature, T_{ref} is reference temperature, T_0 is rejection temperature (Kelvin), m_{WH} is mass of geothermal fluid produced at wellhead, h_{WH} is specific enthalpy of geothermal fluid produced at wellhead, h_{ref} is specific enthalpy of geothermal fluid at reference temperature, h_0 is specific enthalpy of fluid at final state, s_{WH} is specific entropy of fluid at wellhead, s_0 is specific entropy of fluid at final state, ρC is volumetric specific heat of reservoir, V is reservoir volume, Rg is recovery factor, W_A is available work (exergy), E is power plant capacity, η_u is utilization factor (that includes energy ratio of steam fraction separated from the fluid and exergy efficiency), F is power plant capacity factor and L is power plant life.

While it is said that this is a good approach from theoretical perspectives, it includes issues to be discussed when used for liquid dominant geothermal fluid recovered at wellhead.

S K. Garg et al (2011) pointed out that the "available work" of USGS methodology is a strong function of the reference temperature, and that the utilization factor (i.e. ratio of electric energy generated to available work) depends on both power generating system and reference temperature. On the other hand, the AGEG Geothermal energy Lexicon (compiled by J. Lawless 2010) described that recovery factor of the USGS method rejects both the fraction of heat below commercially useful temperature and fraction of unrecoverable heat, when used for liquid dominant geothermal fluid. These and other relevant references we reviewed suggest that we should examine utilization factor and/or recovery factor in connection with both of liquid-steam separation process and reference temperature when we use the USGS method for a flash type power cycle using liquid dominant geothermal fluid. The determination of these parameters with considerations on the relations among these, will require proper and deep understandings of geothermal generation system. In addition, we observe that the equation (1) to (4) appear to be imbalancing, because the equations (1) to (3) include two reference-related parameters (T_{ref}, h_{ref}) whereas the exergy equation (4) does not include reference-related parameters in the square bracket. We also observe that the calculations using the USGS equations that include variable T_r dependent-parameters (h_{WH}, s_{HW}), with

Monte Carlo simulations, would be laborious. Thus, we consider that the USGS method would not be easily applicable for assessment of electric capacity of a geothermal reservoir with Monte Carlo simulations.

In place of the USGS method, the different method is being used by many prevailing references for geothermal resource estimations. We name this different method "the prevailing method". The equation of the prevailing method is given as follows.

$$E = R_g \eta_c \rho CV(T_r - T_{ref})/(FL) \quad \text{[kJ/s] or [kW]} \qquad (6)$$

Where η_c is named as "conversion factor".

The core term $\rho CV(T_r - T_{ref})$ in the equation (6) is exactly the same as the equation (1) of the USGS method. The theoretical concept, however, appears to be quite different. The prevailing method adopts much higher temperatures such as 150 ºC, 180 ºC or others to the reference temperature (T_{ref}); while the USGS method defines that the reference temperature (T_{ref}) for all cycles is chosen as 15 ºC (i.e. the average ambient temperature of the USA) and the rejection temperature as T_0=40 ºC (i.e. a typical condenser temperature) in the calculation of available work (W_A) of the equation (4). The reference temperature in the prevailing method is sometimes named as the abandonment temperature.

The prevailing method is said to be derived from Pálmason, G. *et al* (1985, in Icelandic). There seems however to have been variations in slecting the temperature (AGEG, 2010 refers to various cases). It is explained sometimes in such a way that it adopts a separator temperature to the reference temperature to exclude the geothermal energy to be abandoned as liquid form that is separated from fluid at separator. Here, a question arises on how the equation distinguishes the steam and the liquid; both separated in the separator at the same temperature; thereafter the liquid is to be abandoned whereas the steam to be used. Another application is that a cut-off temperature is sometimes selected. It would be conceived that the cut-off temperature is included in the equations to exclude non-economically-valuable fluid produced from the reservoir that has already been delineated by practitioners, where the cut-off temperature is understood as the one that defines the outer limit of the reservoir. Here, another question arises on why the cut-off temperature should be included in the equation if the outer limit of the reservoir has already been defined by the cut-off temperature to exclude non-economically-valuable fluid. Both cases above seem to be illogical.

The other different point is that the prevailing method adopts the conversion factor η_c ranging from 0.13 to 0.16 approximately; while the USGS method recommends 0.4-0.45 to the utilization factor η_u defined by the equation (5). *Obiter,* the equation (6) appears to be nothing but expressing a thermodynamic process: the term $R_g\rho CV(T_r - T_{ref})$, ($T_r$ >0 ºC and $T_{ref}>0$ ºC are assumed here), is the recovered heat energy that is made available when the temperature of fluid changes from T_r to T_{ref}, the fluid that conveys the heat from the reservoir. The term $R_g\rho CV(T_r - T_{ref})$ in the equation (1) of the USGS method expresses the heat energy available at the temperature condition of T_{ref}; in this context, it is clear that the utilization factor η_u was intended to include the steam energy ratio against the recovered energy and the exergy efficiency. On the other hand, it appears not to be clear what efficiencies are included in the conversion factor η_c because inclusion of the T_{ref} of much higher temperature in the equation (6) makes the thermodynamic implication of the equation ambiguous.

Thus, we consider that the prevailing method might be an empirical method based on field wisdom that attempts to assess electric capacity of geothermal reservoir that produces liquid dominate fluid at wellhead by modifying the concept of the USGS method. This is further discussed in the section 6 of this paper.

Instead, we herein propose a rational and practical method that defines the aboveground-related key parameters; that reflects the steam-liquid separation process in the calculations; that can be used with the Monte Carlo method also. The proposed method enables us to select a reference temperature, a recovery factor and a conversion/utilization factor rationally and independently, and separately from consideration of the steam-liquid separation process; that results in clearer understanding of the resource estimation.

2. INTRODUCTION OF AVAILABLE THERMAL ENERGY FUNCTION ζ

We begin our explanation with turbine side; because our primary interest lies on electrical power generation, and for that reason here includes the key point of this paper. We calculate electric energy by using the adiabatic heat-drop concept (or exergy concept) at turbine. This is widely used for design of turbine-generator system. In Figure-1 we illustrated the conceptual model of geothermal generation system we assumed. The electric capacity produced at turbine-generator system is written as;

$$E = \eta_{ex} m_{tbin}(h_{tbin} - h_{tbout})/(FL) \quad \text{[kW]} \qquad (7)$$

or

$$E = \eta_{ex}(q_{tbin} - q_{tbout})/(FL) \quad \text{[kW]} \qquad (8)$$

Where η_{ex} is exergy efficiency, $m_{tb\,in}$ is mass of steam at inlet of turbine, $h_{tb\,in}$ is specific enthalpy at inlet of turbine, $h_{tb\,out}$ is specific enthalpy at outlet of turbine, $q_{tb\,in}$ is thermal energy at inlet of turbine, $q_{tb\,out}$ is thermal energy immediately after turbine.

Here, we introduce the "available thermal energy function" defined by the following equation.

$$\zeta = (q_{tbin} - q_{tbout})/q_{WH} \quad \text{[-]} \qquad (9)$$

Where ζ is the available thermal energy function.

The available thermal energy function (9) we introduced, represents the ratio of the heat-drop at turbine against thermal energy available at wellhead. In other word, it represents the ratio of available thermal energy for electrical power generation against thermal energy available at wellhead.

Combined with the available thermal energy function (9), the equation (8) is rewritten as;

$$E = \eta_{ex}\zeta q_{WH} / (FL) \qquad \text{[kW]} \qquad (10)$$

Further, combined with the equations (1) and (2), the equation (10) is rewritten as;

$$E = \eta_{ex}\zeta R_g \rho C V (T_r - T_{ref}) / (FL) \qquad \text{[kW]} \qquad (11)$$

where

$$\rho C = (1-\varphi) C_r \rho_r + \varphi C_f \rho_f \qquad \text{[kJ/(kg°C)]} \qquad (12)$$

Where C_r is specific heat of reservoir rock matrix, C_f is specific heat of reservoir fluid, ρ_r is density of reservoir rock matrix and ρ_f is density of reservoir fluid.

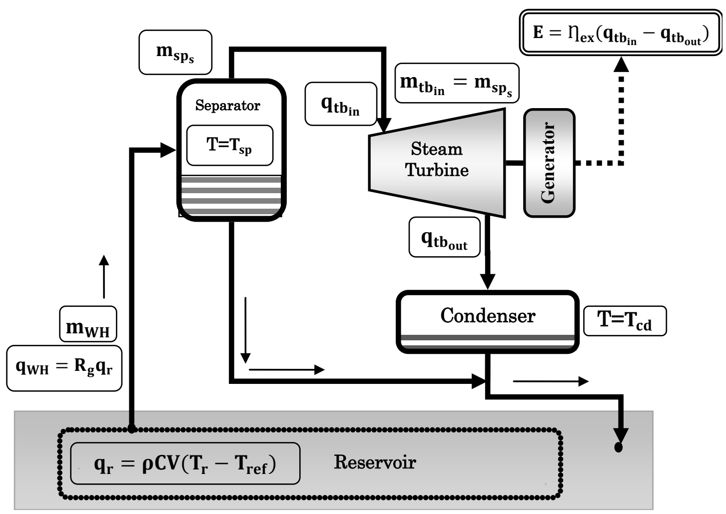

Figure 1 Simplified single flash power plant schematic

The available thermal energy function ζ in the equation (11) exclusively includes the thermal energy of the steam fraction only that is used for power generation. By introducing the available thermal energy function ζ to the volumetric method calculation, we can limit our considerations about utilization factor or conversion factor to turbine-generator related matters; and we can also limit our considerations about recovery factor to underground phenomenon. Thereby, the proposed method enables a rational assessment of electrical capacity of a geothermal reservoir by rationally defined parameters of the equations of the volumetric method.

3. INTRODUCTION OF READILY CALCULABLE EQUATIONS FOR ζ

In this section, we will describe the procedure of how we obtain calculable equations of the available thermal energy function ζ ; and thereafter, we will introduce approximation equations of the available thermal energy function ζ for practical uses, as direct functions of a reservoir temperature T_r .

3.1 Assumptions

We assume that geothermal energy is recovered as saturated and single-phase liquid. This is not only for a simplification of calculation; but also for a reason that S. K. Sanyal et al (2005) pointed out that the “explicit consideration of the two-phase volume in reservoir estimation is not critical”.

We also assume a single flash power cycle with a separator of a typical pressure. Dry steam is assumed at inlet of turbine; wet steam is then assumed immediately after turbine to obtain near-realistic power output. We will assign a typical temperature to condenser, too.

3.2 Determination of "available thermal energy function ζ"

3.2.1 Geothermal energy recovered at the wellhead (q_{WH})

The geothermal energy recovered at wellhead is defined by the equation (3) when the final state of the fluid is the one under the ambient condition. However, since we assume a geothermal power plant of single flash type, the final state of the fluid contributing power generation should be under the condenser condition. We will assume at a later part of this paper the condenser temperature. Thus, at this step of calculation we assume that all the recovered heat at the well head will be sent from the wellhead to the separator.

$$q_{WH_L} = m_{WH_L} h_{WH_L} \quad \text{[kJ]} \quad (13)$$

Where $q_{WH\,L}$ is geothermal energy recovered as liquid phase at wellhead, $m_{WH\,L}$ is mass of single phase geothermal liquid produced at wellhead, $h_{WH\,L}$ is specific enthalpy of single phase geothermal liquid produced at wellhead.

3.2.2 Thermal energy at the inlet of the turbine ($q_{tb_{in}}$)

The thermal energy at turbine inlet ($q_{tb_{in}}$) should be the thermal energy of dry steam separated at separator from fluid recovered at wellhead. The following equations give the mass of the steam fraction separated at separator, and to be sent to turbine.

$$m_{sp_S} = \alpha_{sp_S} m_{WH_L} \quad \text{[kg]} \quad (14)$$

$$\alpha_{sp_S} = (h_{WH_L} - h_{sp_L}) / (h_{sp_S} - h_{sp_L}) \quad \text{[-]} \quad (15)$$

Where $m_{sp\,s}$ is mass of steam fraction separated at separator, $\alpha_{sp\,s}$ is ratio of steam mass fraction separated at separator, $h_{sp\,L}$ is specific enthalpy of liquid fraction separated at separator, and $h_{sp\,S}$ is specific enthalpy of steam fraction separated at separator.

From the above, the thermal energy at turbine inlet is given by;

$$q_{tbin} = m_{sp_S} h_{sp_S} = \alpha_{sp_S} m_{WH_L} h_{sp_S} \quad \text{[kJ]} \quad (16)$$

3.2.3 Thermal energy immediately after the turbine($q_{tb_{out}}$)

The dry steam in turbine is losing its thermal energy; and becomes wet steam when exhausted from turbine. The adiabatic heat-drop concepts explains this process. The following equation gives the dryness (quality) of the wet steam immediately after turbine.

$$\chi = (s_{sp_S} - s_{cd_L}) / (s_{cd_s} - s_{cd_L}) \quad \text{[-]} \quad (17)$$

Where χ is quality of steam (dryness of steam), $S_{sp\,S}$ is entropy of steam fraction at separator, $S_{cd\,L}$ is entropy of liquid fraction at condenser and $S_{cd\,S}$ is entropy of steam fraction at condenser.

Then the enthalpy of the wet steam is given by;

$$h_{tbout_{SL}} = h_{cd_L} + (h_{cd_S} - h_{cd_L})\chi \quad \text{[kJ/kg]} \quad (18)$$

Where $h_{tbout\,SL}$ is specific enthalpy of wet steam immediately after turbine, $h_{cd\,L}$ is specific enthalpy of liquid fraction at condenser and $h_{cd\,S}$ is specific enthalpy of steam fraction at condenser.

Since the same mass as that of the dry steam is exhausted out of turbine, the thermal energy immediately after turbine is given by;

$$q_{tb_{out}} = m_{sp_S} h_{tb_{out}SL} = \alpha_{sp_S} m_{WH_L} h_{tb_{out}SL} \quad \text{[kJ]} \quad (19)$$

3.2.3 The available thermal energy function ζ

Replacing the variables of the equation (9) with the equations (13), (16), and (19) gives the following equation.

$$\zeta = \alpha_{sp_S}(h_{sp_S} - h_{tb_{out}SL}) / (h_{WH_L}) \quad \text{[-]} \quad (20)$$

With the equation above, we can obtain specific values of the ζ by giving the enthalpies.

3.2.3 Introduction of approximation equations of ζ for practical uses.

Calculation using the variables in the equation (20) for each reservoir temperature is laborious and not readily usable with the Monte Carlo Method. We will then introduce approximation equations of the ζ from the calculation results of the five typical reservoir temperatures, i.e. 180 ºC, 200 ºC, 250 ºC, 300 ºC, and 340 ºC.

For the calculation we assume that the separator pressure is 5 bar (151.8 ºC), because the produced electrical power would be maximum when the separator pressure is around 4 bar to 5 bar. Let us assume the power generation is E=1.00 when the separator temperature is 150 ºC. A simplified calculation for various separator temperatures gives the following results: i.e. when the separator temperature is

120 ºC, 140 ºC, 160 ºC, and 180 ºC; then, electric energy produced at turbine-generator system will be E=0.95, E=1.00, E=0.98, and E=0.88 respectively. R. Dipippo (2008) shows similar results.

We assume typical values for the other factors as follows.

Condenser temperature(T_{cd}) : 40.0 ºC (a typical temperature of condenser)

The results are shown in Figure-2. It confirms that the ζ can be expressed as functions of the reservoir temperate (T_r). The form of the approximation equation is given below.

$$\zeta = 0.0000000127T_r^3 - 0.00001249007T_r^2 + 0.00465438806T_r - 0.4591082158 \quad [\text{-}] \tag{21}$$

The curve of the equation (21) is shown in the Figure-2. It shows the available heat function ζ will be zero when the reservoir temperature equals to the separator temperature T_{sp} (151.8 ºC). At this state, the recovered fluid no longer flashes in the separator. This temperature shall be "the plant minimum operation temperature" for a flash type system, that is defined only by separator temperature. Note this should be differentiated from "cut-off temperature" that should define the spatial outer limits of the reservoir

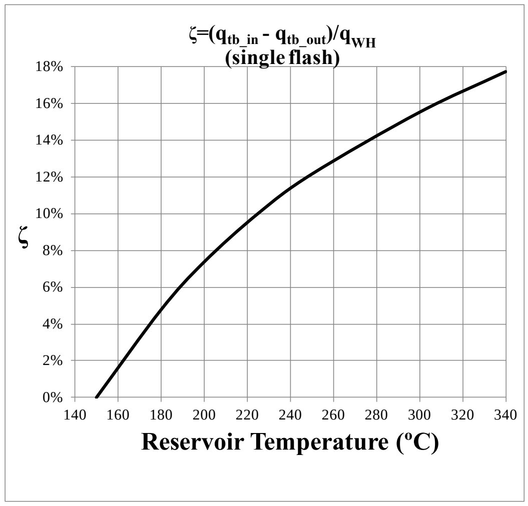

Figure 2: Calculation results of ζ against various reservoir temperatures..

3.3 Selection of Conversion Factor – Turbine-generator efficiency: Exergy Efficiency (η_{ex})

We have started the electric capacity calculation with the equation (7). The coefficient η_{ex} should therefore be defined as:

$$\eta_{ex} = \{E(FL)\} / \{m_{tb_{in}} (h_{tbin} - h_{tbout})\} \quad [\text{-}] \tag{22}$$

Note that this coefficient η_{ex} is the "functional exergy efficiency (DiPippo 2008, p 240)" that is different from both the "utilization factor η_u" defined in the equation (5) of the USGS method and the "conversion factor η_c" in the equation (6) of the prevailing method; the "utilization factor" will include the energy ratio of steam separated from the fluid and exergy efficiency; the "conversion factor" may include the energy ratio of steam separated from the fluid, Carnot efficiency and exergy efficiency (the "conversion factor" of the prevailing method is not necessarily clearly defined, because the method appears not to be explainable from thermodynamic point of view.)

For the parameters in the right side of the equation (22), we examined the 189 existing geothermal power stations all over the world which are listed in the booklet (ENAA 2013 in Japanese), thereafter, we calculated each exergy efficiency defined by the equation (22). In the calculation, steam dryness was also considered immediately after the turbine. After the calculation, we examined the correlation between the exergy efficiencies and the temperature drops $(T_{tbin} - T_{cd})$ between turbine inlet and condenser. Thereby, we obtained the following approximation equation.

$$\eta_{ex} = 0.163897 \ln(T_{tbin} - T_{cd}) - 0.001766 \pm 0.05 \quad [\text{-}] \tag{23}$$

Where $T_{tb\,in}$ is temperature of turbine inlet and T_{cd} is temperature of condenser.

The graphical scatter plot showed large variations; we, therefore, added a distribution range of ± 0.05. This is because the actual efficiencies of turbine-generator system depend on many factors that include the efficiency of basic power plant design, resource temperature, concentrations of dissolved gases in the reservoir fluid, the condition of plant maintenance and so on. Nevertheless and for that reason, the approximation equation (22) reflects actual conditions and therefore applicable for the calculation of the volumetric method.

For our case of $T_{tb_{in}}$ = 151.8 ºC, T_{cd} = 40 ºC,

$$\eta_{ex} = 0.77 \pm 0.05 \qquad [\,-\,] \qquad (24)$$

3.3 About Recovery Factor R_g

There are a number of references that discussed on the recovery factor. M. A. Grant (2014) recently pointed out that the past values of recovery factor have been in all cases high in comparison with actual performance. We herein refer to some of the papers we examined.

GeothermEx (2004) describes: "Based on our assessment of more than 100 geothermal energy sites around the world, we have found it more realistic to apply a recovery factor in the range of 0.05 (Min) to 0.2 (Max) without application of a most-likely value".

C.F.Williams et al (USGS open-file Report 2008-1296) describes that the recovery factor "R_g for fracture-dominated reservoirs is estimated to range from 0.08 to 0.2, with a uniform probability over the entire range. For sediment-hosted reservoirs this range is increased from 0.1 to 0.25".

S.K. Garg and J. Combs (2010) describes: "Prior to geothermal energy well drilling and testing, it will not in general be possible to obtain any reliable estimates of reservoir thickness and thermal recovery factor. Since it may eventually prove impossible to produce fluid from a geothermal energy reservoir, the possibility of the thermal recovery factor being zero cannot be discounted during the exploration phase; therefore, the proper range for thermal recovery factor is from 0 to 0.20 (the latter value is believed to be the maximum credible value based on world-wide experience with production from liquid-dominated reservoirs)".

AGEA compiled by J. Lawless (2010) describes: "In fracture dominated reservoirs where there is insufficient information to accurately characterize the fracture spacing, adopt the mean USGS value of 14%, or 8 to 20 % with a uniform probability over the entire range when used in probabilistic estimates". "In sedimentary reservoirs or porous volcanic-hosted reservoirs, of 'moderate' porosity (less than 7% on average), adopt the mean USGS value of 17.5%, or 10 to 25% with a uniform probability over the entire range when used in probabilistic estimate". "In the case of sedimentary or porous volcanic-hosted reservoir of exceptionally high average porosity (over 7%), adopt the empirical criterion of recovery factor 2.5 times the porosity to a maximum of 50%".

M.A. Grant (2014) pointed out that there are a wide range of recovery factors: 3-17 % covers the entire range of observed results. This indicates that any result is subject to an error of at least a factor of 2, or alternatively ± 70%. One conclusion is immediate: past recovery factors have been too high, and comparison with actual performance show that an average value of 10% should be used.

The decision on what values should be chosen is left to professionals in charge, that depends on the site conditions, past experiences and/or degrees of diagnostic confidence. Note that the proposed method enables that the recovery factor can be determined independently from both the liquid-steam separation process and conversion process of thermal energy to electric energy.

4. EXAMINATIONS OF THE RESULTS

We calculated electric powers per km^2 (power density) by three different methods of the USGS method, the proposed method and the prevailing method for a comparison purpose with the following parameters.

C_r	= 1.0	[kJ/(kg ºC)]
ρ_r	= 2750	[kg/m^3]
C_f	= 5.0	[kJ/(kg ºC)]
ρ_f	= 790	[kg/m^3]
V	= 2	[km^3], (Reservoir thickness 2 k m)
F	= 0.9	[-]
L	= 30	[years to be converted to second when applied]
R_g	= 0.12	[-]
T_{ref}	= 0.01 ºC (h_L=0 kJ/kg for the proposed method assuming all the recovered heat is sent to the separator)	
	= 20 ºC for the USGS method;	
	= 150 ºC or 180 ºC for the prevailing method	
T_0	= 40 ºC for the USGS method (condenser temperature)	
Conversion factor	η_C	= 0.13 for the prevailing method
Utilization factor	η_U	= 0.45 for the USGS method
Exergy efficiency	η_{ex}	= 0.77 for the proposed method

The results are given in Figure-3. It shows that the proposed method is in good agreement with the USGS method. In addition, it gives similar results to the power density ('the main sequence') presented by wilmarth et al (2014). A deviation from the USGS method is observed at lower side of reservoir temperature. This is because that the USGS method adopts a fixed utilization factor; whereas the proposed method adopts 'the available thermal energy function" that is a function of T_r as shown in Figure-2. This suggests that the utilization factor may have to be smaller than 0.45 when reservoir temperature is lower, though its impact will be negligible.

On the other hand, the Figure-3 shows that the prevailing method is considerably different from both of the proposed method and USGS method.

We calculated the electric capacity by the proposed method, for the four cases of recovery factors of R_g =0.08, 0.12, 0.15, and 0.20. The other parameters remain same as above. The results are shown in Figure-4. It demonstrates that selection of the recovery factor will give a significant impact on the calculation results of electric capacity estimation by the volumetric method. Similarly, the other underground-related factors ρC, T_r and/or V will have similar impacts on the calculation; which must be emphasized.

From the above and since we have defined the aboveground-related key parameters, the significant differences between the prevailing method and the proposed method shown in Figure-3 may be attributed to the definition differences of the underground-related parameters. This is further discussed in the section 6 Discussion of this paper.

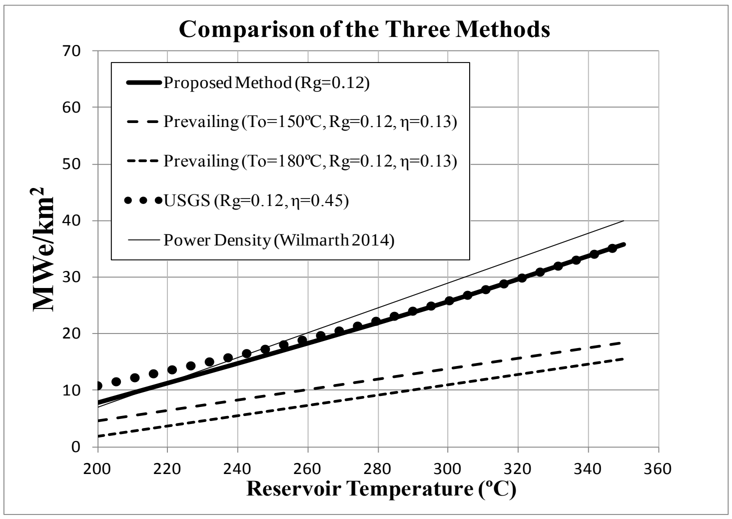

Figure 3: A Comparison of calculated electric power among three methods (Single Flash Power Cycle)

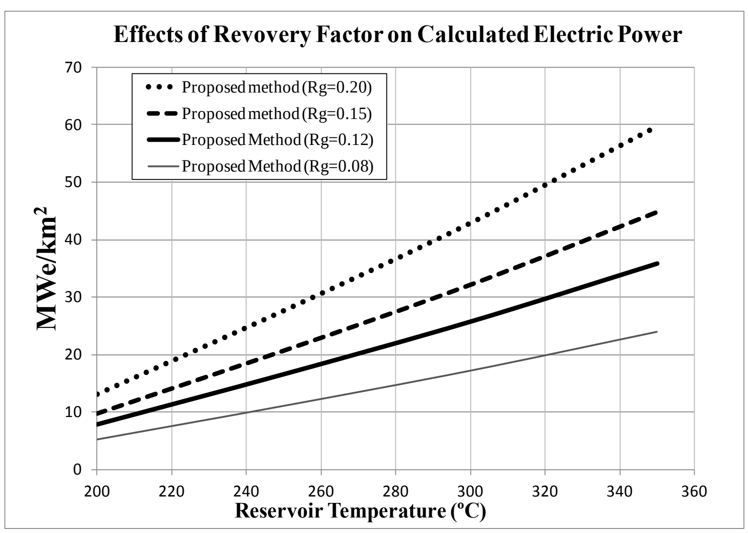

Figure 4: Effects of Recovery Factor on Calculated Electric Power (Single Flash Power Cycle)

5. SUMMARY

We proposed herein a rational and practical calculation approach of the volumetric method by introducing 'the available thermal energy function ζ. The introduction of the available thermal energy function ζ enables us to include the steam-liquid separation process in the calculation equations rationally, which further enables us to examine the underground-related parameters separately and independently from the aboveground-related parameters; i.e the recovery factor and turbine-generator efficiency (exergy efficiency) can be selected independently, without consideration on steam-liquid separation process; thereby, the proposed method realizes rational and practical calculations of geothermal resources of liquid dominant geothermal field; that can used with the Monte Carlo method.

We hereunder summarize the proposed method for a practical use. Assuming saturated single phase geothermal liquid of temperature T_r ºC at wellhead, T_{sp}=151.8 ºC, and T_{cd} =40 ºC, the following equations for the volumetric method will give an estimation result of electricity capacity of a liquid dominant geothermal reservoir if the underground-related parameters are properly selected.

$$E = \eta_{ex} \zeta R_g \rho C V (T_r - T_{ref}) / (FL) \qquad \text{[kW]} \qquad (25)$$

where

$$\rho C = (1-\varphi) C_r \rho_r + \varphi C_f \rho_f \qquad \text{[kJ/(m}^3\text{ ºC)]} \qquad (26)$$

$$\zeta = 0.0000000127 T_r^3 - 0.0000124900 T_r^2 + 0.0046543806 T_r - 0.4591082158 \qquad \text{[-]} \qquad (27)$$

$$T_{ref} = 0.01 \qquad \text{[ºC]} \qquad (28)$$

$$\eta_{ex} = 0.77 \pm 0.05 \qquad \text{[-]} \qquad (29)$$

$R_g = 0.05 - 0.2$ proposed by GeothermEx 2004), [-] (30)

or $R_g = 0.08 - 0.2$ or $R_g = 0.1 - 0.25$ proposed by C.F.Williams (2008),

or $R_g = 0 - 0.2$ proposed by S.K. Garg et al (2010)

or $R_g = 0.05 - 0.2$ or $R_g = 0.10 - 0.25$, or R_g =2.5 times the porosity to a maximum 50%, proposed by AGEA (2010).

or $R_g = 0.03 - 0.17$, 0.10 in average proposed by M.A. Grant (2014)

We may adopt different constants for the available thermal energy function ζ and use a different value of η_{ex} when it should become necessary to change, separator temperature and/or condenser temperature. The calculation procedures are given herein the above. Once the equations are given in a spreadsheet, we can examine as many cases as possible about underground related factors together with the Monte Carlo method.

6. DISCUSSIONS

Having summarized the proposed calculation method above, we continue this paper to examine the relationship between the prevailing method and the proposed method. We regard the USGS method ≈ the proposed method in the following discussions, since the theoretical background of the proposed method is almost same, and the both produce similar calculation results,

6.1 Deriving of Approximation Equations of the Proposed Method

Under the conditions of T_{sp}=151.8 ºC and T_{cd}=40 ºC, Figure 3 implies that the variable term $\zeta(T_r - T_{ref})$ in the equation (11) will be a near liner relation with T_r, thus this liner relation is approximated as:

$$\zeta(T_r - T_{ref}) = (0.3312 T_r - 51.911) \qquad \text{[liner approximation]} \qquad \text{[ºC]} \qquad (31)$$

With the equation (31), the equation (11) becomes;

$$E = \eta_{ex} R_g \rho C V (0.3312 T_r - 51.911) / (FL) \qquad \text{[KW]} \qquad (32)$$

This is further reduced as;

$$E = (0.77 \pm 0.05) R_g \rho C V (0.3312 T_r - 51.911) / (FL)$$

$$E = 0.3312 (0.77 \pm 0.05) R_g \rho C V (T_r - 157) / (FL)$$

$$E = (0.26 \pm 0.02) R_g \rho C V (T_r - 157) / (FL) \qquad \text{[KW]} \qquad (33)$$

The equation (33) shows that the equation (11) of the proposed method has eventually become the same equation form as the equation (6) of the prevailing method. Note that the second constant 157 should be the T_{sp} (151.8 ºC) as shown in the previous section 3.2.3; the constant 157 here is the one that resulted from the linear approximation shown in the equation (31).

6.2 Discussions on the Approximation Equation of the Proposed Method in connection with the prevailing method

As the conclusion, two constants of the equation (33) are mere the products of the linear approximation, therefore, any discussions on the equation (33) relating with resource estimations would appear to be meaningless or misleading. However, step-by-step discussions would be helpful to reach this conclusion for future possible discussions that may be instigated; thereafter we will discuss on possible reasons of the differences between the prevailing method and the USGS method.

6.2.1 Is the second constant 157 the cut-off temperature?

A number of constants have been proposed for the equation (6) of the prevailing method in various references. The constants in the equation (33) might be considered to be a variety of the equation (6) of the prevailing method. Here are our observations on the equation (33) in connection with the prevailing method.

a. The approximation constant 157 in equation (33) appears to be the one that is sometimes named as "cut-off temperature". However, this has to be named as the "plant minimum operation temperature", at which the fluid no longer flashes in separator of the assumed separator temperature (151.8 ºC) as described in the previous section 3.2.3. The "plant minimum operation temperature" is rather a "plant-related temperature" that shall be differentiated from the "cut-off temperature". The cut-off temperature is defined as "the temperature below which there is no economic value in the fluid - the temperature at which wells cease to flow or it becomes uneconomic to pump them. This defines the outer limits of the resource (M A Grant, *et al* 2011, p 47)." Thus, the cut-off temperature is a "reservoir related temperature". The plant minimum operation temperature shall not be larger or preferably sufficiently lower than the reservoir related cut-off temperature to ensure fluid to flash in the separator. From this point, the approximation constant 157 in the equation (33) shall not be replaced with reservoir-related cut-off temperature that has to be separately decided from field observations. (If the separator temperature should be designed at 180 ºC for an instance, then the second constant in the equation (33) will be 180; however, the first constant has to be changed in accordance to the calculation and approximation shown above.)

b. As mentioned before, such explanation that the cut-off temperature is included in the equation to exclude fluid of no-economic value from the already defined reservoir seems to be illogical and unexplainable. The inevitable possibility that drilling wells may fail to produce useful fluid from the reservoir shall be dealt with the recovery factor or probabilistic approaches.

c. In addition, the cut-off temperature (= T_{ref}) in the prevailing method is commented by M.A. Grant (2014) in such a context that "the different approaches also implies unrecognized assumptions about the physical process controlling reservoir depletion". The "different approaches" here means the ones that assign a cut-off temperature to T_{ref}, that are derived from the Icelandic practice. Our observation on the unrecognized assumptions is that such physical process controlling reservoir depletion seems not to be a matter of T_{ref} to be expressed in the thermodynamic equation. If the temperature of a part of the reservoir is expected to fall down below the cut-off temperature during operation period, it seems to be logical to reduce the value of either the reservoir volume or the recovery factor, or the plant life time for an extreme case.

6.2.2 Is the second constant 157 the reference temperature for the power generation cycle?

a. On the other hand, from a thermodynamics point of view, the equation (33) could possibly be interpreted in such a way that the power capacity E calculated is an energy fraction converted from the recovered heat energy when the temperature changes from T_r to 157 ºC, with adjustment by the multiplier (0.26 ± 0.02) and the divisor (FL). In this context, the approximation constant 157 in the equation (33) is the one that is named as "reference temperature", "rejection temperature", "base temperature" or the like; the temperature in the equation (33) shall be defined as the temperature of the final state of the fluid at a point of a power plant. However, this corresponds to the rejection temperature at the separator, not the final state temperature of the whole power generation cycle as seen above. This constant shall not be regarded as the final state temperature of the power cycle. At the same time, the first constant (0.26 ± 0.02) shall not be defined as a kind of a logically-derived efficiency, though it looks seemingly to be a meaningful coefficient.

6.2.3 What are the fist and the second constants in the equation (33)?

Consequently, we have to come back to the equation (33); whereat, we recall that the both constants 157 and (0.26 ± 0.02) were the mere resultants of the linear approximation. They were derived as the impartible combination under the specific assumptions (T_{sp}=151.8 ºC and T_{cd}=40 ºC). Any of these two constants shall not be examined independently or shall not be changed separately. Those two approximation constants, as it were, are "the virtual reference temperature" and "the virtual conversion factor" of "the virtual geothermal power plant" that is virtualized on the basis of the approximation equation (33), that has been derived through the series of calculations, that does not represent the thermodynamic process of any actual power plant. Thus, discussions on these approximation constants will probably be meaningless and possibly be misleading or even harmful when geothermal resource is estimated by the volumetric method.

6.3 Discussions on the Relation between the Prevailing Method and the USGS Method (≈the Proposed Method)

a. Nevertheless, the equation (33) is simple in form, not many variables included, and thus easy to use with Monte Carlo simulation. The prevailing method appears to have been used by adopting approximate a half value of the first approximation constant (0.26 ± 0.02) and a cut-off temperature similar to the second approximation constant 157 to suit field conditions. Although these constants shall not be allowed to use from the thermodynamic point of view, estimations by the prevailing method have been reported to be in accordance with other more precise estimation methods or field observations (Sarmiento et al 2007, which practices the prevailing method, but appears to have referred to Muffler P., et al (1978) of the USGS method as the methodological base. Similar undistinguishing quotations are seen in other references).

b. At the same time and on the other hand, the USGS method (≈ the proposed method) has been used for resource estimations, although the USGS method gives larger results than the ones of the prevailing method when the same underground-related parameters are given to the both methods as shown in Figure -3. Our observations are as follows.

(i) We have defined the aboveground-related parameters for the proposed method (≈ the USGS method), thus the discrepancy may possibly be due to differences of interpretations on underground-related parameters; i.e. for the resource estimation of the same geothermal field, the practitioners of the prevailing method would propose the $(R_g\rho CV)_{prevailing}$ as their underground-related parameters; whereas the other practitioners of the USGS method (≈ the proposed method) would propose the different parameters $(R_g\rho CV)_{USGS}$; $(R_g\rho CV)_{prevailing} \neq (R_g\rho CV)_{USGS}$.

(ii) The USGS method appears to assume that the all the heat energy relating to $(R_g\rho CV)_{USGS}$ should be extracted at the ground surface, because the method (when R_g=0.12 in Figure 3) gives similar results to the "main sequence" of the power density (Wilmarth *et al*., 2014); the analysis of the power density does not include the information of failed wells. In other words, possibility of well failures may not be included in the USGS method. Geothermal wells however are not always successful to produce useful fluid. Sanyal S.K *et al*. (2012) analyzed 2,528 geothermal wells in 52 field in 14 countries and found that the mean success rate was 68%. At early stages of exploitation the rate varies in a range from 20% to 60 % approximately. If the average drilling success rate should be considered for a resource estimation, the resultant recovery factor would be R_g=0.12 x 68%= 0.08; with this R_g=0.08 the USGS method will come close to the prevailing method of T_0=150 ºC as shown in Figure-4. M.A. Grant (2014) strongly pointed out the past values of R_g have been all cases too high, an average value of R_g=0.10 should be used.

(iii) On the other hand, the prevailing method even with R_g=0.25 is reported to be in good agreement with actual performance (Sarmiento et al 2007). Thus, it may allow localized non-productive zones to be included within the reservoir, by adopting amended constants to the places of the first and second constants of the equation (33) "to calibrate" the results to the actual performance. However, again, it shall not be the constants of the equation (33) but the underground-related parameters such as R_g, V and/or others that shall be examined. In other words, the calculation form of the equation (33) may have falsely diverted our attentions from the underground-related parameters to the aboveground-related parameters or the approximation constants in the approximation equations.

6.4 Closing discussion

(i) All those may be resultants from usage of ambiguously defined parameters, which may has allowed practitioners to adopt various values of not only underground-related parameters (R_g, ρC, V, *cut-off temperature*) but also aboveground-related parameters (T_{ref}, T_{sp}, T_{cd}), with considerations on relations with others as if some of those would be functions of others; such considerations however may sometimes not be necessary if the parameters used should be well-defined.

(ii) Instead, we have introduced the equation (11) with clear definitions of the aboveground-related key parameters, including the flashing process with the typical condenser conditions. The proposed method could allow us to examine the underground-related parameters rationally, being independent from considerations of relations with aboveground-related parameters. The proposed method will also allow us to avoid possible misleading that may be caused by the prevailing method in the form of the equation (33).

(iii) In any cases, it is of paramount importance to use the volumetric method with very careful and prudent examinations and considerations together with clear definitions on the underground-related parameters.

7. CONCLUSION

The USGS method is theoretical, but practice with the equations together with Monte Carlo method seems to be laborious; the prevailing method is somewhat questionable from theoretical point of view. We have herein proposed a rational and practical calculation method for volumetric method for a specific but typical case. We would like to recommend to use the equation (25) because the proposed method enables us to assess electrical capacity by clearly and rationally defined parameters for the equations; thereby we could examine the underground-related parameters, resulting in clearer understandings of the electrical capacity estimation of a geothermal reservoir. Once clearer assessment with the specific but typical conditions of the aboveground parameters has been made, one could extend assessments with other conditions of the aboveground parameters for comparisons. If the aboveground-related parameters T_{sp} and/or T_{cd} should be changed to suit a particular field condition, we could modify the constants of the available energy function.

We have also derived the simplified equation (33) that appears to be the same form of the prevailing method and provides us with a simple calculation procedure. It however masks its theoretical background completely, which may hinder us from proper and deeper understanding of underground related parameters to be used for the volumetric estimation. This may mislead us to unnecessary considerations and/or discussions on the virtual "conversion factor" and/or virtual "reference temperature" of the "virtual power plant" virtualized by the equation (33). We therefore would like to recommend to avoid using this equation (33).

Finally, very careful and prudent examinations and considerations shall be required for determination of underground-related factors, in particular R_g and/or V. If estimation results by the proposed method should not be in accordance with other more precise estimation methods or field monitoring results, the underground related parameters have to be examined. Well drilling success rate could be in cooperated when we determine R_g and/or V.

ACKNOWLEDGMENTS

We would like to express our greatest appreciation to Tsuneo Ishido, Daisuke Fukuda, Mineyuki Hanano, Katsuya Kuge and Mayumi Hayashi for helpful discussions and suggestions; Steinar Þór Guðlaugsson, Helga Tulinius and Benedikt Steingrímsson for their comprehensive comments on a drafted paper; and following eminent professionals Jim Lawless, Sabodh K. Garg and Hirofumi Muraoka for kind e-mail communications. We also would like to express our gratitude to our colleagues working together for helpful discussions as well as Nippon Koei Co., Ltd for supporting us to complete this work.

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EoD

添付資料-7　　議事録

Data Collection Survey for Geothermal Development in Republic of Djibouti (Geophysical Survey)

Minutes of Workshop

Place: Palais du Peuple, Djibouti

Date: August/10/2015, 9:00-11:00

Attachment: 1. Agenda of the Workshop
2. Handout material
3. Participants list

The Workshop

1. The ODDEG moderator (Hamoud Souleiman) introduced the Workshop.
2. Mr. Sassadate, the representative of JICA Djibouti office welcomed all the participants and described the geothermal development cooperation between Djibouti-Japan.
3. Mr. Abdou Mohamed Houmed, Director General of ODDEG, expressed gratitude for the assistance in geothermal development extended by the government of Japan and JICA and made his opening address to the participants.
4. Followed by the invitation to the presentation of the survey results, Mr. TAKAHASHI, the Team Leader, and Mr. TAKEDA, the geophysicist of the JICA Survey Team made the presentation in accordance to the handout material attached hereto.
5. The Question and Answer session followed; the minutes of the questions and answers are as follows.

Q&A:

- ✧ Q 1: With no clear cap rock structure observed in resistivity results, how the aerial limitation of the geothermal reservoir was decided ?
  - ➢ A: The JICA team assumed that the reservoir could exist in the portion of in 40 – 160 Ωm approximately in the plateau areas, based on the correlation between the resistivity distribution and the depth of clay minerals in a past well (Hanle-2). The western boundary of the reservoir was assumed to be the main fault delineating the plateau and the plan; the northwest boundary is correspondent to the limit of the survey area; although all those are preliminary.
- ✧ Q 2. The TEM data was used only for the static shift correction. Why did you not analyze the resistivity structure of shallow part (shallower than 300m) despite that the TEM data in shallow area were obtained.
  - ➢ A: It was not analyzed, because the target of this survey is geothermal structure in deep

area . Our effort was concentrated on the purpose we should attain.

- Q 3: Is the deep high resistivity area not corresponded to the cold area? If that is the heat source, cap rock structure would have been created above that area, and it appears in resistivity structure.
  - A: The fact that the plain area is cold was verified by the past survey. The fumaroles that are observed on the plateau area imply that there should be the heat source under the ground nearby. We assumed the heat source should be corresponded to the high resistivity zone in plateau area.
- Q 4: Will a correlation be conducted between the depth of alteration mineral, resistivity value, and the temperature log? It will help you to understand geothermal structure.
  - A: It is of course carried out in the future test well drilling.
- Q 5. The main fault on the SW side should incline to NE direction instead SW direction according to field observation.
  - A: All the information we have not only from desk top work but also field observation the fault on the subject shall be interpreted to incline to SE side. The geological map ORSTOM (1987) shows the similar cross section.
- Q 6. There will be no heat in the plateau unless there should be not dome structure. The heat source in the Hanle Plateau should be structural origin.
  - A: There are a number of volcanic corn on top of the Plateau, which implies a recent volcanic activities. Fumaroles are associated with Rhyolite dyke/vain in many cases. It would be reasonable that the heat could be associated with those volcanic activities.
- Q 7. Correlation between the MT survey and the geological logs of the past well will be useful to understand the geological structures or setting in Hanle.
  - A: The consultant tried such correlation during this analysis period; but, could not get useful results because all geology in the all past wells were classified as basalt. It was not possible to interpret resistivity of rock from the borehole logs. It is also not possible to correlate the MT resistivity with thin changes of rock faces/characteristics

    In Hanle plain, the alluvial sediment is about 100 m deep. This is not a target of the MT survey for the geothermal development.
- Q 8. Was the geothermal reservoir model created by all the geology, geochemistry and geophysical data being put together for consideration? There are much information in Hanle, conducted by Italian consultants in 1980's.
  - A: All and as much information as possible we have at hand were all integrated for the construction of the geothermal reservoir.
- Q 9. Subsurface temperature measurement was very successful in Lac Abe. The additional survey shall include the sub-surface temperature. Measurement in depths (30-50 cm deep) will

work well if measurement is carried out in night. If JICA provides the ODDEG with equipment, which are not expensive, the ODDEG could do the survey by themselves.

- A: The consultant appreciate the proposal and the consultants consider it useful. But, according to a literature the thermo-sensor shall be put in to the ground down to 2 m to avoid the influence by the air temperature, but the Hale Plateau is so rocky that thermo-sensor could not be penetrated in to 2 m depth. This is the reason why the consultant did not propose the subsurface temperature measurement in Hanle. However, we could propose JICA head office to procure tools and equipment for the survey by which the ODDEG would do the survey since those are not expensive.

✧ Q 10. With the additional survey proposed by the Consultant, could it be possible to reach a decision whether test well drilling is to be proposed or not.

- A: It will depend on the results to be obtained. The consultant shall be in a position who shall provide a clear proposal on the decision of test well drilling.

Through the above technical discussions, it was generally agreed that the proposed additional surface survey would be necessary before the test drilling program.

Finally the consultant requested comments on the Draft Final Report to be sent to the Consultant through ODDEG by 24th August 2015.

The work shop was closed.

** End of Document **

Confirmed by:

Le Directeur Général
Abdou Mohamed Houmed
OFFICE DJIBOUTIEN DE DÉVELOPPEMENT DE L'ÉNERGIE GÉOTHERMIQUE • ODDEG •

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Unité – Egalité – Paix

OFFICE DJIBOUTIEN DE DEVELOPPEMENT DE L'ENERGIE GEOTHERMIQUE

(ODDEG)

DATA COLLECTION SURVEY ON GEOTHERMAL DEVELOPMENT IN DJIBOUTI
DRAFT FINAL REPORT

Geophysical Survey in Hanlé Garabbayis

REMARKS AND COMMENTS OF THE DRAFT FINAL REPORT

Made by ODDEG team

With response from the JICA Team

August, 2015

Sublimated to the quality of work of this scientific exercise, We would like to congratulate all the experts of the mission of JICA for the professionalism and precision of this work done with heart and commitment.

The ODDEG's officers have edited some comments which have been summarized below. The remarks and comments can be divided in two main parts. The first part concerns the form of the report and the second part is focused on the content and the technical matters.

1st Remark:

In the cover page and figure 2.5: There is confusion over the drilling location: Hanlé Garabbayis 2 and 2 have been interchanged.

It will be corrected, thank you.

2nd remark:

In paragraph 2.4.2 you mention figure 2.9, but this figure is missing

This will be corrected, thank you.

3rd remark:

Table 2.2: Well Garabbayis 1 is drilled by Djiboutian institution named Genie rural now called Direction de l'eau. It is not drilled by GENZL.

Thank you for your information.

4th remark:

The TEM data was used only for the static shift correction. Why did you not analyze the resistivity structure of shallow part despite that the TEM data in shallow area were obtained?

The subject for interests lies in the deeper part, i.e. approximately 500 m or more, in case for geothermal exploration. The deeper part is explored by MT survey rather than TEM survey. We, therefore, usually use the TEM data only for static shift correction when we conduct MT survey. For this reason, TEM survey plan is made to acquire information up to approximately 500 m, i.e. e-current intensity to be used is decided based on this requirement.

You mention "Layered resistivity structures which show the resistivity variation of high-low-high from surface to deep zone were obtained at almost all stations.'' This is another reason to focalize for TEM.

The high-low-high resistivity structure from the TEM results is within the range of the results of the MT-survey in the range of the depth. The high-low-high structure within 500 m depth will hardly affect the overall interpretation of the reservoir resistivity structures. Only a considerably thick low resistivity cover could be interpreted as a cap-rock structure. We will do the 1-D analysis using the TEM survey and the results are attached here to. .

On the field, in TEM method, the used configuration was central loop with a loop transmitter 100 x 100m. I think that with this configuration we can imaged easily the first 500 meters or more as we can see on this figure below.

The diffusion depth δ (m) of TEM survey is regarded as a rule of thumb of the exploration depth for TEM method and it is estimated by the following equation.

$$\delta = \sqrt{\frac{2t\rho}{\mu}} = (2*0.02*10/1.257*10^{-6})^{0.5} = 564$$

Where, ρ: ground resistivity (ohm-m), t: time after turning off the primary field (sec), μ: magnetic permeability

Because we could acquire good repeatable TEM data till 0.02 sec in this survey, the exploration depth of TEM was around 500 m at most. Due to this reason, the TEM data acquired by this survey can be used upto 500 m deep. We believe that analysis for more than 500 m will be misleading.

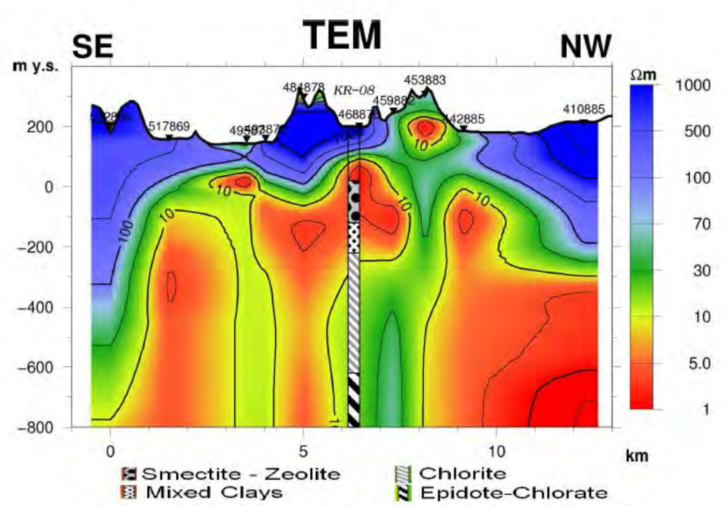
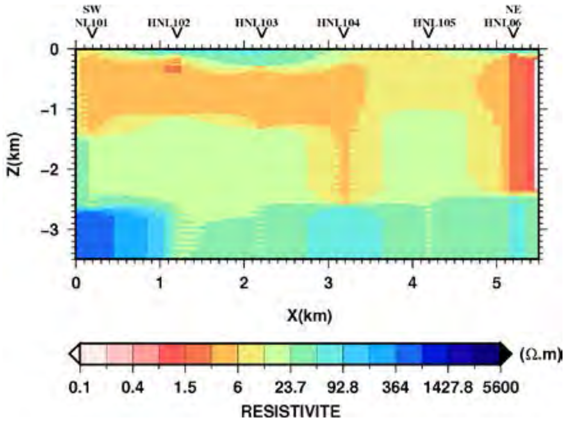


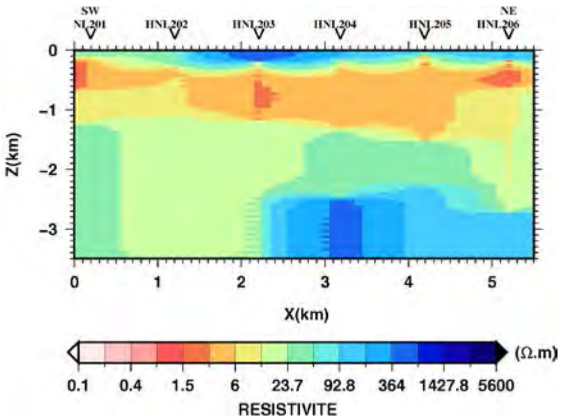
FIGURE 15: Resistivity cross-section from the 1-D inversion of TEM soundings, extending down to 800 m b.s.l.

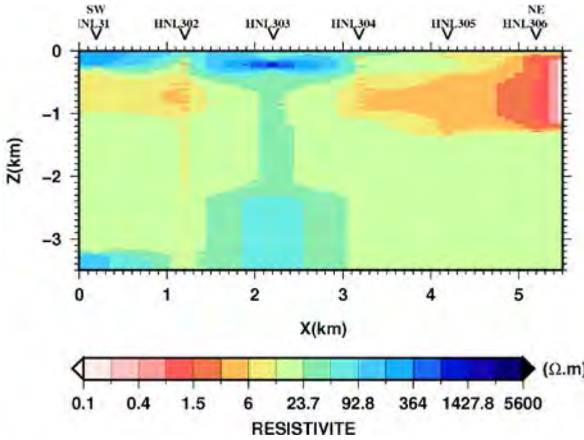
Model obtained by Icelanders with the TEM method on one of their site.

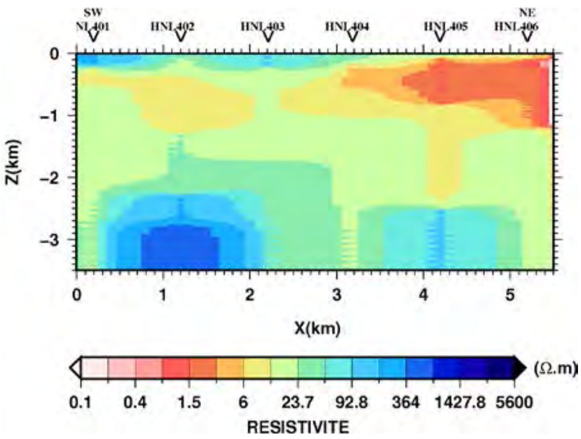
We would like to refrain from any comments on the figure above, because we do not know the survey conditions. One thing we could comment is that the TEM results may be used for area deeper than 500 m if large e-current is applied when measured. This may be done when MT survey is not conducted at the same time.

We have interpreted the MT data from 4 profiles (HNL100 -HNL400) with a 1D approach. The 1D resistivity models obtained are interpolated as profile and we observe the following sequence: high-low-high as we can see on these following figures.









Your geophysical report also mentions this sequence of resistivity in near surface (models TDEM).

So, according to your study unfortunately there is no correlation between the TDEM models and models MT at least in the near surface part (0-1 Km).

Most of apparent resistivity curves obtained this time show that the two curves xy and yx are more or less consistent in shallower zones (i.e higher frequency parts), which implies that 1-D analysis is applicable. On the other hand, the two apparent resistivity curves are not consistent in deeper zones (i.e. lower frequency parts), which implies that 1-D analysis may not be applicable. From the above principle, we are confident that the 2-D analysis is more suitable for deeper part, while 1-D analysis is applicable for shallower parts. We will make TEM 1- D detail analysis and the results are attached hereto.

5th Remark:

Chapter 9 point 9.2:

- For this sentence: "The Assal Geothermal Project is being handled by the EDD. The ODDEG is not now in charge of the project. Much information therefore is not available".
  Replace instead by "The Assal Geothermal Project is being handled by the EDD. The ODDEG and CERD serve like a technical support. Much information therefore is not available''

We will correct it accordingly, thank you.

- Dr. Kayad is a officer in ODDEG not from Ministry of Energy

We will correct it accordingly, thank you.

Chapter 9 Point 9.3

Training in Mai 2015 is postponed in September 2015

We will correct it accordingly, thank you.

6th Remarks:

Chapter 10 Point 10.2:

Instead of PK12, it is PK20

We will correct it accordingly, thank you.

Recommendations

- We want to highlight the time that the environmental survey consume is very high. Our side we do all necessary arrangements to accelerate the procedure, could you make the same from your part?

We will do our best to shorten the time period required.

- For the next survey it is good to add some geological survey like the outcrop. This give a good idea to do the correlation between geophysical case and geological for the subsurface.

We will dispatch a geologist as well. Joint inspection may be proposed if possible.

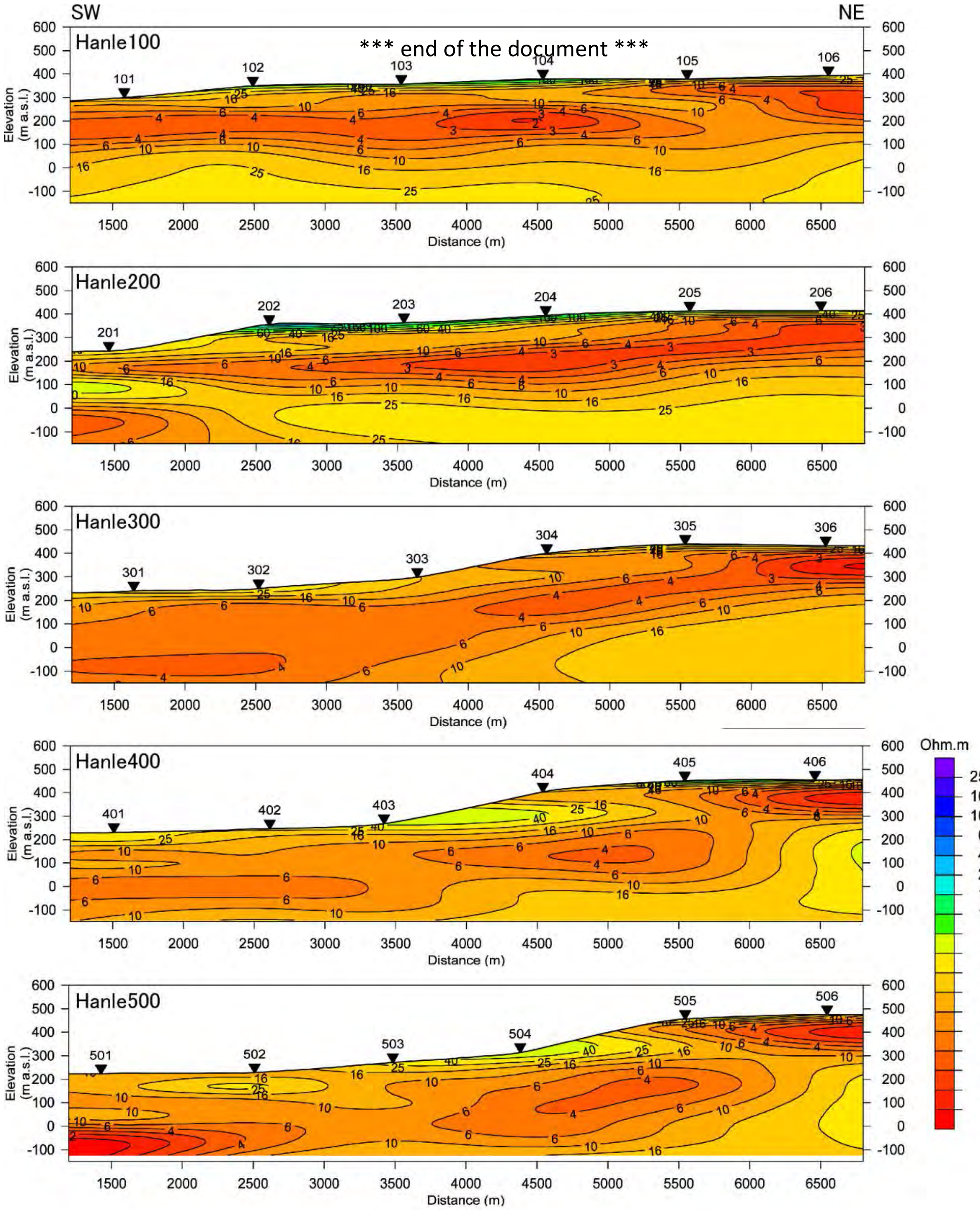
- The TEM is carried out to have static correction of MT data only. And your target of this survey is geothermal structure in deep area. This was our error for Assal area in the past. We ignored shallow reservoir (190°C at 600-700 m .b.s.l). ODDEG need to take account of this shallow reservoir for interpretations. And it is necessary to interpret the shallow deep less than 800 m by using TEM survey because the central loop by 100x100 can go deeper according the literature.

> Thank you for your information on your past experiences.
>
> As we explained above, our TEM survey was designed to use for static correction purposes. Thus, the e-current was selected to collect information from shallower zones. The e-current was not sufficiently large to collect information from area deeper than 500m. Instead, MT survey collect the information from deeper area. A large e-current will be applied to TEM survey only when TM survey is not conducted, as far as we understand.

- And also take account some questions and comments made in the workshop and it is in the minutes of workshop.

> Supplemental explanations have been added to the minutes of the work shop

*** end of the document ***



The resistivity cross sections of the very shallow zone from the results of TEM 1D inversion analysis

Memo between the ODDEG and the JICA survey Team

A conversation was made between the Director General of the ODDEG and the Team Leader of the JICA Survey Team after the workshop for the Draft Final Report held on 10th August, 2015. This memo has been prepared to confirm what were talked about between them, in order for the JICA Survey Team to convince the precise message from the ODDEG to JICA head office.

1. The ODDEG recognizes that the geophysical survey in Hanle Garabbayis has revealed that the resistivity pattern is different from the one of the typical pattern in geothermal prospects.
2. With that information, the ODDEG agrees to the recommendations for the additional surface survey presented by the JICA Survey Team in Hanle Garabbayis site.

3. In parallel with the JICA survey in Hanle Garabbayis, the ODDEG intends to conduct gravity survey and supplemental geophysical survey (MT/TEM survey) in Nord Ghoubbet, where the CERD conducted a pre-feasibility study in 2011. The study included geochemical survey and geophysical survey of 30 monitoring points, together with review of existing information on gravity survey, magnet survey conducted by BGR. An additional survey is to be conducted at about 30 points in Nord Ghoubbet by the professionals of the ODDEG.
4. The purpose of the surface survey intended by the ODDEG is to raise Nord Ghoubbet up to a level where a comparison could be made with Hanle Garabbayis site to select a better site for further exploration. This approach is in accordance to the one that was proposed by the Data Collection Survey of JICA in 2014.

5. In this regard of Nord Ghoubbet, the ODDEG wishes the JICA Survey Team to provide its technical assistance for technical guidance on site and for the data analysis possibly conducted in Japan as well.
6. The ODDEG would like to request to JICA to provide an updated software such as WingLink for MT analysis since the ODDEG has only an outdated software for 1-D analysis, so that the ODDEG could conduct review analysis whenever necessary including the data of other sites with the capacity to be enhanced through the technical assistance from Japan. The software could be utilized for other purposes such survey as groundwater or mining resources or etc.

The ODDEG, as the competent organization for geothermal development of the Republic of Djibouti, sincerely wishes to realize the test well drilling program with the technical assistance from JICA.

(10th August, 2015; recorded by the JICA survey team)

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