

# Surface nuclear magnetic resonance signal contribution in conductive terrains

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## ABSTRACT

To correctly invert and interpret Surface Nuclear Magnetic Resonance (SNMR) data collected in conductive terrains, an accurate estimate of subsurface conductivity structure is required. Given such an estimate, it would be useful to determine, before conducting an SNMR sounding, whether or not the conductivity structure would prevent groundwater being detected. Using SNMR forward modelling, we describe a method of determining the depth range from which most of the SNMR signal originates, given a model of subsurface conductivity structure.

We use the method to estimate SNMR depth penetration in a range of halfspace models and show that for conductive halfspaces ( $< 10 \Omega.m$ ) the depth of penetration is less than 50 m. It is also shown that for these halfspaces, increasing coincident loop size does not significantly improve depth penetration. The results can be used with halfspace approximations of more complicated 1D conductivity structures to give a reasonable estimate of the depth range over which signal is obtainable in conductive terrains.

## INTRODUCTION

The Surface Nuclear Magnetic Resonance (SNMR) is a ground geophysical technique that responds directly to subsurface water and has potential as a tool for hydrogeological modelling. To date, the technique has been used to locate groundwater (Goldman et al., 1994; Portselan and Treshchenkov, 2002; Vouillamoz et al., 2002); delineate aquifer extent (Yaramanci et al., 2002; Dippell and Golden, 2003); and provide estimates of other quantitative parameters such as porosity and permeability in some terrains (Legchenko et al., 2002).

However, the SNMR technique has shortcomings. These include a low signal-to-noise ratio and high sensitivity to geomagnetic field gradients and fluctuations. Another weakness, relevant to its use in Australia, is the effect of conductive ground. A conductive subsurface alters the signal amplitude and phase of an SNMR measurement, and an estimate of subsurface conductivity structure is required for accurate inversion and interpretation of an SNMR sounding in conductive terrains (Weichman et al., 2002). To date, the only Australian SNMR field trials have been confined to magnetically quiet areas characterised by relatively fresh groundwater and low to moderate host conductivity (Schirov

et al., 1991; Dippell and Golden, 2003). However, large parts of Australia are blanketed in variably thick, variably conductive regolith containing, in places, thick conductive clay layers and hosting saline groundwater.

Given that the time required for an SNMR sounding is measured in hours, it would be useful to determine, before conducting an SNMR sounding, whether or not the conductivity structure would prevent groundwater being detected. Here, we forward-model data for water layers of finite thickness and infinite spatial extent, to examine the effect of halfspace conductivity on the maximum depth at which water can be detected, and the depth range from which most of the measured signal originates.

## SNMR SOUNDINGS

Hydrogen protons have a magnetic moment and, if left undisturbed, will align parallel or anti-parallel to the Earth's geomagnetic field direction and precess about it. The precession frequency ( $\omega_0$ ) is known as the resonance or Larmor frequency and is proportional to the strength of the Earth's geomagnetic field  $\mathbf{B}_0$ ,

$$\omega_0 = \gamma |\mathbf{B}_0|, \quad (1)$$

where  $\gamma$  is the gyromagnetic ratio for hydrogen protons. In the equilibrium state, there is a slight excess of protons aligned in the direction of the Earth's field, giving rise to a stationary macroscopic net magnetisation vector  $\mathbf{M}$ . An SNMR measurement is made by disturbing  $\mathbf{M}$  with an oscillating magnetic field transmitted at the resonant frequency that causes  $\mathbf{M}$  to simultaneously tip away from its equilibrium position and rotate about  $\mathbf{B}_0$  at the resonant frequency. As a result,  $\mathbf{M}$  acquires a component in the plane perpendicular to  $\mathbf{B}_0$  that is referred to as the transverse component  $\mathbf{M}_w$ . It is this component that induces a signal in the receiver as  $\mathbf{M}$  relaxes back to its equilibrium state following the cessation of the transmitter on-time. The degree to which  $\mathbf{M}$  is tipped is dictated by the transmitter pulse moment  $q$ , which is the product of the transmitter current and the duration of the on-time ( $q = I\tau$ ). Note the pulse moment differs from transmitter moment, the product of current and loop area.

For a single (coincident) loop transmitter-receiver system using a synchronous detection scheme (Legchenko and Valla, 2002), the time-domain voltage induced in the receiver loop following a transmitter on-time with pulse moment  $q$  is fitted with a function of the form

$$E(q, t) = |E_0(q)| e^{i(\omega_\Delta(q) + \arg(E_0(q)))} e^{-t/T_2^*(q)}, \quad (2)$$

where  $\omega_\Delta$  is the angular frequency difference between the Larmor frequency and the reference frequency of the synchronous detector,  $\arg(E_0)$  is signal phase shift due to conductive ground and magnetic field gradients,  $T_2^*$  is the rate of  $\mathbf{M}_w$  relaxation and  $|E_0|$  is the initial amplitude of the decaying signal.  $E_0$  is measured in volts and given by the volume integral

$$E_0(q) = \omega_0 \int_V b_1^R(\mathbf{p}) |\mathbf{M}_w(q, b_1^T(\mathbf{p}))| e^{i(\varphi(\mathbf{p}) + 2\theta(\mathbf{p}))} w(\mathbf{p}) dV, \quad (3)$$

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where  $b_{\perp}^R$  is the amplitude of the counter-rotating component of the transmitter's (unit current) magnetic field perpendicular to the  $\mathbf{B}_0$ ,  $b_{\perp}^I$  is the co-rotating component,  $|\mathbf{M}_{xy}|$  is the magnitude of the transverse component of  $\mathbf{M}$  as a function of  $q$  and  $b_{\perp}^I$ ,  $\varphi$  is the phase of  $\mathbf{M}_{xy}$ ,  $\theta$  is a phase shift due to ground conductivity and  $w(\mathbf{p})$  is the water fraction of the voxel at position vector  $\mathbf{p}$ . Note that  $E_0$  is generally complex, and phase shifted with respect to the transmitter (Weichman et al., 2000).

An SNMR sounding is made by making a number of  $|E_0|$  measurements at various  $q$  moments (typically with  $\tau = 40$  ms and  $10 < I < 300$  A) to give an  $|E_0|$  amplitude profile. The  $|E_0|$  profile is subsequently inverted to give an estimate of water distribution with depth. With current SNMR instrumentation, the actual initial voltage at the receiver following a transmitter pulse is smaller than  $|E_0|$  by a factor proportional to the receiver 'dead-time' and the rate of  $T_2^*$  relaxation. Here, these considerations are ignored and only the theoretical value of  $|E_0|$  is considered.

In the modelling that follows, it is assumed that there is no magnetic heterogeneity in the volume of Earth being sampled. With this assumption Equation 3 becomes

$$E_0(q) = M_0 \omega_0 \int_V b_{\perp}^R(\mathbf{p}) \sin(0.5 \gamma q b_{\perp}^I(\mathbf{p})) e^{i2\theta(\mathbf{p})} w(\mathbf{p}) dV, \quad (4)$$

where  $M_0$  is the maximum net magnetisation of a unit volume of water. We also assume a Larmor frequency of 2300 Hz and a geomagnetic field inclination of 56°S throughout. Where resistive halfspace data are presented, the resistivity is assumed to be 10 000  $\Omega \cdot m$  and the resistivity of water layers is assumed to be greater than 100  $\Omega \cdot m$ .

**EFFECT OF CONDUCTIVE GROUND**

A conductive halfspace attenuates the initial SNMR voltage response  $|E_0|$  at the receiver in three ways. Firstly, the strength of the transmitter field that disturbs the equilibrium of the hydrogen protons is attenuated with depth. Similarly, for a coincident receiver, the received signal generated by  $\mathbf{M}_{xy}(\mathbf{p})$  returning to equilibrium is attenuated by the same factor. Finally, conductive ground means that the transmitted and received fields are elliptically rather than linearly polarised leading to varying phase at different subsurface locations. This results in phase-shifted signal contributions that, when integrated, form an interference pattern at the receiver (Weichman et al., 2002). These effects limit the depth at which water can be detected in conductive halfspaces.

Where conductivity structure is not well represented by a halfspace, the effect on the received signal is more complicated. For example, conductive layers in 1D layered-earths have a 'screening' effect (Trushkin et al., 1995; Shushakov, 1996) whereby the SNMR response from water overlying the layer is increased and the response from water below the layer is decreased. Figure 1 shows the effect on  $|E_0|$  profiles of introducing a 1  $\Omega \cdot m$  layer at 10–20 m in a 20  $\Omega \cdot m$  halfspace, compared with those from a resistive halfspace. In both earth models, deeper water causes the  $|E_0|$  profile maximum to have a smaller amplitude and appear at higher  $q$  than shallower water. However, when comparing profiles between the two earth models, it can be seen that in the conductive layer case, the response from water above the conductive layer has larger amplitude; the response from water in the conductive layer has approximately the same amplitude (which has consequences when water is the conductive layer – e.g., saline water horizons). Below the conductive layer, fields are much weaker, resulting in a much smaller responses.

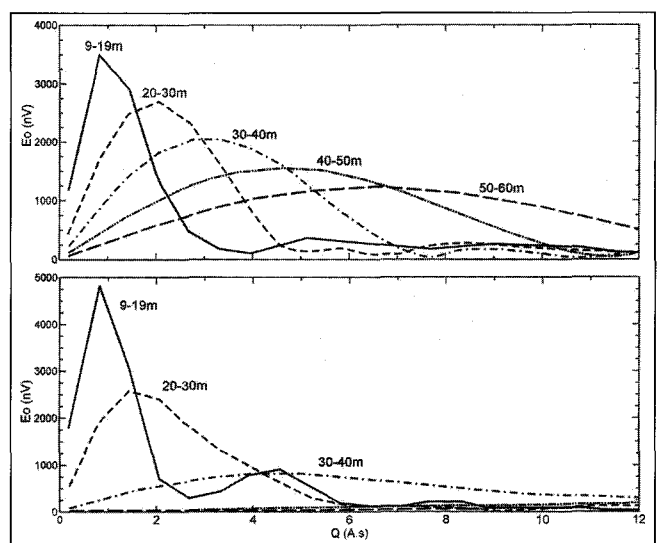
As seen from this example, data collected in conductive ground and inverted assuming a resistive earth will over- or underestimate

aquifer depth and water content, depending on the geometry of the groundwater with respect to conductivity structure. As a result, in conductive terrains a model of conductivity structure (from TEM or down-hole induction) is required for accurate inversion of SNMR data. Given such a model, it would be useful to determine, before conducting an SNMR sounding, whether or not the conductivity structure would prevent groundwater being detected.

**DEPTH OF SIGNAL CONTRIBUTION**

Given a model of subsurface conductivity structure, we obtain the depth range from which most of the SNMR signal originates in the following way. Firstly, we find the maximum detection depth ( $Z_{MDD}$ ) beyond which no subsequent amount of water is detectable. We then assume that the area under the  $|E_0|$  profile resulting from modelling a spatially extensive, fully saturated water body from near surface to the maximum depth of detection ( $1 - Z_{MDD}$ ), represents the maximum signal obtainable. Because the model given in Equation 3 assumes a linear contribution from all sub-volumes, a signal contribution depth can then be measured as a proportion of the maximum signal by finding the depth at which the area under the  $|E_0|$  profile for successively thinner water models differs from that of the maximum  $|E_0|$  profile. Here we have chosen to find the depth range from which 95% of signal contribution originates ( $Z_{95\%}$ ).

In previous work, Legchenko et al. (1997; 2002) defined the  $Z_{MDD}$  to be the depth at which a 1 m thick, fully saturated water layer resulted in an  $|E_0|$  profile where the maximum amplitude did not exceed some detection threshold (10–20 nV). Although a 1 m layer may be undetectable, thicker layers at the same depth can make a measurable contribution to the  $|E_0|$  profile (Figure 2). The contribution will be additive or subtractive depending on the relative phase between these and other water-bearing layers (Schirov and Rojkowski, 2002). Here we consider the depth at which no amount of subsequent water contributes significantly to the  $|E_0|$  profile by redefining the  $Z_{MDD}$  to be the depth at which a thick (50 m), rather than a thin (1 m), fully saturated water layer fails to produce an  $E_0$  amplitude greater than 20 nV (where  $0 < q < 12$  A.s). Using the procedure outlined above, we found that the thin layer definition corresponds to the depth at which over 98% of the total response has been accounted for.



**Fig. 1.**  $|E_0|$  profiles of a 10 m thick, 100% water layer at various depths in a halfspace with resistivity equal to free-air (top) and in a 1D layered-earth (1  $\Omega \cdot m$  conductive layer between 10–20 m in a 20  $\Omega \cdot m$  host) (bottom).

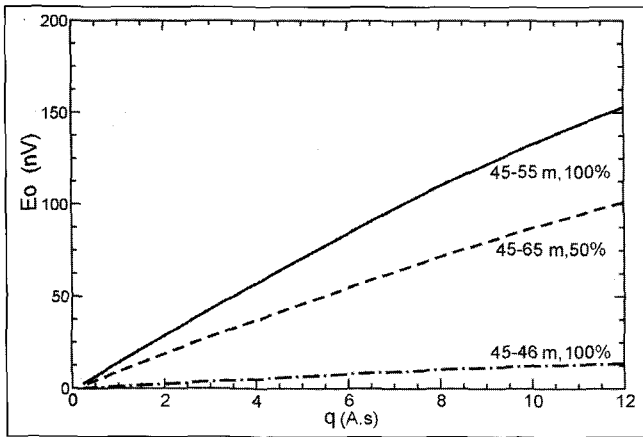


Fig. 2.  $|E_0|$  amplitude response for water layers of varying thickness and water content (% saturation) in a conductive ( $2 \Omega.m$ ) halfspace. At large  $q$ , a 1 m thick water layer is undetectable but thicker layers make a measurable contribution to the  $|E_0|$  profile.

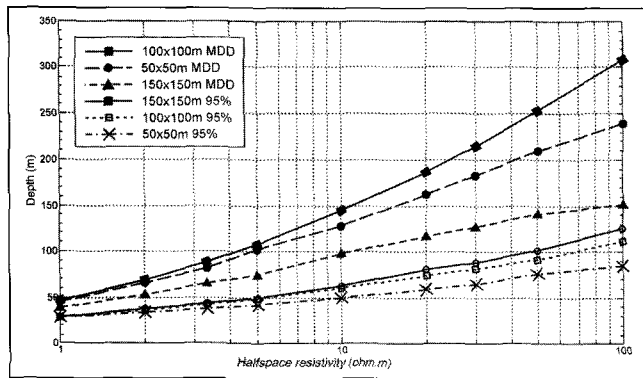


Fig. 3.  $Z_{MDD}$  and  $Z_{95\%}$  depths for 50, 100, and 150 m square coincident loops. Note that in low-resistivity halfspaces, increasing loop dimensions does not significantly increase depth of signal contribution.

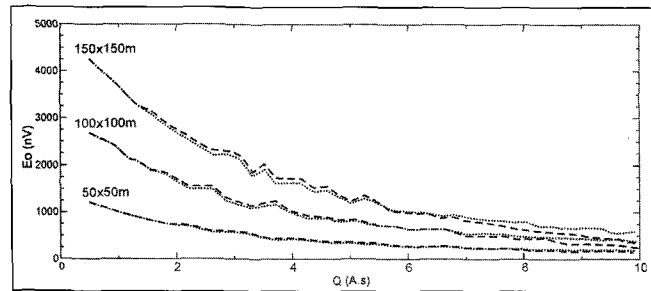


Fig. 4. Effect of loop dimension on two saturated water models, 1–30 m (dashed) and 1–50 m (dotted), in a  $1 \Omega.m$  halfspace. These correspond to the  $Z_{95\%}$  and  $Z_{MDD}$  depths. Increasing loop dimension results in larger signal amplitude but makes little difference to the  $|E_0|$  sounding profiles for the two models. That is, increasing loop size has little effect on detecting deeper water beyond  $Z_{95\%}$ .

### Halfspace Signal Contribution

Figure 3 shows the results of performing the  $Z_{MDD}$  and  $Z_{95\%}$  analyses for three square coincident loop sizes (50, 100, and 150 m) over a range of halfspace resistivity (1–100  $\Omega.m$ ). The results show that 95% of SNMR signal contribution comes from approximately half the maximum depth of detection. For very low-resistivity halfspaces (< 10  $\Omega.m$ ), 95% of signal contribution is accounted for within the top 50 m (approximately one skin-depth at 2300 Hz).

The results also show that as halfspace resistivity decreases, larger loop sizes do not significantly improve the depth penetration.

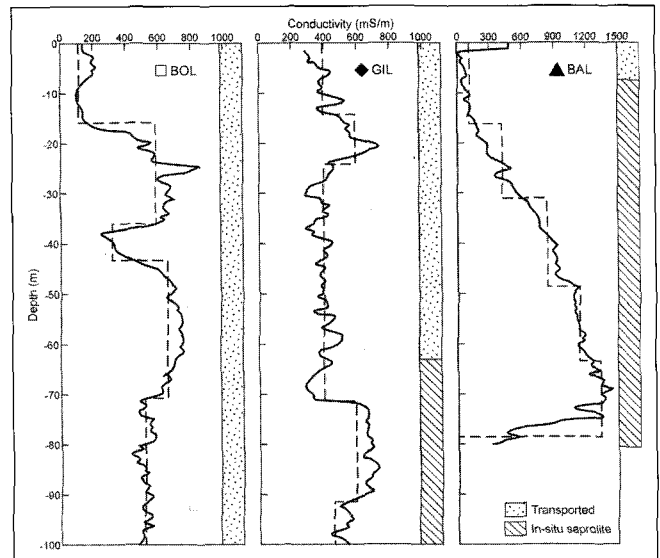


Fig. 5. Examples of non-halfspace conductivity structure. EM-39 (solid), 1D layered-earth model (dashed).

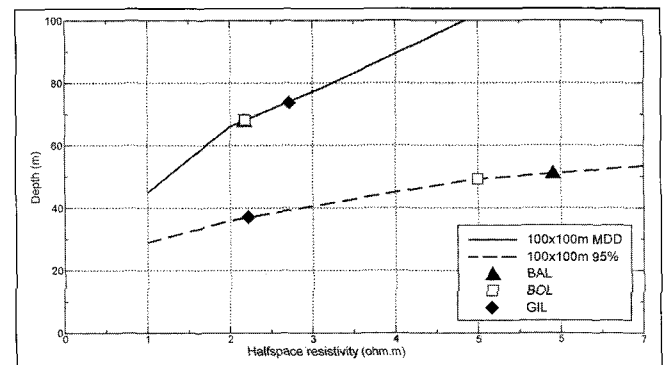


Fig. 6. Enlarged view of the low-resistivity region of the  $100 \times 100$  m MDD and 95% curves in Figure 3, with  $Z_{MDD}$  and  $Z_{95\%}$  results for the example models shown in Figure 5.

For example, from Figure 3 it can be seen that, for halfspace resistivity less than 5  $\Omega.m$ , increasing loop size from 100 m to 150 m increases  $Z_{MDD}$  by less than 10 m and makes a negligible difference to the 95% signal contribution depth.

If water horizons in very conductive areas (< 3  $\Omega.m$ ) have sufficient spatial extent, then larger loop dimensions will result in increased signal amplitude but negligible additional depth penetration (Figure 4). Increased SNMR depth penetration can only be achieved by increasing the range of  $q$  over which the sounding is performed. With typical transmitter on-time durations of  $\tau = 40$  ms, increasing  $q$  from 10 to 15 requires an increase of transmitter current from 250 to 375 Amps.

### Non-halfspace 1D Conductivity Structure

As outlined above, non-halfspace conductivity structure complicates SNMR soundings. Here we examine the effect of 1D conductivity structure on the depth of signal contribution by considering the conductivity structure given by down-hole inductive logs for three example boreholes (Figure 5). 1D layered-earth models were constructed by simplifying the high-resolution EM-39 data shown in Figure 5. The  $Z_{MDD}$  and  $Z_{95\%}$  analyses were then performed for a  $100 \times 100$  m coincident loop overlying these layered-earths. The resulting  $Z_{MDD}$  depths for these boreholes were then plotted on the  $100 \times 100$  m  $Z_{MDD}$  line of Figure 3 (reproduced for clarity in Figure 6). According to the  $Z_{MDD}$  procedure,

the conductivity structures have an apparent resistivity of 2–3  $\Omega\cdot\text{m}$ , implying that 95% of signal contribution comes from the top 40 m. However, the depths produced by the  $Z_{95\%}$  procedure vary from this, as is shown in Figure 6. Whereas the GIL example is approximated well by a halfspace, the BOL and BAL structures appear more resistive in the  $Z_{95\%}$  procedure. This is due to their conductivity structure augmenting the response of deeper water. Although the apparent resistivities from the two procedures differ by more than a factor of two in these examples, the difference in signal contribution depth is only approximately 10 m.

The  $Z_{\text{MDD}}$  and  $Z_{95\%}$  analyses are time-consuming procedures and are not considered feasible for field use. However, as seen in Figure 3, the results (particularly  $Z_{95\%}$ ) vary relatively slowly as a function of estimated halfspace resistivity. This indicates, and the above example demonstrates, that large errors in a halfspace approximation of a conductivity model lead to relatively small errors in estimating the signal contribution depth.

## CONCLUSION

Conductive ground affects SNMR soundings and an accurate model of conductivity structure is required for accurate inversion. Given such a model, a method of determining the depth range over which a significant proportion of the SNMR signal originates is described. The method is used to estimate SNMR depth penetration in a range of halfspace models for three square coincident loop sizes.

It is shown that for conductive halfspaces ( $< 10 \Omega\cdot\text{m}$ ) the depth of penetration is less than 50 m and that increasing loop size does not significantly improve depth penetration. The results can be used with halfspace approximations of more complicated 1D conductivity structures to give a reasonable estimate of the depth range over which signal is obtainable in conductive terrains.

These findings imply that in conductive terrains, SNMR will be restricted to shallow applications (e.g., salinity) but can be performed with smaller transmitter loops. These applications will also benefit from the fact that in conductive ground, shallow water produces an SNMR signal amplitude that is greater than or equal to water in resistive ground.

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## 高導電性浅部地層の存在が SNMR 信号へ与える影響

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**要旨:** 電気伝導度の高い地層で取得された地表核磁気共鳴(SNMR)データを正確に逆解析し解釈するためには、地表下の電気伝導度構造を正確に推定することが要求される。そのような推定をもとに、高導電性地層の存在が地下水検知の妨げとなるか否かを、SNMR 探査の前に予測しておくことは有用と考えられる。本論文では、SNMR のフォワード計算から、与えられた電気伝導度構造モデルについて十分な SNMR 信号が生じる深度範囲を決定する方法について述べる。一連の半無限媒質モデルについて SNMR の透過深度を推定し、高導電性半無限媒質( $<10\Omega\text{m}$ )では、信号の透過深度は 50m 未満であることを示す。また、このような半無限媒質モデルでは、送受信ループのサイズを増加しても信号透過深度はほとんど増加しない。より複雑な 1 次元電気伝導度構造についても、半無限媒体に近似し、この手法を適用することによって、SNMR 信号を受信できる深度範囲を適切に推定することができる。

## 전도성 지질에서의 SNMR 신호 특성

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**요약:** 전도성 지질에서 얻어진 지표 핵자기 공명(SNMR) 자료를 올바르게 역산하고 해석하기 위해서는 지하의 전기전도도 분포에 대한 정확한 추정이 필요하다. 이러한 추정 결과는 SNMR 수직탐사를 수행하기 이전에 전도도 구조가 지하수 탐지를 방해할 것인지에 대해 결정하는데 유용할 것이다. 이 논문에서는 SNMR 모델링을 이용하여 지하 전기전도도 구조가 주어졌을 때, 대부분의 SNMR 신호를 발생하는 심도 범위를 결정하는 방법을 서술하였다. 이 논문에서는 반무한 공간에서 SNMR 침투 심도를 추정하는 방법을 사용하였으며 전도성 반무한 공간( $<10\text{ ohm-m}$ )에서는 침투심도가 50 m 이내라는 것을 보였다. 또한 이러한 반무한 공간 모델에서는 동일위치 방식의 loop 크기를 늘리더라도 침투심도를 뚜렷이 증가시키지 못함도 알 수 있었다. 이러한 결과는 좀 더 복잡한 1 차원 전도도 구조에 대한 반무한 공간 근사를 통해 전도성 지층에서 신호가 얻어질 수 있는 심도 범위를 합리적으로 추정하는데 사용될 수 있을 것이다.

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