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Application of Transient Electromagnetic (TEM) Method for Delineation of Mineralized Fracture Zones

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Abstract. Fracture zones have always been areas of interest in mineral exploration. These geological structures are often studied and mapped as prospective zones for mineralization through the process of hydrothermal alteration. The transient electromagnetic (TEM) survey has been utilized to delineate the possible mineralized fracture zone of eastern Kuantan, Pahang. 35 single loop TEM soundings were acquired in a scattered manner over a region of high relief terrain, encompassing an area of approximately 5 km^2. Data acquisition was conducted using the TerraTEM system by Monex Geoscope, with a 30 m x 30 m wire loop. The wire loop functions both as the transmitter coil and the receiver coil. The TEM responses indicate the presence of 3 electrically conductive zones (A, B and C) which are attributed to possible mineralized fracture regions within the country rock. All three regions record high conductivity readings with values of more than 15 mS/m and have a directional trend of NW-SE orientation. Target A is observed to be 300 m in width (E-W) and extends to 100 m in depth while B and C both have larger dimensions, exceeding 400 m in length (E-W) and up to depths of 150 m. The 3-D model generated from the 1-D soundings of the TEM dataset demonstrates the anomaly patterns that could be caused by the electrically conductive fracture zones within a resistive metasediment country rock. Geoelectrical properties of targets A, B and C may suggest the location of possible mineralized fracture zones within the study area.

1. Introduction

Electromagnetic (EM) surveys have been utilized in the sector of geological exploration for more than seventy years. Several uses of the EM method includes the exploration for iron ore deposits [1], detection of buried valleys [2], delineation of freshwater and saltwater boundary [3], reservoir explorations [4] and many more. The method is selected due to its simplicity of usage and ability to produce diagnostic data within a short period of time. Most EM systems are conducted in the frequency-domain and involve constant transmission at a predetermined frequency. The more current development of time-domain electromagnetic systems, also known as transient electromagnetic (TEM) methods, offer considerable advantages over the conventional electromagnetic systems. In the TEM system, signals are transmitted, and the transient decay of the resultant secondary field is recorded after the primary field has been switched off. Many of the TEM systems generate a train of primary pulses with measurements made in the interval between each pulse.

The concept of utilizing TEM signals in the field of exploration for electrically conductive ore bodies was constructed upon the theoretical grounds back in year 1951 by Wait [5]. Advancing from there, geoscientists from Russia have also been active in the progress and application of the method [6]. In the west, Barringer Research assembled an airborne version of the geophysical survey method and acquisitions were successfully conducted [7]. The TEM surveys have been conducted for multiple purposes and yielded many successful results. It is one of the most reliable geological prospecting methods and therefore was selected to map the study area of eastern Kuantan, Pahang.

Fracture zones are described as regions where cracks in rocks and minerals reduced the tensile strength of the overall material. It is one of the most common geological structures due to many contributing factors such as movements of the tectonic plates, compressional and extensional forces, and even plutonic uprising activities. Displacements and void spaces generated by the Mode I fractures are termed as joints. The void spaces within the joints serve as conduits for meteoric fluid and gasses. Formation of hydrothermal veins within these fracture zones are favorable locations for mineralization process and therefore are highly sought after by exploration geoscientists. Geophysical prospecting has significantly reduced the time and cost of mineral exploration and therefore is often used for initial studies when exploring a new study area.

Sections of the subsurface with high concentration of sulphides, graphite and magnetite are areas of mineralization potentials that would cause anomalies in the EM readings. The objective of this study is to explore and locate the possible regions of mineralization that is recorded to be confined within certain structural features such as fracture zones. This survey focuses on the electrical characterization of the subsurface sections within the high relief regions of the study area in Sungai Lembing, Pahang. The TEM soundings were acquired using the single loop configuration with a 30 m x 30 m loop size.

1.1. The electromagnetic method

All TEM systems function on the principle of inducing eddy currents into the subsurface and examining the decay time of the resultant signal to provide information of electrically conducting materials in the ground. The acquisition process begins when the alternating current in the transmitting coil (Tx) generates a magnetic field in the nearby location which in turn, induces an electrical field in any proximal electrical conductors, thus forming eddy currents. The induced electrical fields generated depend on the conductivity, shape and size of the conductor material and its location with respect to the acquisition coil. After the initial signal generation, the eddy currents in the conductor material tend to diffuse inwards towards the center of the body, gradually dissipated by resistive heat losses to the surrounding. In the case of highly conductive body, the current tends to circulate within the boundary of the material and decays at a slower rate.

The eddy currents, which are essentially the secondary magnetic field, decay within a relatively longer period depending on the electrical and geometrical properties of the conductive material. The receiver coil (Rx) records an output voltage which is relative to the time derivative, also known as the rate of decay, of the vertical component from the resultant secondary field. In general, the EM properties of mineralization within the subsurface produce transient decays lasting from a fraction of a millisecond to approximately 20 milliseconds. Figure 1 briefly explains the process of a general EM surveying method. Firstly, an EM field is generated by the transmission of alternating current through a large loop of ungrounded wire at Tx. Next, the primary EM field travels from Tx to Rx via paths, both above and below the surface. Electrically conductive bodies in the subsurface generate eddy current through the magnetic component of the primary EM field penetrating the ground. The eddy currents in return generate a secondary EM field that is detected by the Rx and the difference between Tx and Rx fields indicate the presence and properties of conductive bodies.

EM methods measure the electrical conductivity of materials. The apparent conductivity of a quantified body is given by

$$\sigma_a = \frac{4}{\omega \mu_0 s^2}\left(\frac{H_s}{H_p}\right) \qquad (1)$$

where σ_a is the value of the apparent conductivity of the material (Siemen/m)
ω = angular velocity (rad/s)
= $2\pi f$ where f is the frequency of the EM wave (f in Hz)
μ_0 = permeability of free space

s = distance between Tx and Rx (meters)
H_s = secondary magnetic field at Rx
H_p = primary magnetic field at Rx
Permeability in electromagnetism is defined as the measure of a material's ability to support the formation of a magnetic field within itself. It is the degree of magnetization that a material obtains in response to an applied magnetic field. Ore-bearing rocks have very high magnetic permeabilities and are able to impact the measured responses of EM surveys.

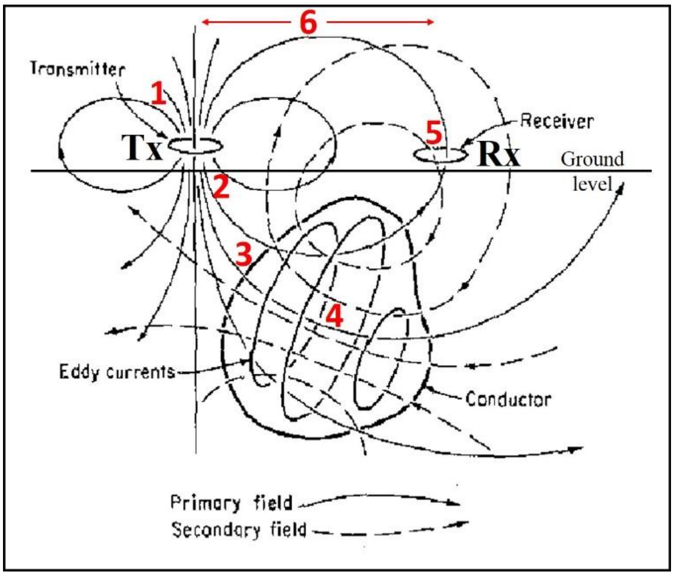

Figure 1. A generalized schematic of the EM surveying method [8].

1.2. Geology of study area
Sungai Lembing is located approximately 30 km NW from Kuantan, Pahang. The study was conducted in the hilly regions of a secondary forest near the town, with elevations ranging from 20 m to 270 m above sea level. The majority part of the study area is covered by dense vegetation. Slate and phyllite are the two main lithologies recorded within the study area. The strike directions of the beddings observed were NE-SW and NW-SE. Two others minor lithologies that were found within the survey area were shale and quartz. Weathering profiles of the surface outcrops ranged from slightly weathered to highly weathered. Structural features such as quartz veins and fractures were also observed and documented to be mainly trending E-W and NE-SW within the study area. It is recorded that the faulting and folding of the argillaceous beds of Sungai Lembing are the effects of the granite intrusions [9]. Mineralization of the hydrothermal vein deposits are also genetically supported by these plutonic uplifts. Geological studies within the area of Sungai Lembing revealed that the hydrothermal veins were found to be situated within the sedimentary rocks following the azimuthal trend of E-W, NW-SE, SE-NW and NE-SW. Paragenesis of the minerals studied within the same area are composed of cassiterite, followed by arsenopyrite, pyrite, pyrrhotite, sphalerite, chalcopyrite and galena. Several other minerals such as limonite, malachite and dendritic manganese oxides were also found within the study area due to a high degree of weathering.

Other studies recorded that mineralization of the deposits were also observed to be confined within the contact zones and the intruded country rocks. Alteration and deposition of minerals via hot ascending waters of uncertain origin [10] through the fracture zones of the country rocks have contributed to the formation of the mineralized zones. Sungai Lembing is interpreted to be constrained locally by steeply dipping faults that range from 70° to 90° in angle. Vein swarms that were observed to occur in large amounts throughout the entire study area forms potential mineralized regions through the process of hydrothermal vein deposition. These deposits can be explored by using appropriate geophysical techniques and therefore, the TEM survey is selected to locate these potential mineralized zones.

2. Methods and materials

35 single loop TEM soundings were acquired in a scattered manner over the high relief regions of the study area. The geoelectrical survey encompasses an area of approximately 5 km^2. Figure 2 illustrates the layout of the 35 TEM sounding points over a topography map of the study area. Each survey point had a minimum separation distance of 200 m from another survey point. This was to ensure proper distribution of the TEM data. The 1-D TEM soundings were conducted using the TerraTEM system by Monex Geoscope that was connected to a single square loop setup that functions both as the Tx and the Rx. The dimension of the square loop was 30 m x 30 m and the value of the electrical current was set to 10 amperes. Maximum depth of penetration for each TEM sounding point was approximately 150 m. GPS location for each survey points were obtained by using a handheld Garmin GPS at the center of the loop after each reading was acquired. The setup of the acquisition system is demonstrated in Figure 3.

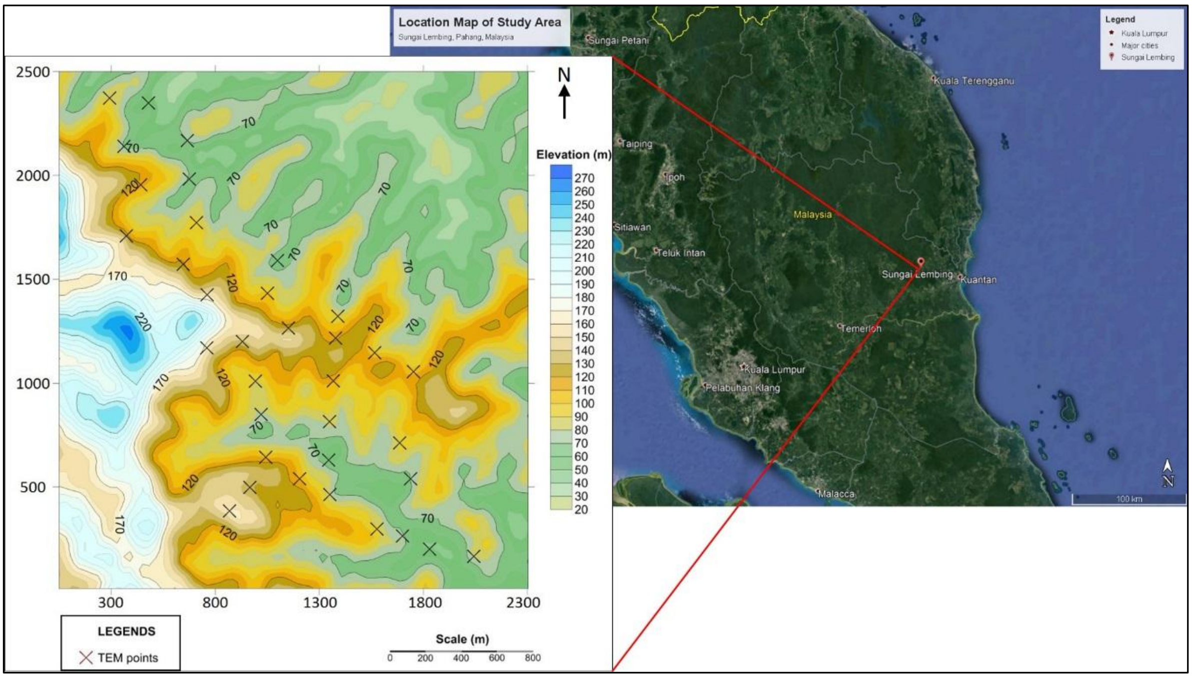

Figure 2. Location map and layout of the 35 TEM sounding points over the high relief region of Sungai Lembing, Pahang.

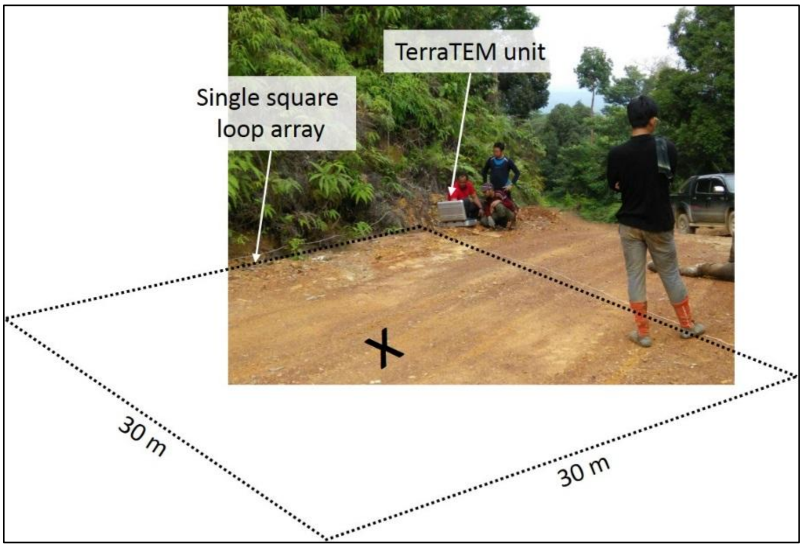

Figure 3. Setup of the TerraTEM acquisition system with the single square loop array. Scale of the loop is not drawn to size but for illustration purpose only. X is the midpoint of the square loop that indicates the location of the TEM sounding.

During the model construction procedure, all 35 TEM sounding data were processed and compiled to obtain a 3-D conductivity model of the subsurface. The decay time of the EM field that was acquired is then transformed into images using the TEMPlot software. This data alteration involves the inversion of time series into space domain using the SPIKER algorithm [11]. During the inversion process, all physical characteristics of the recorded TEM decay has been taken into deliberation such as the value of the original voltage and the rate of decay. In the space domain, the 1-D TEM sounding data is imaged as a depth-conductivity plot. 2-D contour maps (depth slices) are extracted from the 3-D electrical conductivity model produced by using the Oasis Montaj software. The contour maps were then overlaid onto the Digital Elevation Model (DEM) to present the vertical and lateral continuation of the geoelectrical responses measured.

3. Results and discussion

The TEM survey have been conducted by discrete sampling procedure. Based on the results, three high electrical conductivity zones can be observed: Zone A, B and C. These anomalies are distinct and have an elongated pattern that trends E-W when observed from the TEM contour maps. The results suggest that all three anomalies may indicate regions of possibly mineralized fracture zones. Based on the 3-D model produced, the vertical and lateral continuation of the target zones can be observed and studied. Four contour maps from different depths were extracted and presented in Figure 5. The electrical conductivity response of the study is presented in milli Siemens per meter (mS/m) with the highest recorded value at target C with readings above 1000 mS/m.

The possible mineralized fracture zone of target A is located at the NW section of the study area. Target A is observed to be 300 m in width and extends to a depth of 100 m into the subsurface before the response fades off. Target B and C are imaged at the central and SE part of the study area respectively. Both targets are considerably larger than A, with widths over 400 m in length and having positive anomaly response up to a depth of 150 m. All three target zones produced significant anomaly responses in contrast to the electrically resistive country rocks. A cross-section of Target B with respect to depth is obtained from the 3-D conductivity model and displayed in Figure 4. The high electrical conductivity target of zone B is observed at the central region of the cross-section and is labeled.

All TEM contour maps were overlain onto the DEM of the survey area to study the possible relationship between the high relief regions and recorded geoelectrical responses. Figure 6 illustrates the contour map at depths of -50 m that was overlain onto the topographic structures of the study area. It is observed that the trend of the electrical conductivity targets is NW-SE, along the ridges at all three zones instead of EW as initially interpreted from the contour maps. Zone A, B and C are independent, elongated bodies that are identified as the possible mineralized fracture zones.

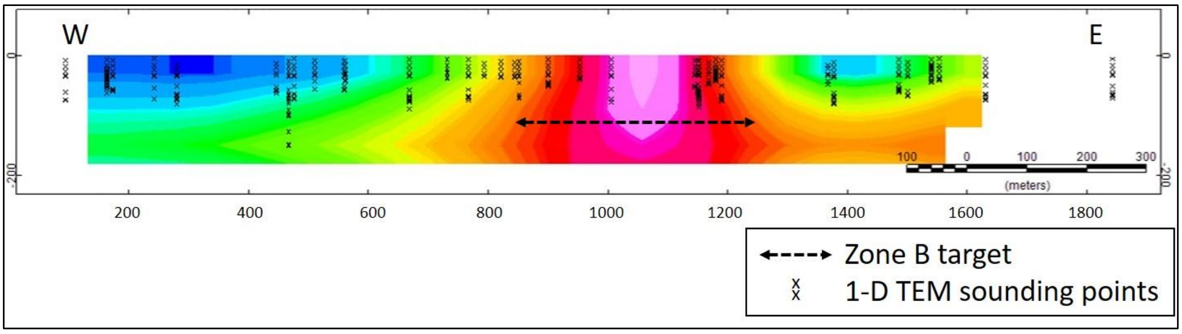

Figure 4. Cross-section of Target B and TEM sounding points with respect to depth. High electrically conductive zone measures up to 450 m in width.

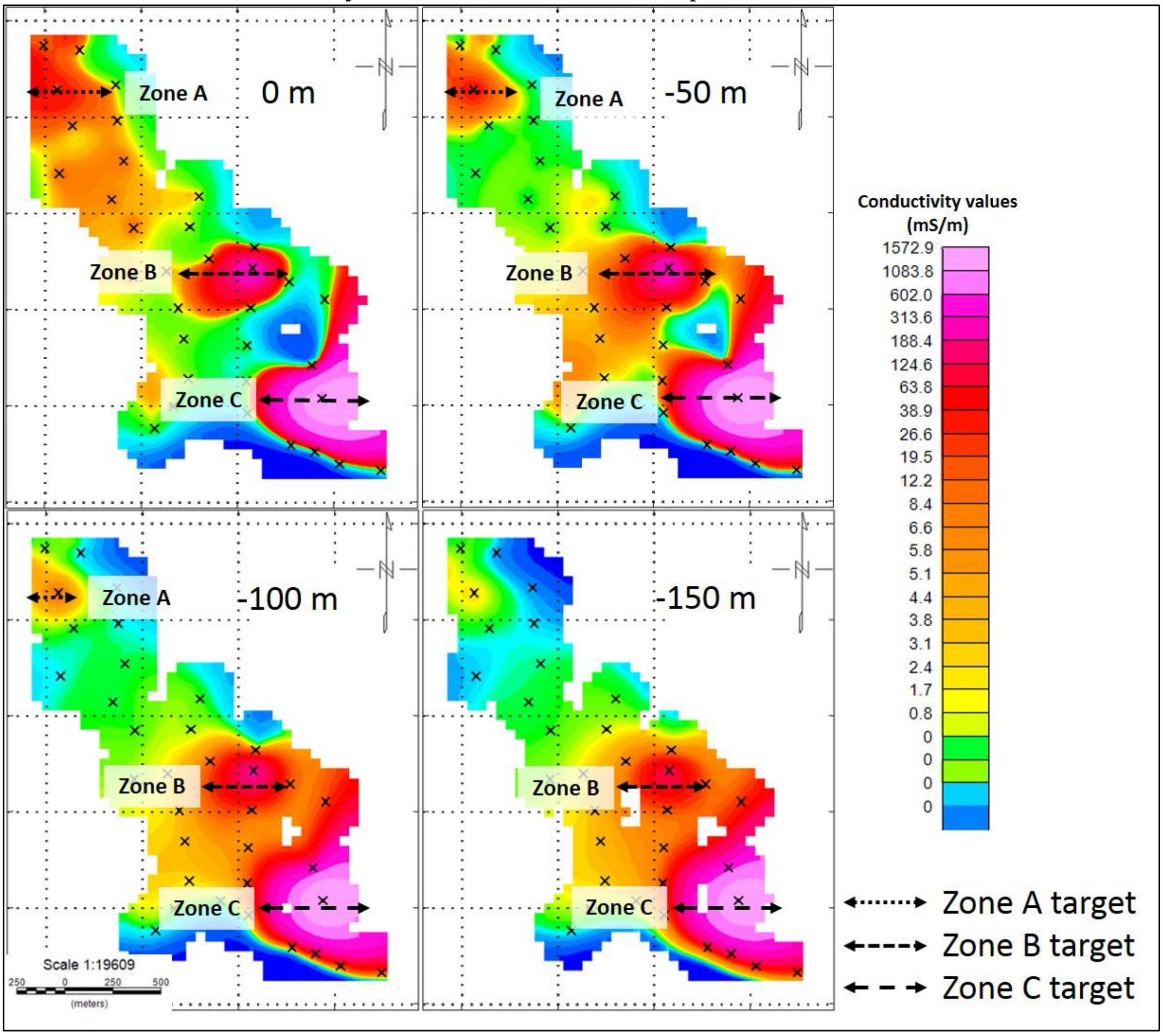

Figure 5. Contour maps of various depths to study the vertical and lateral continuity of the geoelectrical responses. Targets A, B and C have high electrical conductivity responses and are interpreted as possible mineralized fracture zones.

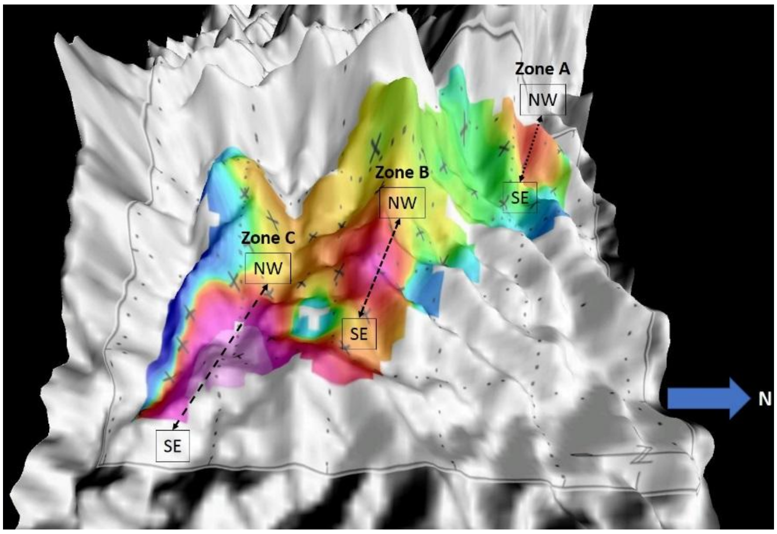

Figure 6. TEM contour map of -50 m overlaid onto the DEM of the study area. Three independent, elongated bodies of high electrical conductivity response may suggest possible mineralized fracture zones along the ridges with directional trends of NW-SE.

4. Conclusion and recommendations

The TEM survey have successfully been utilized to study the geoelectrical characteristics of the hilly region of Sungai Lembing, Pahang. A 3-D electrical conductivity model of the study area have been constructed based on 35 single loop TEM soundings that have been acquired. Contour maps in the form of depth slices have been extracted from the model to study the vertical and lateral continuity of the geoelectrical data. Three high electrically conductive anomalies have been determined and are labelled as target A, B and C. These targets are observed to have a directional trend of NW-SE along the ridges based on the contour maps that are placed over the DEM of the survey area. Targets A, B and C are identified as possible mineralized fracture zones and further investigations such as drilling and other geophysical studies should be carried out to support this initial finding. The TEM method has proven successful as an initial geoelectrical mapping and prospecting method.

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