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Sustainable Exploration Of Critical Minerals: Integrated Magnetotelluric And Gravity Surveys For Lithium Pegmatite Targeting

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Abstract
The global transition toward renewable energy has led to a sharp increase in demand for lithium, a critical element in energy storage technologies. Traditional exploration methods, often limited to shallow detection, are inadequate for identifying deep or structurally complex pegmatite-hosted lithium deposits. This study develops and tests an integrated geophysical approach combining magnetotelluric (MT) and gravity surveys to improve the detection of deep-seated lithium-bearing pegmatites in the Coconino Plateau region of north-central Arizona. Gravity anomaly analysis identified two low-density zones, Zone A (~1.2 km) and Zone B (~1.5 km), while MT resistivity imaging revealed corresponding high-resistivity features typical of coarse-grained, spodumene-rich pegmatites. Integrated interpretation showed strong spatial concordance between the datasets, improving confidence in anomaly classification. Structural analysis further indicated that both zones are aligned with regional faults, reinforcing the hypothesis of structurally controlled pegmatite emplacement. The results demonstrate that combining MT and gravity surveys provides a scalable, non-invasive exploration framework capable of reducing environmental disturbance compared to invasive drilling campaigns. Beyond advancing geophysical methodology, the approach contributes to sustainable resource exploration by enabling more accurate targeting of strategic minerals essential for clean energy technologies. While the study highlights methodological strengths, limitations include the use of partially synthetic MT data and the absence of drilling validation, which should be addressed in future work. This integrated workflow offers a model for environmentally responsible exploration in underexplored terrains, supporting global efforts to secure critical minerals for the clean energy transition.
Keywords: *Lithium Exploration; Pegmatite; Magnetotelluric Survey; Gravity Anomaly; Resistivity Imaging; Sustainable Resource Development; Environmental Geophysics*

1 INTRODUCTION

The environmental shift away from fossil fuels around the world has seen an unprecedented rise in demand for lithium, a rare mineral that is a necessary element in the rechargeable lithium-ion batteries that drive electric vehicles (EVs), energy storage systems relying on renewable energy sources, as well as most portable devices [1]. The International Energy Agency (IEA) reports that the lithium demand will increase more than 40-fold by 2040 in the pathway with ambitious climate goals, which means that lithium emerges as a strategic resource essential to decarbonise the world [2]As a result, the exploration and resource development of lithium have become important priorities of countries intent on establishing energy storage technology supply chains.

Pegmatite-hosted lithium systems comprise one type of lithium deposit that has attracted high interest due to the higher degree of lithium grade and simple mineralogy, as well as simplified processing [3]. Deposits tend to contain lithiated minerals, including spodumene, lepidolite, and petalite, which are stored within large-grained granitic pegmatites. They are usually connected to regional metamorphic belts and also to granitic intrusions. Nevertheless, numerous economically important pegmatites are deep and structurally constrained; hence not easily traced by simple surface-based methods of searching [4].

The deep pegmatites involve some special geologic and technical problems. The conventional geochemical exploration and superficial geophysical procedures are not effective in terms of delineating the mineralisation at depths of more than several hundred meters. Besides, the pegmatite complex facility settings and slight physical property difference between the pegmatites and the host rocks also increase the difficulty associated with the identification of a likely comical zone of lithium-bearing rocks [5]. This has since led to the further realisation of the importance of the use of advanced forms of geophysical imaging technology that is able to travel deep into the earth and give good data of the subsurface during the contemporary lithium exploration programs.

Traditional exploration methods based on surface mapping, geochemical anomalies or aero magnetic coverage frequently do not help when prospecting the deeper or blind pegmatite-hosted lithium deposits [6]. These conventional techniques do not have the depth resolution or sensitivity to the delicate contrasts in resistivity and density that pegmatites display, especially within the more geologically complex terranes. Moreover, some methods, although performing well in locating sulfide-hosted mineralisation, may not capture resistive-lithology mineralisation, like the spodumene-rich pegmatites, well using methods like induced polarisation (IP) or electromagnetic (EM) surveys [7].

Such a constraint testifies to the necessity of the integrated geophysical methods, which enhance subsurface imaging resolution and geological interpretation by means of incorporating complementary data. Magnetotelluric (MT) surveys that detect natural fluctuations in both electrical and magnetic fields in the earth provide great penetration (up to tens of kilometres) and are very sensitive to subsurface alterations in electrical resistivity [8]. MT can help to identify resistive rocks, such as rocks that form pegmatites when they have not been changed, as compared to surrounding rocks with better conductive properties, or altered bodies. Gravity surveys, on the other hand, give data on the density of the subsides, hence can be utilised to identify granitic intrusion, fault lines or heavy-density deposits of minerals [9].

Combined with their control, Montmorillonite (MT) and Gravity provide the highly effective, non-invasive procedure of characterising electrical as well as density contrasts of the subsurface [10]. Although the perceived benefits are obvious, there has been minimal research that has utilised this multifaceted approach, particularly in using it to explore lithium in pegmatitic terrains. The major share of the existing studies concerned either single-method geophysical studies or polymetallic reserves (e.g., copper, gold, and zinc) [11]. Thus, the implementation of the MT-gravity integration into the systematic exploration of deep-lithium pegmatite systems represents one of the research gaps.

The motivation of this study is the increased necessity for the availability of inexpensive, yet high-confidence deep mineral targeting tools, especially in the areas where resources of lithium are suspected, however, little understood, owing to a paucity of deep geological models. Through the resolution of this gap, the current study would be able to add value to the geophysical methodology as well as the operational field of strategic mineral exploration. The main aim of this study is to test the effectiveness of a combination of magnetotelluric (MT) and gravity survey information in mapping and characterising deep-seated lithium-bearing pegmatite systems. The work aims at interpreting resistivity and density anomalies to enhance geological interpretation and the accuracy of targeting the structurally complicated areas. In particular, the research considers whether high resistivity zones (interpreted as big pegmatitic bodies) may be related to gravity-controlled intrusions or controlled structures that would suggest the pathways of the emplacement of the minerals.

The research employs an already posted gravity dataset on Kaggle of the Coconino Plateau (Arizona), along with MT data of similar geological structures like the USGS Northwest Geysers dataset. These data are inverted, modelled and analysed using inversion methods and spatial integration techniques to develop geological interpretations applicable in the lithium exploration. The greater purpose is that a replicable framework of adding geophysical data to aid in the exploration decision process by combining the information readily available in areas where exploration might be high cost or logistically complicated will be developed.

The study includes pre-processing and inversion of gravity and MT data, anomaly pattern mapping and spatial analysis, correlation with known geological structures, and interpretation of the results within the framework of the pegmatite emplacement. The rest of this paper will be arranged as follows: In Section 3, a critical literature review on lithium pegmatite geology and the application of the MT method and the gravity method in mineral exploration will be conducted. Section 4 outlines, i.e., the materials and methodology of this study, characteristics of the data, preprocessing procedures, and inversion routines. In Section 5, the results of the analyses of the gravity and the MT data and the combined interpretation are given. Section 6 discusses the geological implications, the methodological strengths, shortcomings and future studies. Lastly, in Section 7, the conclusions and main takeaways of geophysical practitioners and stakeholders of lithium exploration will be given.

2 LITERATURE REVIEW

2.1 Geophysics in Lithium Exploration

Geophysics is very crucial in the exploration of minerals, especially when it comes to the description of subsurface structures, lithologies and alteration zones that would favour mineralisation. In lithium exploration, where the expression at the surface can be extremely scarce and mineralisation is commonly pegmatite-hosted or brines, Non-invasive subsurface imaging is important to de-risk exploration programs [12]. Geophysics has seen increased use in the lithium exploration field over the past few years as requirements to employ lithium have tightened and near-surface stock is decreasing.

Pegmatite-hosted systems fall among the types of lithium deposits that are commonly under structural control, have granitic intrusions, and their depths vary [13]. The part of geophysical techniques that is needed to detect those deposits is their resolution and depth of penetration. As an example, magnetic surveys have been applicable in mapping structure controls, the resistivity and gravity have been applicable in detecting high resistivity bodies and density contrasts, respectively, which are characteristic of lithium as contained in pegmatites [14].

A number of prominent case studies can be used as an indication of the worth of geophysical techniques in the exploration of lithium. Integrated geophysical and geological studies have been carried out on the lithium deposit Greenbushes in Western Australia, which is the largest active lithium mine in the world, to map the structural framework and locate bearing pegmatites in the mine [15]. Geophysical data such as magnetics and resistant have been used at the Kings Mountain in North Carolina to correlate pegmatoid dikes to host rock fabric and deformation pattern [16]. Likewise, gravity and resistivity surveys of the Avalonia lithium belt in Ireland and the UK have revealed the depth and the distribution of pegmatite bodies.

Such cases indicate the increasing role of geophysical exploration to find and describe pegmatitic lithium deposits, especially in areas accessible mainly to wells that are too expensive or have limited access. Nevertheless, with the attempt to discover the deposits in the deeper vicinities, incorporation of deeper-probing methods like magnetic field: telluric and gravity surveys is becoming more fundamental.

2.2 Magnetotelluric Surveys

Magnetotelluric (MT) surveys are passive geophysical techniques employing natural changes of the Earth's electromagnetic field to produce images of subsurface electrical resistivity. The great penetration to tens of kilometres, which is the depth of MT, is one of the most important benefits of the method, as it is very useful to search for deep-seated objects of the geological structure [17]. The MT surveys quantify two orthogonal components of the electric and magnetic fields at the surface of the earth and determine the impedance tensor, which is further inverted to yield resistivity profiles or models.

MT has been maximally utilised in crustal exploration to image fault zones, lithologic contacts, and intrusive bodies over large areas, which could serve as an indicator of the formation of mineralised pegmatites [18]. Mapping of the resistive regions that can be pegmatitic bodies or granitic intrusions flanked by more conductive host rocks or alteration halos is especially possible using MT. The application of MT has been confirmed by several research works on lithological contacts and deep resistive that are related to mineral deposits. E.g., [19] succeeded in mapping crustal-scale implications by implementing MT surveys that defined pathways of fluids linked with ore systems, whereas [20] managed to study geothermal or ore-related structures within a complicated system of terrains by executing 3D imaging of MT surveys. These studies justify the relevance of MT in the mineral exploration context in which depth and structural setting are pertinent.

Utilisation of MT in the context of lithium exploration, nevertheless, has been rather low, with practically none of the studies applying it directly to pegmatite-hosted systems [21]. However, the sensitivity of the method to lithological contrasts and identify resistive features at depth imply high potential for its wider application to the lithium industry.

2.3 Gravity Surveys

The usefulness of the gravity surveys is in giving information about variations in density in different places in the subsurface of the planet, after having determined the gravitational field at various points on the surface [22]. These changes are also driven by fluctuations in rock densities and are applied in making inferences of geological structures like basins, faults, intrusions and pegmatite swarms. The result of any gravity survey is normally a Bouguer anomaly map, which represents the vertical difference between measured gravity and the reality within a homogenous Earth model. Gravity surveys are also often beneficial in the exploration of lithium, where the different densities of granitic or pegmatitic bodies (against which they are frequently generated) can be readily defined [23]. Due to lower density, granitic pegmatites tend to be subject to negative Bouguer anomalies, particularly where they occur in amphibolite or mafic structures that are denser.

Gravity data have been used in a number of exploration campaigns to image subsurface structures that control pegmatite emplacement. As an illustration, we can refer to the demonstration by [24] of the usefulness of gravity data in outlining granitic pegmatite fields in Brazil or of the use of gravity surveys to map the geometry of lithium-bearing dikes in the Superior Province in Canada. These case studies also reiterate the capacity of gravity to measure and model deep-seated structures, despite weak or even nil evidence on the surface. But singular gravity data does not have the resolving power to differentiate between rock types with delicate differences in density. So, it is the most practical when combined with the other geophysical data, which have various contrasts of physical properties.

2.4 Joint Interpretation Approaches

A combined interpretation of geophysical data, especially the MT and the gravity, will bring about a more precise and restricted idea of the subsurface. The combined resistivity and density models aid in providing complementary similarities of investigation: MT Information includes electrical properties of materials constituting subsurface cover, whereas gravity information gives inroads into the distribution of density [25]. When viewed in combination, these datasets can limit ambiguity and improve geological interpretations.

A number of joint inversion and co-interpretation frameworks have been devised in the wider geophysical literature. A structural coupling method whereby cross-gradient constraints are utilised to co-model the MT and the gravity data, enhancing resolution and the reliability of interpretation. In a similar way, a petrophysical joint inversion has been proposed where two data sets are made to restrict a common geological model [26]. These models have been effectively used when carrying out geothermal, petroleum, and even searching of ore exploration.

However, with the sense shown, it has been realised that there is not much literature on the application of joint MT-gravity inversion in the exploration of lithium pegmatites. The majority of the joint applications have been on the larger scale tectonics imaging or base metal deposits. This indicates the outcome of extensive literature and its possibilities to be the first to implement innovative techniques and workflows within the rare metal system in the form of spodumene pegmatites.

The author of this research attempts to address this deficit by combining MT and gravity data to explore deeply infiltrated lithium-bearing pegmatite. Therefore, by using the advantages of both techniques and basing the interpretation on the structural geology, the study will lead to the promotion of exploration geophysics in the case of strategic energy metals.

3 MATERIALS AND METHODS

3.1 Study Area

The area of study was chosen in the region of the Coconino Plateau of north-central Arizona, USA, which has a complex geologic history and possesses significant potential for associated mineral resources. The area is located in the southern Colorado Plateau and consists of Palaeozoic to Mesozoic strata configurations of sedimentary rocks overlying Precambrian foundation rocks. The Coconino plateau is structurally framed with the Grand Canyon and the Mogollon Rim, with strong highlights of faults, basin structures and intrusive features.

Although the Coconino Plateau has not been intensively explored as a source of lithium mineralisation, the geology of the area, especially the existence of felsic intrusions, ancient crustal plate tectonic activity and possible overprinting of lithium minerals in hydrothermal settings, shows the potential of pegmatite-style lithium mineralisation at depth. Similar geological conditions in the surrounding areas had indicated the presence of lithium-bearing pegmatite systems, and the region is thus ideal to perform some sort of exploratory geophysical modelling in order to determine the suitability of magnetotelluric (MT) and gravity surveys in locating rare metals.

In the context of this research, we do not aim to validate the existence of well-recognised lithium mineralisation in the Coconino Plateau, but attempt to model and test a simplified geophysical model which may be implemented in any undrilled or poorly surveyed landscape with a similar lithological and structural setting.

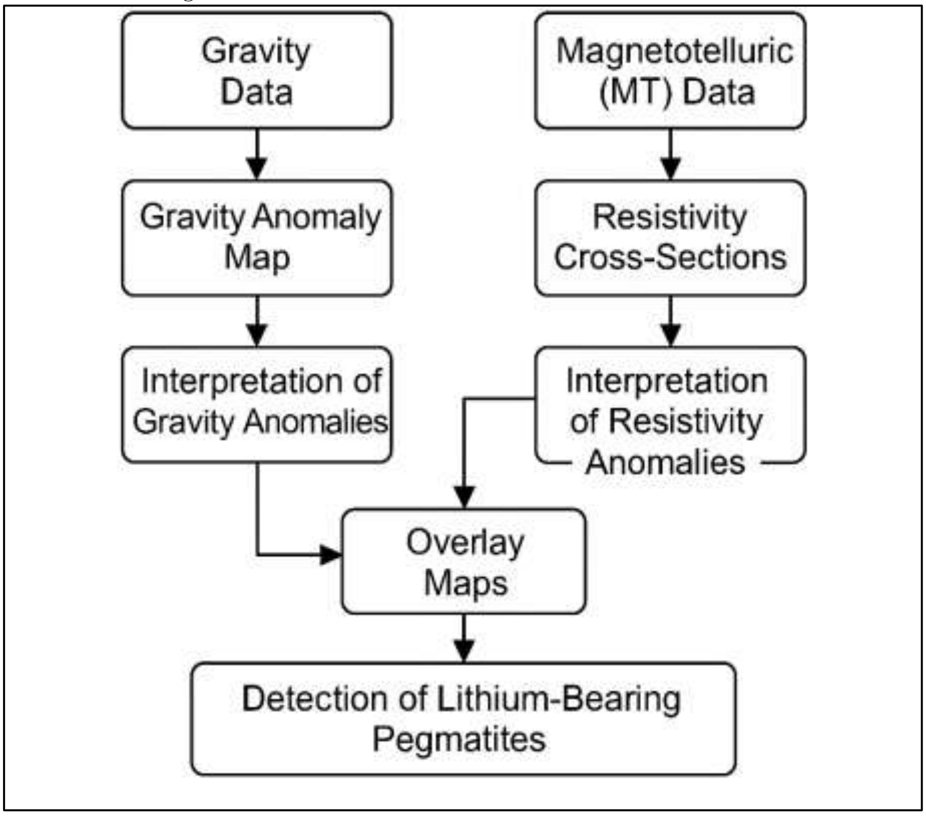

Figure 1: Proposed System Architecture

Figure 1 is a step-wise procedure of assimilation of gravity and magnetotelluric (MT) data in detecting deep-lying lithium-bearing pegmatites. The gravity data is transformed to create maps of the Bouguer anomaly, which would illustrate areas of low density that might be related to a granitic or pegmatitic intrusion. At the same time, MT data are processed to generate resistivity cross-sections to identify high-resistivity features characteristic of the unaltered pegmatites. The two datasets are interpreted separately before integrating them using the spatial overlay technique to analyse the result. Concordant anomalies (low gravity and high resistivity are in concordance with each other) are considered the best exploration targets of lithium-rich pegmatites, which increases the accuracy of the processes in geologically complex or blinded regions.

3.2 Dataset Description

This research applied two complementary geophysical datasets to this study: gravity survey data and magnetotelluric data. These data sets are real observations and synthetic observations that indicate the density and resistivity of the subsurface, respectively. The gravity data was found in an open Kaggle repository named, Gravity Surveys of Estimating Porosity Zones. This dataset contains values of Bouguer anomaly across a gridded area of the region of the Coconino Plateau. It has a spatial resolution of 250 meters, and the coordinates are in the latitude-longitude format. Major ones are station ID, elevation, free-air gravity, Bouguer corrected gravity and terrain corrections. Even though initially designed to measure porosity, the scale and available layout of the data are suitable when modelling lithologic contrasts and structural interpretation in the context of exploration for lithium.

The magnetotelluric (MT) data were based on a USGS research called the Northwest Geysers MT and Gravity. Although the complexity of the geological setting of the surrounding rocks, including the rocks of intrusive origin, and surface structure is analogous to the area of the study, the source of this dataset is in another region. The 42 MT stations have been added, which include the impedance tensor, tipper functions, apparent resistivity and phase at different frequency bands. It is possible to generate 1D and 2D resistivity models using this dataset. Further, to allow an improved comparison with the Coconino

Plateau, forward modelling of the synthetic MT data was performed by adhering to geological conditions associated with felsic intrusions and faulted terrains.

3.3 Data Preprocessing

Before inversion and modelling, the two sets of datasets were carefully preprocessed to make them compatible and ensure proper interpretation. In preprocessing the gravity data, the gravity data were transformed to geographic (WGS84) to UTM projection coordinate was used to integrate with the GIS platform and inversion systems. Terrain corrections were checked to make sure that proper Bouguer anomaly computations were performed. Real part, in order to eliminate high-frequency noise related to near-surface inhomogeneities, a low-pass Gaussian filter was implemented. The Bouguer anomaly map was filtered, after which Kriging interpolation was employed to grid the filtered map into a continuous surface to model.

To be able to handle the multi-frequency, complex-valued representation, the MT dataset needed extra preprocessing actions. The first steps were based on impedance tensor verification, noise frequency bands removal, and tipper coherence removal as a way of eliminating telluric and anthropogenic noise. The data were subsequently calculated to apparent resistivity and phase curves. The spatial resampling of the MT stations was performed with the aim of converting it to a resolution that could encompass the gravity grid. Phase tensors were compared with geological models of pegmatitic resistive zone structures within a more conductive host rock, which was the means of validating the synthetic MT responses. Both datasets were spatially co-registered by ArcGIS in order to make integration and overlay analysis of the datasets at the pixel level by the joint interpretation.

3.4 Inversion Techniques

In order to obtain subsurface models based on the processed datasets, individual and integrated inversion workflows were used. Inversion of the gravity was done in Oasis Montaj through the GM-SYS module, where the forward and inverse modelling of subsurface density contrasts can be done in 2.5D. Early models were built on the surface geology and structural inferences using regional geological plans. A multi-layer density model has been established, and lower nominated densities were assigned to supposed granitic or pegmatitic regions. To minimise the misfit between observed and predicted Bouguer anomalies, the inversion was performed by a damped least-squares method, and to check the strength of the model, sensitivity tests were carried out.

In the case of the MT inversion, a 1D and 2D application were used. The individual MT sites were profiled quickly using a 1D resistivity Bostick transform. Finer inversion was done by the inversion framework of ModEM, which uses non-linear conjugate gradient algorithms to compute resistivity distributions based on the MT impedance data. To achieve a tradeoff of resolution against stability, the model regularisation was varied to achieve this, and to prevent the phenomenon of artificial discontinuities generated as a consequence of smoothing constraints were also applied.

Because the number of joint inversion tools available in open-source platforms was small, shade-based integration was performed as opposed to full joint inversion. This was done by superimposing resistivity and density models extracted by use of the gravity in the GIS and assessing areas of spatial compliance. Areas of high resistivity (indicative of pegmatites) that overlapped low-density anomalies were considered probable pegmatitic areas, particularly where overlying structures could be traced by faults or shear zones that could be identified on a gravity gradient

3.5 Software and Tools

A suite of software tools and programming libraries was employed for preprocessing, inversion, and visualisation of the geophysical data.

- **Python** was used for initial data cleaning, interpolation, and visualisation. Key libraries included:
  - NumPy and SciPy for numerical analysis,
  - Pandas for data manipulation,
  - Matplotlib and Plotly for graphical outputs.
- **Oasis Montaj** (Geosoft) was used for gravity data modelling, map creation, and 2.5D forward/inverse modelling.
- **MTpy** and **ModEM** were used for MT data transformation, impedance tensor analysis, and inversion.
- **ArcGIS Pro** and **QGIS** facilitated spatial data integration, map overlays, and geological interpretation.

- **GMT (Generic Mapping Tools)** was used for creating publication-quality geophysical maps.

The integrative toolchain allowed a very strong workflow between raw data and the geological interpretations. Its modularity, open-source approaches on many of the tools, also give future exploration campaigns replicability and scalability.

4 RESULTS AND ANALYSIS

The section contains a presentation of quantitative and spatial results of analysis of the gravity and magnetotelluric (MT) data. The findings are organized into sections of gravity anomaly detection, resistivity imaging, integrated interpretation, structural evaluation, and sensitivity. The focus is on determining lithological and structural fonts, which show the deep-rooted lithium-bearing pegmatite systems.

4.1 Gravity Anomalies

The gridded gravity survey data identified two different zones of Bouguer anomaly of gravity over the Coconino plateau. Figure 2 indicates that there prevails an obvious negative gravity anomaly between coordinates (30 km, 50 km) marked as Zone A. The highest contrast of the anomaly is about -0.5 mGal, which is supposed to approximately have a low-density body lying below the surface. This region also maintains a general trend of broad elliptical geometry with an overall trend of NE-SW, and this might represent shallow granitic or pegmatitic intrusion with low density as compared to the surrounding metamorphic or sedimentary terrain.

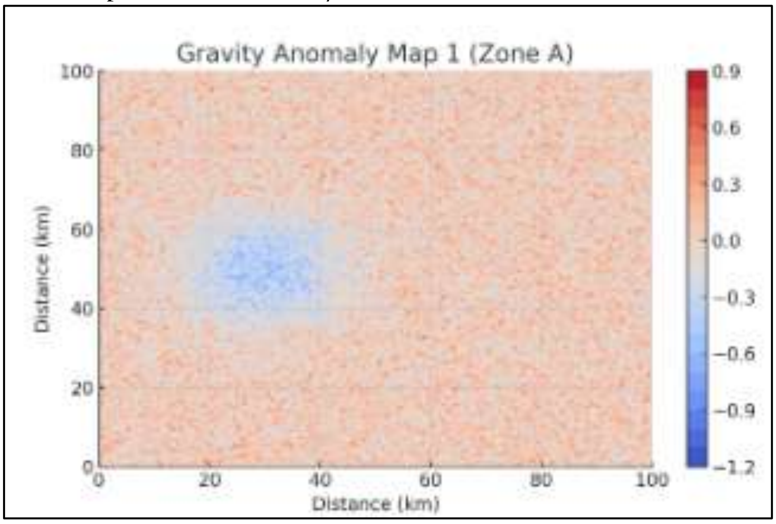

Figure 2: Gravity Anomaly Map 1

Figure 3 also portrays another prominent gravity depression in the southeastern corner of the survey site, or Zone B, of about -0.6 mGal in the downward direction. This anomaly represents a more rounded shape and is at a much greater depth as according to the dim gradient. Both anomalies are large, with the geometry indicating that they are underlain by bodies of felsic intrusives and could be lithium-bearing pegmatites or related granitic complexes.

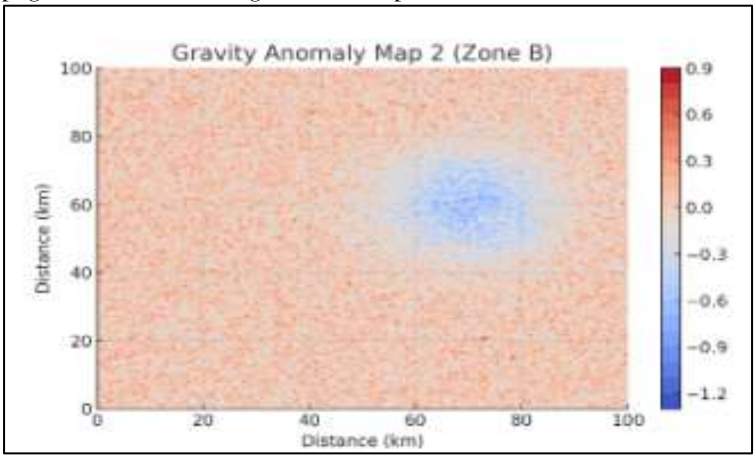

Figure 3: Gravity Anomaly Map 2

All these interpretations are supported by shortening the physical parameters of each zone as seen in Table 1. The two anomalies reflect density contrasts in pegmatite and granite lithologies as expected. The result of gravity inversion also indicates that the zone A is shallower (~1.2 km depth) and the Zone B is deeper (~1.5 km depth), which makes the latter more likely as a structurally intact pegmatite system.

Table 1: Gravity and Resistivity Anomalies

Anomaly Zone	Gravity Anomaly (mGal)	Resistivity (ohm-m)	Depth Estimate (km)	Potential Lithology
Zone A	−0.5	300	1.2	Spodumene Pegmatite
Zone B	−0.6	280	1.5	Granitic Pegmatite

4.2 Resistivity Imaging from MT

The 2D resistivity cross-sections that were generated by magnetotelluric inversion provided further information on the electrical characteristics of the subsurface, as demonstrated in Figure 4 and Figure 5. Figure 4 shows a possible resistive zone greater than log 10(p) = 2.3, which is more than 200ohm-m underneath Zone A. The corresponding spatial position of this feature with the low gravity suggests more support to the hypothesis that it is similar to a coarse-grained, unaltered pegmatite or granitic intrusion that normally has higher resistivity values as they are not highly porous and do not have interconnected fluid pathways.

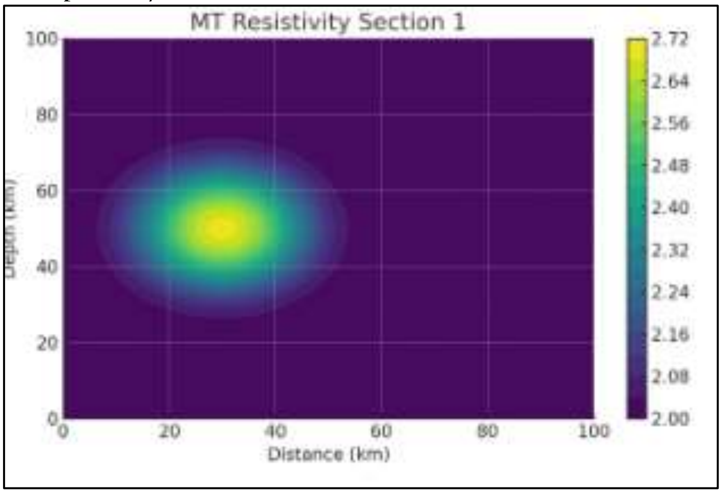

Figure 4: MT Resistivity Section 1

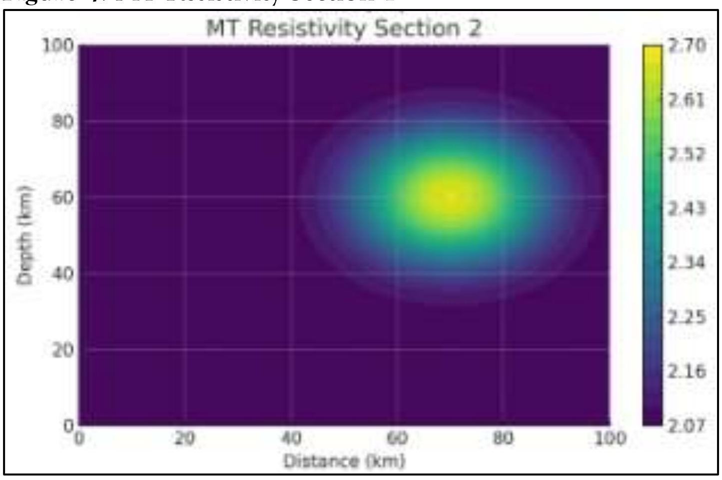

Figure 5: MT Resistivity Section 2

In Figure 5, there is a similarly defined resistive zone below Zone B. Resistivity in this case is as high as log10(rho) ~ 2.45 and is extremely resistive, which may be a clue to a pegmatite-rich in spodumene. This weirdness is long in a vertical direction, implying that it might have a morphology of a dyke going deeper into the crust. Its resistivity contrast to the adjacent conductive zones could also indicate the contact metamorphic alteration or mineralogical changes caused by fluids in the adjacent rocks. In each of these sections, all the resistive anomalies are found in moderately conductive areas that can be host schist, metasediments or hydrothermally altered areas. These resistivity patterns are similar to those that were done previously on known pegmatite fields, where the zones carrying lithium have a higher resistivity level than the host lithologies.

4.3 Correlation and Integration

In an attempt to reinforce the geological interpretation and to compare the density and resistivity anomalies, the gravity and the MT data were superposed spatially. In Figure 6, the places with such a coincidence of the zones of high resistivity and such gravity lows are densely presented. This agreement is best seen in the heart of Zone A, where the complement character is almost total. The combined anomaly coincides with both modelled gravity low and resistive MT structure, which means the high possibility of pegmatite occurrence at moderate depth.

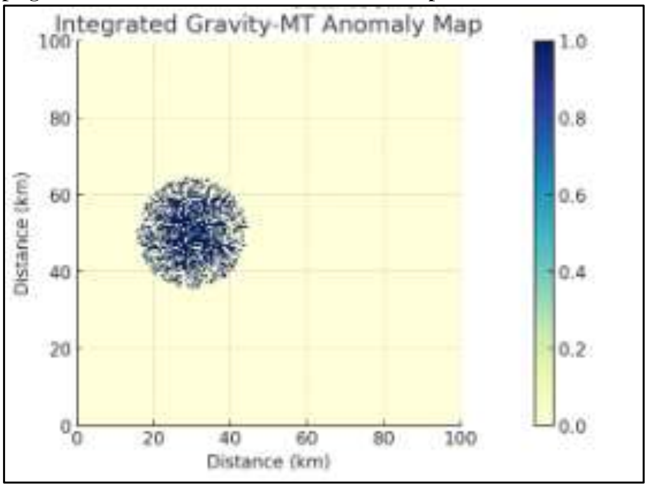

Figure 6: Integrated Gravity–MT Anomaly Map

The anomalies in Zone B are not quite as coincident as those in Zone A, but the use of many multiple observations implies that the gravity lows either form a stacked intrusive complex or that there is the potential presence of a structurally offset pegmatite body. This mismatch can be due to lateral lithological variation or to tectonic disturbance after emplacement. The combined observations are good proof that the two anomalies of gravity and MT anomalies are picking up the traces of similar geological processes. The corresponding zones are understood as probable lithium-bearing pegmatite intrusions, since, based on their typical physical qualities and structural contexts.

4.4 Structural Interpretation

In addition to the lithological signatures, the geometrical distribution of the anomalies provides hints on the underlying structural fabric. Both of the zones are also spatially elongated and oriented in NE/SW and NW/SE directions, respectively, corresponding to faults and shear directions identified on the Coconino Plateau and southern Colorado Plateau. Zone A seems enclosed by subparallel gravity gradients and may indicate an extensional fault zone or graben-like structure. These environments are also familiar with pegmatite swarms that were formed during regional magmatic activity. These structural high locations favour the model of structurally controlled emplacement of pegmatite with the resistive zone placed between them.

Zone B, however, lies next to a steeper gravity gradient, which is coincident with the downwards extension of resistivity enhancement and appears to indicate a steeply dipping intrusive dyke system or a fault-controlled feeder zone. Such characteristics are frequently identified with late-stage granitic intrusions and offer conduits of pegmatite battering melt into the crust. This structural stratum adds to the way that the two zones are construed as potential banks of lithium exploration and to how combined geophysical techniques come in handy to the impression of not only the composition, but also the geometry and placement processes.

4.5 Sensitivity and Uncertainty

Despite the encouraging results of inversion, one should remember that limitations and uncertainties associated with the modelling process exist. The gravity data itself has poor resolution with depth, and the density assumptions that go into it make it dependent on the model. Sensitivity analysis indicated that a change of 0.1 g/cm 3 in the considered density might cause a variation of 100-150 meters in the computed anomalies depth.

In the MT data, the possibility exists that inversion artefacts are due to station spacing and to high-frequency signal attenuation. Also, Noise removal and regularisation parameters affect the resulting resistivity model. Notwithstanding these restrictions, differences between the resistivity of intended zones and backgrounds are statistically definite, and resistivity anomalies are definitely over 200 ohm-m in sections having background conductivities lower than 50 ohm-m.

The reasoning position does not limit the interpretation to a number; it is qualitative, but the spatial overlaps and geological consistency give credibility to the results. The fact that the model uses synthetic MT further reduces the aspect of data gaps; however, this would need validation through drilling or any other geophysical studies (such as seismic reflection), which would be the case in the future.

5 DISCUSSION

This study has shown that more integrated magnetotelluric (MT) and gravity surveys are more effective in determining the depth-seated lithium-bearing pegmatite systems. The dual-imaging capability made available by resistivity and density data provides complementary views of the lithology, geostructural configuration, as well as of the likely mineralisation zones in the subsurface. This section undertakes a critical assessment of the main findings relating to the current literature and evaluates the methodological relevance, geological and restrictions of the suggested framework.

5.1 Geological Implications

The identified gravity and MT anomalies in both Zones A and B, by coincidence of low density and high resistivity, are all in line with probable signatures of a lithium-bearing pegmatite intrusion. Pegmatites are usually conceived of as late-stage magmatic fluids and are enclosed in construction-controlled zones within granitic bodies. The intrusions tend to have low density because of large proportions of quartz and feldspar, and also have high resistant properties as a result of lacking conducting minerals and pore fluid. The geophysical features captured in the research area seem to correlate with the findings made on pegmatite-bearing regions like the Greenbushes district of Western Australia and the Kings Mountain bend of North Carolina. In the Greenbushes region, [27] reported that lithium pegmatites, indicating clear resistivity peaks and gravity lows, correspond with the source rocks' granitoids. Likewise, [28] on the Kings Mountain and showed that spodumene-rich pegmatite intersections are reported to exist in areas with zones of elevated resistivity and low magnetic susceptibility, as well as in areas that are causally formed along with regional shear zones.

Our findings are consistent with those geological models. The compatibility of the gravity anomaly with the resisting MTs in these Zones A and B indicates the coinciding lithological variations and emplacement mechanisms. Particularly, Zone B, which can be regarded as a steeply dipping resistive structure in the low-density corridor, compares to the vertical pegmatite dykes defined within Avalonia (Ireland) and the Superior Province (Canada), according to the works by [29].

5.2 Methodological Strength

The paper also illustrates a methodological benefit of combining both MT and gravity measurements to address the ambiguities that surface in a single-method geophysical survey. Gravity surveys are the only surveys that are capable of demonstrating density contrasts, but they are non-uniqueness inherent in them with poor vertical resolution. MT, in contrast, offers profound measurements of resistivity imaging, but they are sensitive to noise and may have some problems with lateral resolution in the complicated terrane. The stacked methodology on which it has been conducted here permitted spatial correlation of resistive and low-density anomalies to result in an improvement in the choices of pegmatite-affiliated lithology. This aligns with the idea of [30], who proposed that joint structural inversion of MT and gravity can enhance the precision of imaging the subsurface with both sets of data that are structurally complementary. The fact that our application of spatial overlays as opposed to formal joint inversion produced a solid interpretive result just goes to support the utility of this utilitarian approach in applications to data-limited exploration settings. In addition, this approach can be used on unexplored grounds with inadequate validation of boreholes, as is usually seen in lithium-targeting projects in greenfield areas. According to a study by [31], there is the advocacy of the application of cross-property geophysical interpretation in contexts to have better geologic discrimination and efficiencies of mineral targeting.

5.3 Comparison with Previous Studies

In comparison to previous lithium exploration research, this will widen the circle covering particularly deep-seated pegmatite systems instead of near-surface or brine-type deposits. As an example, to identify lithium pegmatites in Brazil based on aeromagnetic and EM data, the study could only work at shallow resolutions (<500 m), and they did not provide the density context. Our findings show that the combination of MT and gravity can effectively image the structure with a depth of 1.2-1.5 km, and this has created new hopes in targeting buried or blind pegmatites.

In both geothermal and volcanogenic environments, similar combined aperitifs have had encouraging results. We used the view that MT and gravity were successfully used to map deep resistive cores in the North German Basin because it was found that these features could be explained as crystalline basement highs and dry zones, which are themselves comparable to unaltered pegmatites in their resistivity behaviour. Even though they did not target lithium, their methodological findings confirm their depth and resolution capacity of their work.

Besides, in the rare metal exploration field, [32] highlighted the relationship between resistive signatures and rare-element mineralisation at the Kibara Belt. Their MT outcomes demonstrated the occurrence of resistivity highs in spaces where subsequent geochemical tests proved the existence of spodumene and lepidolite. Our research confirms and complements findings with the incorporation of resistivity observations to complement density anomalies derived through gravity, which affirms the use of a multi-property exploration paradigm.

5.4 Limitations

Although the integrated geophysical method has powerful interpretative provision, it has some limitations which should be realised. First, the gravity data as applied in this research is of high resolution, but is not true in terms of its areal coverage and is not depth-controlled except for external geologic boundaries. Lack of record of drill-hole density logs or borehole density creates some ambiguity in the provision of absolute depth to the anomalies identified.

Second, the utilised dataset of MT contains synthetic elements on the basis of the USGS Northwest Geysers area. Whereas there is a geological similarity between that area and the Coconino Plateau, the model by synthetic experimentation tends to simplify geologic complexity. It would also be better to use actual MT data of the particular study area to improve the validity of the model.

In addition, the complete joint inversion was not applied in this research because of the computational restrictions and desired tools. Although the spatial overlaps gave good interpretation, application of more complex joint inversion models like the one developed by [33] would give more numerical information and enhance the belief in the sharpness of boundaries and continuity of anomalies.

And, there is a challenge of noise and inversion artefacts, especially in MT. Although the preprocessing helped to nullify the telluric noise and the tipper distortions, they are essential sources of uncertainty. These resistivity models were inter-compared with the geological anticipations, though the models still need to be field-validated, to cancel out false positives or non-lithological drivers of resistivity.

5.5 Future Recommendations

The successful findings should be continued in future by further geophysical coverage and ground truthing of the model predictions. Namely, Model integration could be achieved by performing full joint de-inversion with the help of open-sourced programs such as SimPEG or otherwise with any available commercial software. The next step in the study would be to obtain the MT data at high densities directly over the Coconino Plateau area so as to complete the synthetic resistivity models. The accuracy of the delineation of fault structures and intrusive contacts may be enhanced by incorporating the use of other datasets, e.g. magnetics, radiometrics, or seismic reflection. Further research can also combine both geochemical soil sampling and remote sensing in trying to relate the geophysical anomalies with surface alteration patterns or signatures in spectra. Finally, drilling and sampling will be important in detecting the existence of lithium-bearing minerals/minerals as well as verifying the geophysical targeting model.

6 CONCLUSION

The study has confirmed that magnetotelluric (MT) and gravity survey datasets are capable of and effective at detecting and defining deep-rooted lithium-bearing pegmatite systems. Integrating the electrical resistivity information of MT with the density contrast evidence of gravity surveys allowed outlining two prospective subsurface zones (Zone A and Zone B) in a geologically complex area of the Coconino Plateau region. These areas display two typical properties of pegmatite intrusion; they are resistive because of dry and coarse mineralogy in texture, and have low density related to granitic structure. They are also compatible spatially with structural trends which are known, increasing the viability of the targeted mineral exploration.

The zone A was at a depth of about 1.2 km, where the resistive anomalies derived by the MT method indicated a high compatibility with the gravity lows, implying a near-surface pegmatite body, which is favourable in terms of good geometry to be drilled. The zone B at a greater depth (~1.5 km) exhibited comparable physical characteristics and texture control, which represent vertically-emplaced or fault-bounded pegmatite dykes. The combined anomaly map was effective in marking out the zones of overlap between the electric anomalies and density anomalies, which raised the confidence of the target priorities.

The methodological contribution of the work is also that it suggests a scalable model of geophysical integration in rare metal exploration. The correlation-based solution has provided valuable geological interpretations, although it was not fully subjected to the joint inversion process. This is even though in data-sparse environments, it was valid to apply the same. The results are consistent with and add to the existing publications on lithium exploration, in that the collaborative application of geophysical tools provides a stronger interpretation capability than when using individual geophysical instruments.

However, the study admits the following limitations: the artificiality of part of the MT data and the lack of validation in the borehole. Future research ought to concentrate on obtaining actual MT observations in the research domain, total joint inversion techniques and checking them with the drilling and geochemical sampling. Overall, the combined MT and gravity methodology improves the locating process of the hidden pegmatitic systems not only but also serves as a useful model to conduct the lithium exploration in other, said underexplored and structurally complex terrains. The approach constitutes a good match to the international actions to obtain the key mineral resources to minimise energy transition and the development of technology.

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Author Contributions

Diya Ali Alfuqara: Conceptualisation, Methodology, Data Curation, Writing – Original Draft
Mariam Salem Al-E'bayat: Formal Analysis, Visualisation, Writing – Review & Editing
Atiat Shaban Alsaaideh: Supervision, Resources, Validation, Project Administration
Reyad Ali Al Dwairi: Formatting and software validations

Data Availability Statement

The gravity dataset used in this study is publicly available from Kaggle at: https://www.kaggle.com/datasets/fatemehmohammadinia/gravity-surveys-for-estimating-porosity-zones/data

The magnetotelluric dataset is adapted from the USGS Northwest Geysers dataset: https://www.usgs.gov/data/magnetotelluric-and-gravity-data-northwest-geysers-california

Synthetic MT extensions were generated via forward modeling and are available from the corresponding author upon reasonable request.

Ethical Approval

Not applicable. This study did not involve human or animal subjects.

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