

Global Benchmarking of Lithium Grade in Geothermal Brine and the Feasibility of Recovery from the Menengai Field in Nakuru County Kenya

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ABSTRACT

The limits used for assessing lithium recovery from geothermal brine are those widely cited as 50 mg/L, but not always tested against the systems that have been developed. In this study, the Menengai geothermal field was compared against thirty two geothermal and brine fields around the world and the following questions were asked: What are the physical properties of the brines that make them developed or undeveloped? Twenty-nine samples of brine from the Menengai area were analysed by flame atomic absorption spectrophotometry and comparison systems were taken from published geochemical surveys. The capacity of each property to discriminate developed systems was quantified by the area under the ROC curve with stratified bootstrap confidence intervals, and position was expressed in terms of percentile rank, after regressing the data for each property on total dissolved solids to remove the confounding effect of bulk salinity. Principal component analysis and Ward clustering were used to analyze the behavior of multivariate structure. Menengai was the 28th of 33 systems with a grade of Lithium, and ranked at the 18th percentile. There is a significant global correlation between salinity and lithium (slope = 1.019, 95% CI = 0.734 to 1.303; $R^2 = 0.632$), and Menengai had 0.32 times the lithium expected for its salinity, ranking it one of the most depleted in this regard. When discriminated developed systems were considered, grade discriminated almost perfectly (AUC 0.951, 95% CI 0.852 to 1.000) with a Youden-optimal threshold set at 150mg/L (95% CI 150 to 195), a threefold increase from the nominal and eighty-eightfold increase from the Menengai mean. The ratio of magnesium and lithium did not discriminate between developed and non-developed systems, but five out of six developed systems had higher ratios than Menengai. The purity of geothermal brines is not the factor that determines what is developed, it is the grade, and at the present time, the brines at Menengai aren't sufficiently pure to allow recovery of lithium.

Keywords: benchmarking; bootstrap; economic feasibility; geothermal brine; lithium grade; Menengai; receiver operating characteristic; salinity normalisation.

INTRODUCTION

Lithium has been designated a critical mineral by several major economies on the strength of projected demand from battery manufacture and grid-scale storage (Fortier et al., 2018), and the geographic concentration of current supply has prompted interest in alternative feedstocks (Grosjean et al., 2012). Geothermal brine is attractive among these because the fluid is already produced and reinjected as part of electricity generation, so the incremental environmental and capital burden of extraction is limited to the recovery circuit itself (Stringfellow & Dobson, 2021).

Resource assessments of geothermal lithium are routinely measured against a threshold of approximately 50 mg/L, below which direct extraction is described as uneconomic. The figure circulates widely but its provenance is unclear, and it is applied uniformly across systems that differ by orders of magnitude in salinity, temperature,

flow rate and matrix chemistry. Screening exercises that have attempted a more systematic economic basis have generally worked from assumed recovery efficiencies rather than from the observed characteristics of resources that reached operation (Neupane & Wendt, 2017). A threshold quoted without reference to what has actually been developed offers a weak foundation for national resource decisions.

A second difficulty is that grade is not the only property that matters. The literature on direct lithium extraction emphasises the competing-ion burden of the feed, and in particular the molar magnesium to lithium ratio, because Mg^{2+} and Li^{+} have similar charge density and hydrated radius and are therefore adsorbed competitively by manganese and titanium oxide ion sieves, co-precipitate in carbonate and hydroxide routes, and are incompletely separated by nanofiltration (Flexer et al., 2018; Sun et al., 2021). Continental salar brines carry ratios of order unity to ten and require dedicated magnesium removal before extraction (Munk et al., 2016). Calcium contributes a parallel problem through carbonate and silicate scaling in production and process equipment (Gallup, 2009). If purity were a binding constraint alongside grade, developed systems should be both concentrated and clean. Whether that expectation holds has not been tested systematically.

Geothermal fluids differ from evaporitic brines in this respect. Magnesium is strongly incompatible at reservoir temperature and is removed from solution into chlorite, smectite and related secondary phases, so equilibrated geothermal liquids are characteristically magnesium-depleted (Ellis & Mahon, 1977; Giggenbach, 1988; Nicholson, 1993). Trace element behaviour in volcanic-hosted systems is correspondingly distinct from that in sedimentary basins (Kaasalainen & Stefánsson, 2012).

Companion investigations established the lithium baseline for the Menengai field and characterised the geochemical controls on its distribution. The first reported a field mean of 1.671 mg/L with marked and statistically significant contrasts between wells; the second found the brine strongly depleted in magnesium and calcium, with a molar magnesium to lithium ratio some three orders of magnitude below continental salar brines. Taken alone, the second result invites optimism. Its significance can only be judged against the properties of systems that have actually been developed.

This study therefore places Menengai within a global comparison set and addresses three specific questions. First, where does the field rank on grade and on purity? Second, is its lithium content low simply because the brine is dilute, or is it depleted beyond what salinity explains? Third, which brine properties in fact distinguish developed from undeveloped resources, and what threshold do they imply?

MATERIALS AND METHODS

A. Research Design

The study was conducted by comparative study with cross sectional design, with the unit of the geothermal system. Each row corresponds to one geothermal field (Menengai) or one brine system (published geochemical surveys), and is described by lithium concentration, temperature, total dissolved solids, major cation composition and the current status of extraction.

B. Menengai Values

Values for Menengai were directly calculated from the field data set that underpinned the companion studies, twenty-nine samples of brine were collected from ten production wells between June 2023 and March 2026 filtered at 0.45 μm , acidified in the field and analysed by flame atomic absorption spectrophotometry using certified reference materials and procedural blanks at a rate of one sample per ten. Arithmetic mean of these samples is taken in a single row that represents the field, thus the comparison is between fields and not between individual wells. The reservoir occurs in comenditic trachytes and phonolites of the Menengai caldera shown in the Central Kenya Rift (Leat, 1984; Mibei, 2012) and the fluid chemistry produced at the well is similar to that documented earlier for the field (Kipng'ok, 2011).

C. Comparison Systems

These systems range from volcanic fields with vapour to hypersaline sedimentary basins across 5 continents and 16 system types. They include the East African Rift fields of Kenya, Ethiopia and Djibouti (Omenda, 1998), the rhyolitic Taupo Volcanic Zone of New Zealand (Milot et al., 2012), the Upper Rhine Graben systems of France and Germany (Sanjuan et al., 2022), and the hypersaline Salton Sea brines of California. They both have an extraction status of commercial, pilot or exploration/non-viable. Commercial & pilot were both considered as developed for discrimination analysis.

D. Comparability of Measurement Basis

An important qualification applies to every comparison reported here. Literature values for the comparison systems are reported at reservoir conditions, with temperatures between 230 and 380 °C. The Menengai values are wellhead-separator measurements taken at 91 to 163 °C. Because steam separation concentrates non-volatile solutes in the residual liquid, the Menengai figure is, if anything, an overestimate relative to reservoir fluid, so the comparison is conservative with respect to the conclusion drawn. It is nonetheless not strictly like for like, and the magnitude of the offset cannot be quantified without enthalpy and steam-fraction data or the geothermometric and isotopic corrections that such reconciliation requires (Fournier, 1977; Arnórsson, 2000). Temperature is therefore reported for completeness but is not interpreted as a comparable quantity.

E. Data Provenance and Screening

Two provenance constraints are recorded for transparency. First, the compiled comparison table, as originally assembled, showed three rows for Menengai for which the values were inconsistent with the measured field data, including those for lithium between six and twenty-four times the analysed values, and over two orders of magnitude more calcium than in the field programme, and one well identifier not included in the field programme. The rows were deleted and replaced with the field average measured. Secondly, each and every literature value has to be cited to its primary source and the comparison ought to be regarded as provisional until it can be verified.

F. Statistical Analysis

All analyses were carried out using R version 4.3.1, R Core Team (2023). Menengai's position was reported as percentile rank, which is the percentage of systems in the comparison set that are at or below his, or her, position. Lithium, salinity and cation ratios were transformed to base ten logs and group comparisons made using the Mann-Whitney rank-sum test; p values across the set of comparisons were adjusted for false discovery rate (FDR) by Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995). The degree of grade was regressed on total dissolved solids (TDS) in the log-log scale and the residuals of this regression were taken as a measure of lithium enrichment that was salinity normalised. A unity slope in this parameterisation means isometric scaling, or scaling of lithium that is proportional to the total salinity. Optimal cut points to classify developed and undeveloped systems were determined by the area under the receiver operating characteristic curve (Hanley & McNeil, 1982) and the estimated optimal cut point was based on the Youden index (Youden, 1950), which was calculated using the package pROC (Robin et al., 2011). The number of systems developed was six, which is the minimum number required to estimate discrimination statistics; percentile confidence intervals were calculated separately in both the developed and undeveloped groups preserving group sizes (Efron & Tibshirani, 1993) and the stability of the threshold was further assessed using leave-one-out resampling. An interval other than 0.5 was cited as evidence of discrimination. Multivariate structure was investigated using principal component analysis on the variables standardised by log transformation (keeping components on Kaiser criterion) and by Ward hierarchical clustering on the same matrix (Ward, 1963).

RESULTS

A. Global Position

Menengai is the 28th of 33 systems and is at the 18th percentile of global distribution of dissolved lithium (Table 1, Figure 1). It has a mean concentration of 1.701 mg/L, which is around one-fifth of the global median

concentration of 8.20 mg/L. The low grade of the fluid in the field is not just because it is an unusually low salinity fluid, however, because it is also at the forty second percentile of the salinity field. The field is ranked 12th percentile on Li/Total Dissolved Solids ratio. Menengai's ratio of magnesium to lithium is the only one that is above the median, making it the twelfth cleanest out of thirty-three ratios (Figure 2).

Table 1: Position of the Menengai field within the global comparison set

Metric	Menengai	Global median	Percentile	Rank of 33
Dissolved Li (mg/L)	1.701	8.20	18.2	28
TDS (mg/L)	6,715	8,200	42.4	20
Li/TDS ($\times 10^{-3}$)	0.263	1.154	12.1	30
Mass Mg/Li ratio	0.0266	0.0571	66.7	12
Temperature ($^{\circ}\text{C}$)	132.6	260	6.1	32

Note: Percentile is the proportion of systems at or below the Menengai value on a favourability scale, so that a higher percentile is always more favourable; for Mg/Li the scale is therefore reversed and the rank counted from the lowest (cleanest) value. Menengai temperature is a wellhead-separator measurement and is not directly comparable with the reservoir temperatures reported for other systems.

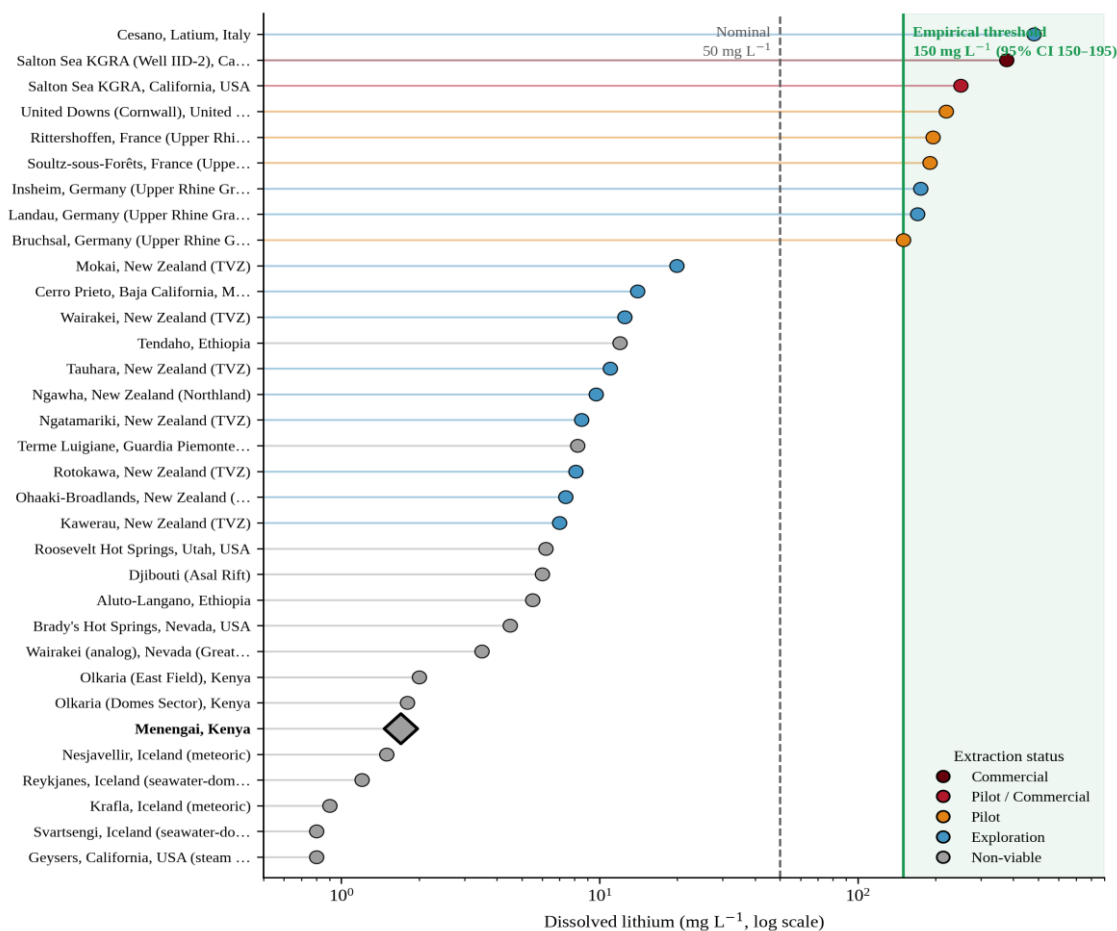


Figure 1. Dissolved lithium grade across the global comparison set, ranked and plotted on a logarithmic scale, with systems coloured by extraction status. Menengai is marked by a diamond. The dashed line marks the nominal 50 mg/L threshold and the solid line the empirically derived threshold of 150 mg/L, with the shaded band indicating the region occupied by all developed systems.

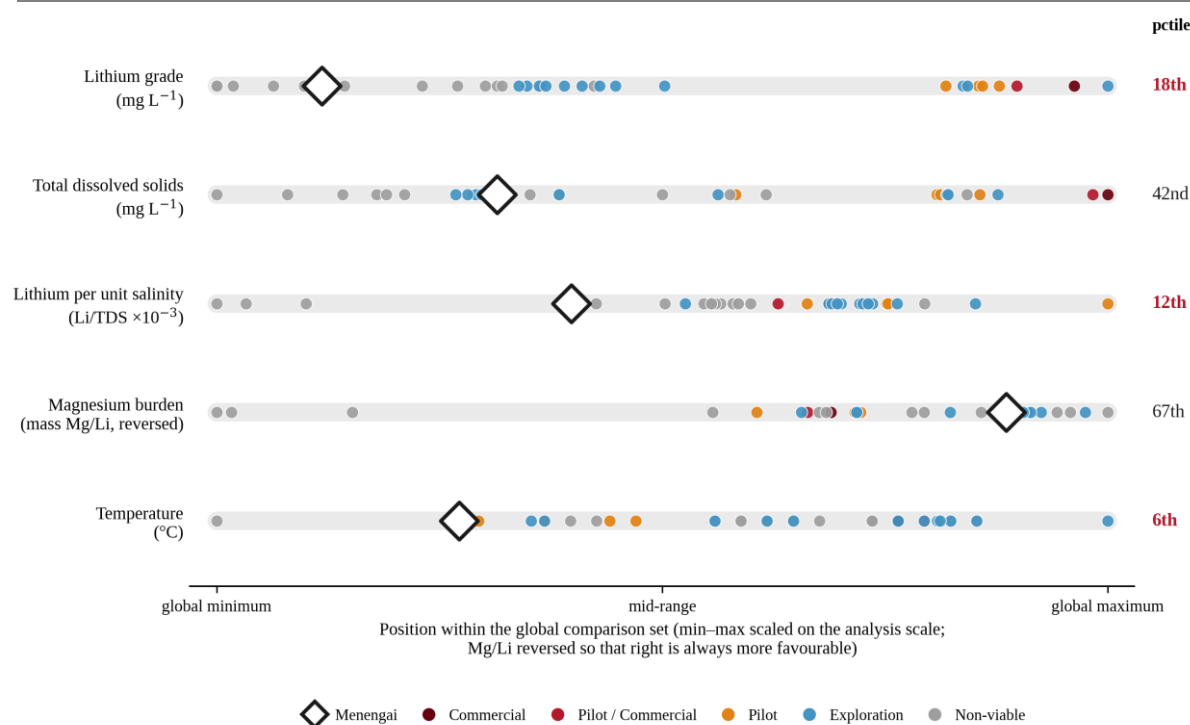


Figure 2. Position of the Menengai field on each resource metric relative to the global comparison set. Each strip is scaled between the global minimum and maximum on the analysis scale, with the magnesium axis reversed so that a position further right is always more favourable. Menengai falls in the lowest quartile on lithium grade, on lithium per unit salinity and on temperature, and above the median only on magnesium burden.

The development status significantly affected the grade ($H = 23.51$, $p < 0.001$, Kruskal-Wallis). The median of the systems with a non-viable classification was 2.00 mg/L, with the systems under exploration showing a median of 11.75 mg/L and the six systems in pilot or commercial stage had a minimum of 150 mg/L and a median of 207.5 mg/L (Table 2). All of the systems below 150 mg/L have not yet progressed to the exploration stage.

Table 2: Lithium grade and brine properties by extraction status

Extraction status	n	Li minimum	Li median	Li maximum	TDS median	Mg/Li median
Commercial	1	377.0	377.0	377.0	285,000	0.292
Pilot / Commercial	1	250.0	250.0	250.0	260,000	0.400
Pilot	4	150.0	192.5	220.0	101,000	0.203
Exploration	12	7.0	11.75	480.0	7,000	0.027
Non-viable	15	0.8	2.00	12.0	6,200	0.082

Note: Li and TDS in mg/L; Mg/Li is a mass ratio. Menengai is included in the non-viable category.

B. Grade Relative to Salinity

To isolate a lithium enrichment from bulk concentration, grade was regressed on total dissolved solids (TDS), a brine quality measurement that contains more of all elements. Across the comparison set the relationship was strong and indistinguishable from isometric ($\log_{10}\text{Li} = -3.17 + 1.019 \log_{10}\text{TDS}$; slope 95% CI 0.734 to 1.303; $R^2 = 0.632$, $F(1, 31) = 53.3$, $p = 3.3 \times 10^{-8}$). A slope that fits easily within the interval [0.5, 2] suggests a direct

proportionality between the two, thus most of the variation in grade in the global set is not caused by lithium-specific enrichment process, but rather by the overall concentration of the brine.

Menengai is well below that level with a residual of $-0.50 \log_{10}$ units or 0.32 time the lithium expected for a brine of its salinity (Figure 3). Icelandic systems (Reykjanes and Svartsengi) and the Asal Rift brine (Djibouti) are the only exceptions to the seawater-dominated systems, and in all three cases, the seawater signal dominates but dilutes the lithium signal. The field is not just dilute, it's poor in lithium even for its own salinity. The New Zealand Taupo Volcanic Zone fields are the other, similarly dilute and similarly clean, and are above the fitted line.

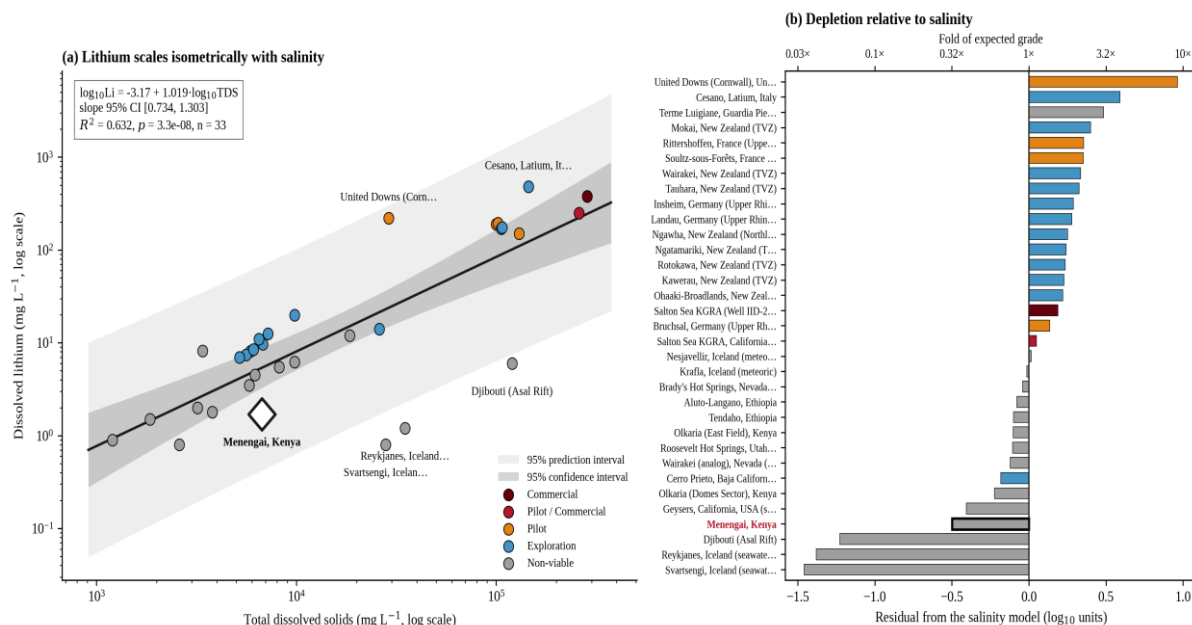


Figure 3. (a) Dissolved lithium against total dissolved solids across the global comparison set, both on logarithmic scales, with the fitted ordinary least squares line, 95% confidence interval for the mean and 95% prediction interval. Systems departing from the fit by more than 0.58 log units are labelled. (b) Residuals from the same model ranked by magnitude, with the upper axis expressing each residual as a fold of the expected grade. Menengai carries 0.32 times the lithium predicted from its salinity.

C. What Distinguishes Developed Systems

The developed lithium grade discriminated almost perfectly from the undeveloped systems (AUC=0.951, 95% bootstrap confidence interval: 0.852-1.000, Table 3, Figure 4a and 4b). The Youden-optimal cut-point was 150mg/L, which achieved a 100% sensitivity and an 89% specificity, but the three false positive systems are all high-grade ones still in the exploration stage: Cesano, Insheim and Landau. The total dissolved solids and sodium were nearly as good, as would be predicted by the isometric relationship between grade and salinity.

The bootstrap distribution of the threshold was very narrow, ranging from 150 to 195 mg/L, and leave-one-out resampling resulted in only two different thresholds (150 and 190 mg/L) with the AUC between 0.948 and 0.987 across all omissions (Figure 4c). The nominal concentration of 50 mg/L is significantly higher than the range in all resampling designs.

There was no difference in development between the magnesium/lithium ratio. The point estimate also does not correspond to the direction of a discriminatory capacity: the median mass ratio of developed systems (0.251) is greater than the median mass ratio of undeveloped systems (0.027). The range (0.481 to 0.877) includes 0.5, which supports the data having no capacity at all. Five of the six developed systems have a greater magnesium load than the Salton Sea and Upper Rhine Graben brines by almost an order of magnitude and only United Downs in Cornwall has a cleaner system (Figure 5). Temperature was discriminated in the negative direction, with an interval of 0.099 to 0.593, and a span of 0.5.

Table 3: Capacity of each brine property to distinguish developed from undeveloped systems (n = 33; 6 developed)

Variable	Developed median	Undeveloped median	p	AUC	95% CI (bootstrap)
Li (mg/L)	207.5	7.00	0.0007	0.951	0.852 – 1.000
TDS (mg/L)	116,000	6,715	0.0019	0.914	0.796 – 0.988
Na (mg/L)	32,500	1,350	0.0022	0.883	0.741 – 0.975
Li/TDS ($\times 10^{-3}$)	1.611	0.750	0.0642	0.747	0.531 – 0.914
Mass Mg/Li ratio	0.251	0.027	0.1584	0.691	0.481 – 0.877
Temperature ($^{\circ}\text{C}$)	195	260	0.2334	0.340	0.099 – 0.593

Note: p-values from Mann-Whitney rank-sum tests, unadjusted; lithium, TDS and sodium remain significant at a Benjamini-Hochberg false discovery rate of 0.05. AUC = area under the receiver operating characteristic curve, with percentile confidence intervals from 5,000 stratified bootstrap resamples. An AUC below 0.5 indicates the variable is higher among undeveloped systems. Intervals containing 0.5 are consistent with no discrimination.

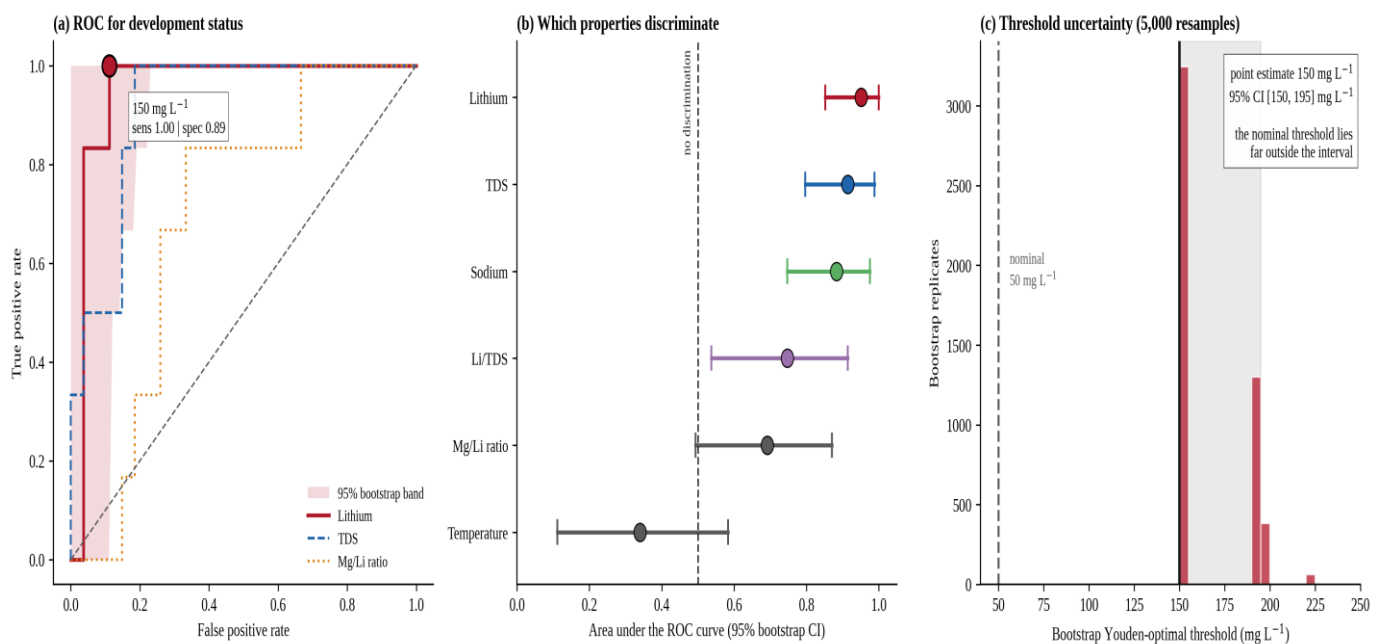


Figure 4. (a) Receiver operating characteristic curves for lithium, total dissolved solids and the magnesium to lithium ratio as predictors of development status, with the 95% bootstrap band for lithium and the Youden-optimal cut-point marked. (b) Area under the curve for each property with 95% bootstrap confidence intervals; intervals crossing the dashed line at 0.5 indicate no discrimination and are shown in grey. (c) Bootstrap distribution of the Youden-optimal lithium threshold over 5,000 stratified resamples, with the nominal 50 mg/L threshold shown for comparison.

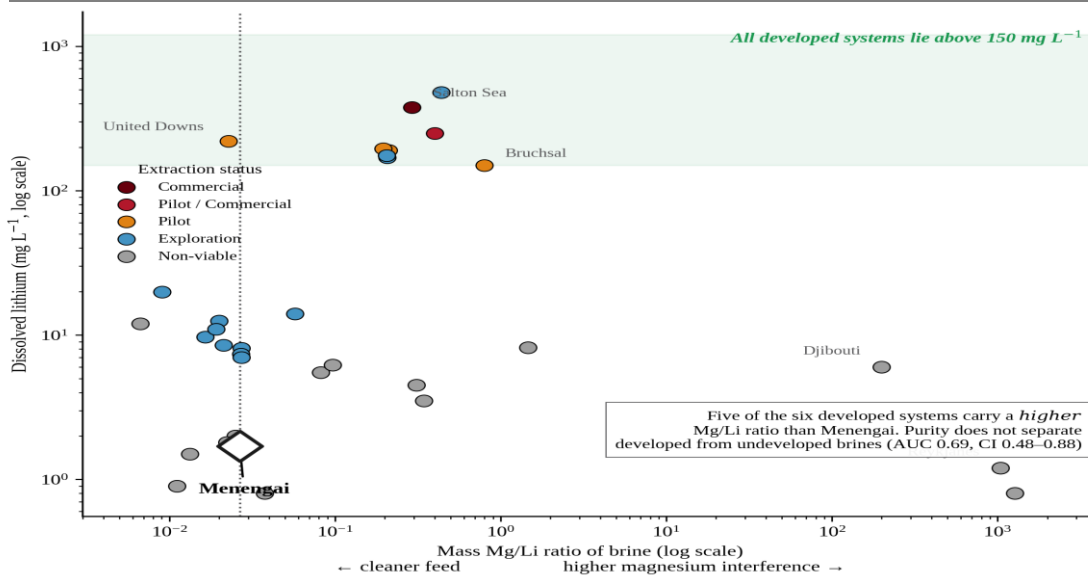


Figure 5. Lithium grade against magnesium to lithium mass ratio for the global comparison set, both on logarithmic scales. Developed systems occupy the upper region of the plot irrespective of their position along the purity axis, while Menengai combines a comparatively clean feed with a grade two orders of magnitude below any developed system.

D. Feasibility Gap

The mean of the Menengai samples is 3.40% below the nominal value of 50 mg/l, and the mean below the threshold is a deficiency of twenty nine folds. It is 1.13% below the empirically derived threshold of 150 mg/L and eighty-eight fold below the median grade of developed systems (Table 4). The highest grade single sample from the field is 3.08 mg/L (still forty-nine times less than the empirical limit), and this is not due to average samples from wells of varying grade.

Table 4: Feasibility gap between the Menengai field mean (1.701 mg/L) and each benchmark

Benchmark	Value (mg/L)	Menengai as % of benchmark	Shortfall
Nominal DLE threshold	50.0	3.40%	29.4×
Empirical threshold (Youden)	150.0	1.13%	88.2×
Lowest developed system	150.0	1.13%	88.2×
Median developed system	207.5	0.82%	122.0×

Note: The empirical threshold and the lowest developed system coincide at 150 mg/L; the Youden procedure selects the observed minimum among developed systems because sensitivity is complete at that value.

E. Multivariate Structure

The log transformed grade, salinity, temperature and ratio variables yielded two principal components with eigenvalues greater than one (2.068 and 1.817) which accounted for 77.7% of variance. The first component (41.4%) combined lithium (0.679), lithium per unit salinity (0.528) and salinity (0.460) and could be interpreted as an "overall resource-quality axis". The second (36.3%) distinguished "magnesium burden" (0.693) and "salinity" (0.520) from "lithium yield per unit salinity" (−0.451) to separate the hypersaline magnesium-bearing systems from the dilute clean ones. Menengai was found towards the low end of the distribution for both components, with scores of −1.14 for the first component and −0.13 for the second, thus positioning this sample close to the centre of the purity axis and in the low end of the distribution for the first component (Figure 6). The

multivariate expression of the discrimination result is called PC2 and the developed systems are grouped together at high positive PC1 regardless of its position on PC2.

Table 5: Principal component loadings and variance for the global comparison set (n = 33)

Variable	PC1	PC2	PC3
log Li	+0.679	+0.132	+0.121
Temperature	-0.146	-0.166	+0.963
log TDS	+0.460	+0.520	+0.224
log Mg/Li	-0.166	+0.693	-0.019
log Li/TDS	+0.528	-0.451	-0.090
Eigenvalue	2.068	1.817	0.974
Variance (%)	41.36	36.34	19.48
Cumulative (%)	41.36	77.70	97.18

Note: Eigenvector signs are arbitrary; the convention adopted here places lithium positive on PC1. PC3 is dominated by temperature, which is not a comparable quantity across the set and is retained only for completeness.

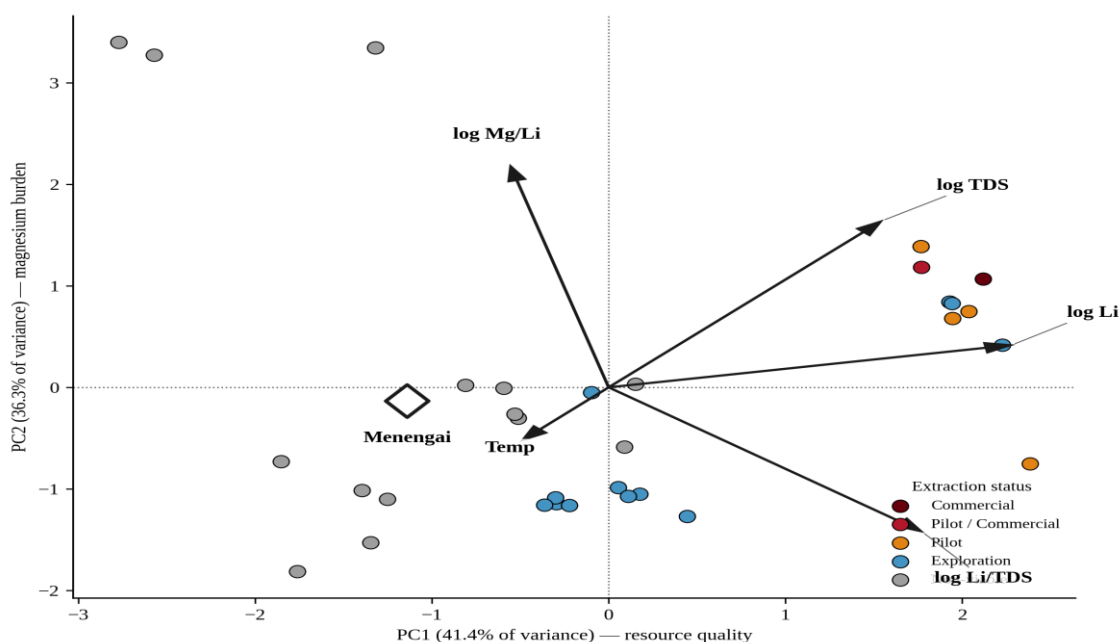


Figure 6. Principal component biplot of the global comparison set on standardised log-transformed variables, accounting jointly for 77.7% of total variance. Developed systems cluster at high PC1 regardless of their position on the magnesium axis. Menengai is marked by a diamond.

Three clusters were identified by ward clustering. All six developed systems are in the first that has a median grade of 195 mg/L and a median salinity of 107,000 mg/L. The second is the three seawater-dominated and hypersaline systems Reykjanes, Svartsengi and Asal, which contain high concentrations of magnesium and low levels of lithium. Twenty-one systems with a median grade of 7.0mg/L are in the third, which includes Menengai,

the four Kenyan and Ethiopian rift systems and the entire New Zealand Taupo Volcanic Zone group. No development has been made in this cluster of systems (Figure 7).

Table 6: Ward cluster summary for the global comparison set

Cluster	n	Li median (mg/L)	TDS median (mg/L)	Mg/Li median	Developed systems
1 — concentrated	9	195.0	107,000	0.211	6
2 — seawater-influenced	3	1.2	35,000	1041.67	0
3 — dilute volcanic	21	7.0	6,100	0.027	0

Note: Menengai falls in cluster 3, which contains no developed system.

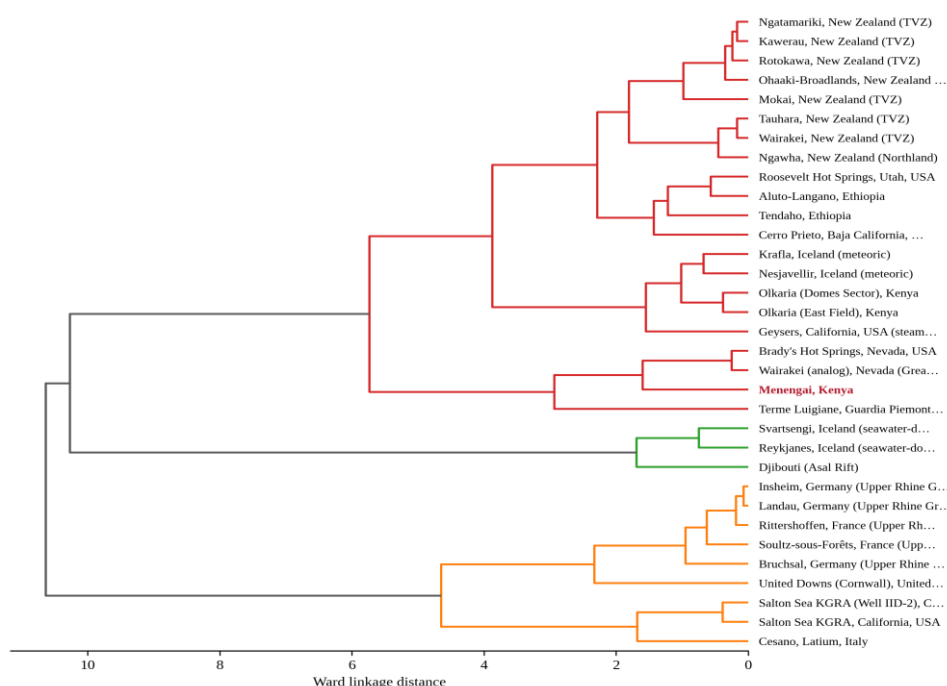


Figure 7. Ward hierarchical clustering of the global comparison set on standardised log-transformed lithium, temperature, salinity, magnesium to lithium ratio and lithium per unit salinity. Menengai, highlighted, falls within the large dilute volcanic cluster containing no developed system.

DISCUSSION

A. The Operative Threshold Is Higher Than Usually Stated

The first handy one was that 50 mg/l is an underestimate of what has been required in development. Areas under the curve of the systems compiled here range from 0.951 for the lowest grade that reached pilot operation to 0.975 for the highest grade. For a single variable, exceptional discrimination was obtained for the lowest grade, 150mg/L and the highest grade, 207.5mg/L, and the optimal cut-point was found to be 3 times the conventional grade of 50mg/L with a bootstrap interval that does not include it. If the number reported is an order of magnitude off the mark, the assessment is reporting a resource as approaching viability because it is an order of magnitude close to 50 mg/L.

This should be read with due caution; three limits should be explicitly stated. This empirical threshold, though, is not considered a physical limit, and as extraction technology improves, the concentration at which it is possible that it can be recovered keeps decreasing (Stringfellow & Dobson, 2021). When sensitivity is complete at a

developed system, the point estimate is the observed minimum, and is therefore not between developed values. It is based on a limited number of developed systems and the number of cross systems (six) is relatively small, but the results of the bootstrap and leave-one-out tests suggest it is robust to the omission of any single system. The analysis does not conclude that 150 mg/L is a law but that the threshold that has actually worked out in practice has been significantly greater than 150 mg/L.

B. Salinity Is the Master Variable, and Menengai Underperforms It

The total dissolved solids concentration of the lithium scales with grade with a slope that is not significantly different from unity, so most of the scatter in grade from the global set is due to the concentration of the brine in general. That is why total dissolved solids and sodium discriminate development as well as lithium itself, and that it finds the fundamental constraint at Menengai is the low total dissolved solids of the brine (6,700 mg/L) compared with the median of 116,000 mg/L for the developed systems.

Dilution is not the only solution. However, lithium is only 0.32 times the amount expected given its salinity, making it one of the most depleted on this parameter of the set. A plausible explanation is a trachytic and phonolitic host assemblage in a meteoric-recharged caldera: such systems do not have evaporite and clay-rich sedimentary sources that are responsible for lithium in the brines of the Salton Sea and Upper Rhine Graben (Munk et al., 2016; Sanjuan et al., 2022). The Taupo Volcanic Zone has similarly low concentrations, 7-20 mg/L, and salts similarly normalised, rather than below the fit; it is similarly clean, and similarly dilute. In the class of dilute volcanic geothermal systems, Menengai is at the low end and the deficit cannot be attributed to dilution.

C. Purity Does Not Determine Development

The scale of lithium with total dissolved solids has a slope close to one and the vast majority of the spread on the global set is due to the overall concentration of the brine. That is why TDS and sodium discriminate development almost as well as lithium itself, and the fundamental constraint, at Menengai, is a low concentration solution, with a concentration of about 6,700 mg/L total dissolved solids (TDS), which is a much lower concentration than the median of 116,000 mg/L TDS for developed systems.

Dilution isn't all it takes. Menengai has only 0.32 of the lithium it would have based on its salinity, and is one of the most depleted on this criterion. This is most likely explained by a trachytic and phonolitic host assemblage in a meteoric-recharged caldera, as neither the Salton Sea brines nor the brines of the Upper Rhine Graben have evaporite and clay-rich sedimentary sources that can provide lithium. This is most likely explained by a trachytic and phonolitic host assemblage in a meteoric-recharged caldera, that is not the case for the brines of the Salton Sea and Upper Rhine Graben, which have evaporite and clay-rich sedimentary sources that supply lithium. In this context, it is instructive to compare with the Taupo Volcanic Zone: these fields are also dilute and similarly clean and have grades between 7 and 20 mg/L, four to twelve times higher than that of Menengai, and lie above the salinity-normalised fit rather than below (Millot et al., 2012). Menengai is at the low end of the volatile, dilute geothermal class and dilution cannot account for the deficit.

D. Implications for Kenyan Resource Assessment

The clustering result indicates that Menengai is not developed for lithium and is grouped with the Olkaria sectors and the Ethiopian rift field; the latter also do not have lithium development projects. The East African Rift entries, as a cluster, have a grade distribution that falls in the lower half of the global distribution. This implies that the poor grades recorded here are not unique to Menengai, but are more typical of the rift province than of any individual system, and reflect the magmatic-hydrothermal nature of the systems and meteoric recharge (Omenda, 1998). The proposition is a hypothesis to be tested, because there are only 4 fields to say that, and the comparison values need to be verified. If true, resource effort aimed at lithium in geothermal brines in Kenya will likely not be rewarded, and a systematic screening of the geochemical infrastructure in place will be to find other co-produced species (Neupane & Wendt, 2017).

The findings are still relevant even if it is a negative feasibility finding. They provide a quantitative baseline to compare other Kenyan fields and future monitoring to them, as well as other geothermal systems around the

world, and they represent the first use of a geothermal system in the East African Rift Valley of which the viability threshold has been derived based on observed development results.

E. Limitations

These are qualifications to these conclusions. The comparison values are drawn from secondary sources and may need to be cross checked with the primary literature; the global positions reported here will be provisional until that has been undertaken. The measurement bases are also not strictly comparable as the values reported in the literature are at reservoir conditions and the values in the Menengai are at the wellhead separator, and if enthalpy and steam-fraction data are not available, the offset cannot be quantified. The development status represents a coarse and partly economic classification based on the commercial decision making process under varying regulatory and market conditions, thus other factors are involved and the three high-grade exploration-stage systems identified as false positives demonstrate this. There is a wide uncertainty in the estimated threshold as there are only 6 developed systems and the bootstrap interval is a lower bound on that uncertainty since it does not represent systems not in the compilation. Lastly, the analysis only considers concentration without including other factors such as brine flow rate, reinjection constraints, plant capital cost and lithium price, which are not available here.

CONCLUSION

Menengai is the 28th of 33 geothermal/brine systems in terms of grade of lithium and 18th in the world. The field is less concentrated than would be expected from the salinity of Menengai, which has only a third of the lithium present, and less than would be expected from isometric scaling with salinity for lithium.

Grade discriminates developed from undeveloped systems nearly as well, with an empirical threshold of 150 mg/L, instead of the usual 50 mg/L. The mean of the Menengai samples falls eighty eight times below that, and the most enriched sample forty nine times below. The magnesium to lithium ratio is not significant in the distinguishing of developed systems and five of the six developed systems have a higher magnesium burden than Menengai, suggesting that the grade rather than the purity of the feed controls which geothermal brines are developed. Based on current data, it is not possible to recover lithium from the geothermal field of Menengai.

RECOMMENDATIONS

1. In Kenyan resource assessment, change the nominal threshold of 50 mg/L to a threshold based on evidence and specify the reference set used; provide for feasibility statements to be audited and updated as extraction technologies evolve.
2. Report lithium grade with a salinity-normalised measure because raw concentration would mix up real lithium enrichment with bulk concentration of the brine, and mask the behaviour of an actual dilute system.
3. Do not use purity as a screening factor for geothermal brines, but rather a cost factor.
4. Check each compiled literature value against the original source of information and document the citation along with the datum before making any comparative assessment available or included in policy.
5. Continue geochemical screening of Kenyan geothermal fluids for co-produced species (other than lithium) with concentration ratios that may be more favourable than those reported here relative to the concentration thresholds for recovery.

Ethical Considerations

This study did not include human participants, animals or biological materials, and reviewed geothermal brine samples and collated published geochemical data; therefore, no review by a human-subjects ethics committee was applicable. The Kabarak University Research Ethics Committee (Ref.) gave institutional clearance. No.

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Competing Interests

The authors declare that they have no competing interests, financial or non-financial, that could have influenced the work reported in this manuscript.

Data Availability

The field geochemical dataset, the compiled comparison table and the analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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