PREDICTIVE MODELLING OF OROGENIC GOLD MINERALIZATION IN THE HARARE-SHAMVA GREENSTONE BELT

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LAY OUT

- Species distribution modelling (Origin and applications)
- Maximum Entropy principle & MaxEnt modelling)
- Orogenic gold deposits (definition & origin)
- Definition of parameters and conditions of occurrence
- Methods
- Results
- Discussions
- Conclusions and Recommendations

Common Mineral Prospectivity Methods (mpm)

- **Knowledge based**

Fuzzy logic

Wildcat mapping

Outranking method

- **Data based**

WofEv (Bonham Carte et al., 1989)

Evidential belief functions (EBF) (Carranza&Hale, 2003; Lieu et al., 2015)

Logistic Regression (Carranza & Hale, 2001

Neutral Network Analysis (Porwal et al., 2003)

Support Vector Machine (Zuo & Carranza, 2011, Abedi et al., 2012)

Boltzman machine (Chen eta al., 2014, Chen, 2015)

Maximum Entropy Model (Lieu et al., 2017, a, b)

Species distribution modelling (SDM) concept and Maximum Entropy Application.

SDMs found wide applications in several research areas (conservation biology, ecology, evolution). The models are used to understand how environmental conditions influence the occurrence or abundance of a species, and for predictive purposes (ecological forecasting).

SDMs use known locations of a **species** and information on **environmental conditions** to predict species distributions. SDM use a variety of algorithms to estimate relationships between species locations and environmental conditions and predict and map habitat suitability (Franklin 2010)

- Maxent algorithm is a machine learning method, and thus iteratively builds multiple models. It has two main components:
- **1. Entropy**: the model is calibrated to find the distribution that is most spread out, or closest to uniform distribution throughout the study region.
- **2. Constraints**: the rules that constrain the predicted distribution. These rules are based on the values of the environmental variables (called features) of the locations where the species has been observed.

MaxEnt predicts '**species**' occurrences by finding the distribution that is most spread out, or closest to uniform, while taking into account the limits of the environmental variables of known locations.

Maxent only uses **presence data** and the algorithm compares the locations of where a species has been found to all the environments that are available in the study region

WHY PREDICTIVE MODELLING

- Predictive mapping for mineral exploration is an economic decision.
  - ✓ focuses on reducing financial risks
  - ✓ enhances mineral exploration targeting
  - ✓ improves chances of mineral discovery
- Helps identify proxies for key ore-forming processes into mappable variables (ore-controlling variables).

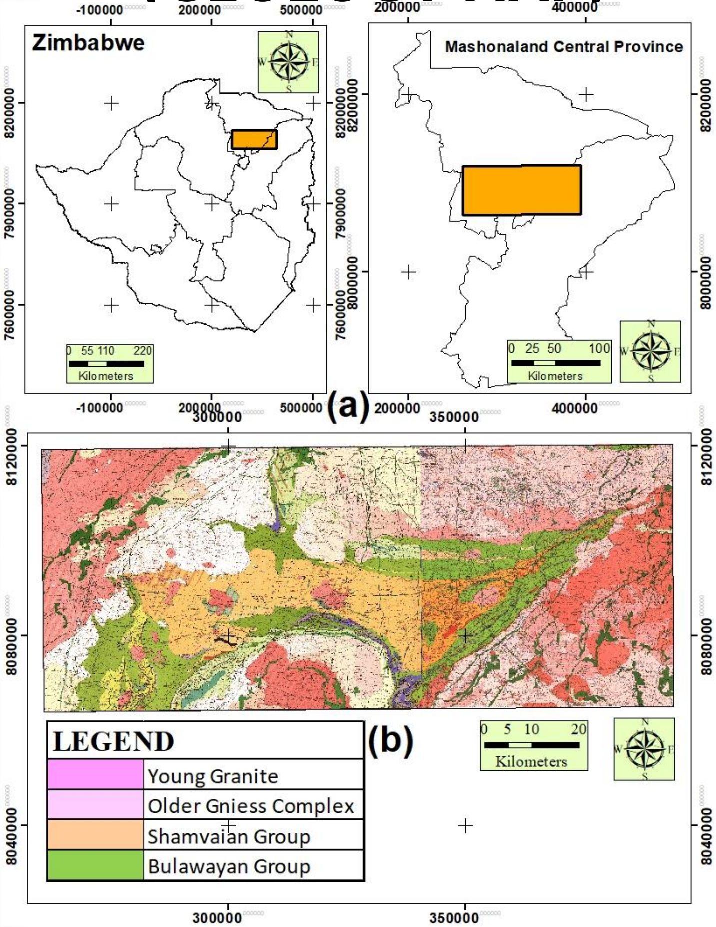
OVERVIEW OF OROGENIC GOLD MINERALIZATION SYSTEMS

- Orogenic gold deposits account for 75% of global gold output (Phillips, 2009) including Wits gold the world's largest district (~30% of gold extracted).
- Formation is estimated at crustal depths of more than 4 km and restricted to Archean to Phanerozoic.
- For long postulated to have been formed vertically along crustal faults at pressures and temperatures covering a wide range of depths, from the sub-greenschist to granulite metamorphic facies (Groves 1993; Groves et al. 1998, 2003) (the 'crustal continuum model'). However, the crustal continuum was an empirical and not genetic model.
- The key parameters accounting for their formation thus remain hazy and under discussion.
- Critical components and processes in a mineralising system, from base to the top included the following;
  - (1) the fluid sources;
  - (2) the appropriate ligands and their sources;
  - (3) the solubility of gold and its potential sources;
  - (4) the function of faults as conduits; and
  - (5) the mechanisms for precipitating gold.

CONTINUED

- Addressing key parameters for the genesis of orogenic gold deposits have therefore been difficult due to a wide range extreme conditions. In short, given such a large range of physicochemical conditions, recognising the key parameters for addressing the formation of orogenic gold deposits was very difficult.
- Phillips and Powell 2009, 2010; Tomkins and Grundy 2009; Tomkins 2010), all challenge the ‘crustal continuum model’ arguing against its validity over wide range of temperatures and pressures but only for restricted ranges of depth and temperature mostly corresponding to the greenschist metamorphic facies.

GEOLOGY OF HARARE-SHAMVA GREENSTONE BELT (GEOLOGY MAP)



- Archean Granodiorites
- Bulawayan Supergroup (2.7Ga).
- Shamvain Supergroup (2.6Ga)

MAXIMUM ENTROPY (CONCEPT)

Integrated algorithm for modeling the geographic distribution of species using presence-only data from n-dimensional environmental variable space (Phillips et al., 2004, 2006).

- Aim of MaxEnt model is to determine the target probability distribution of maximum entropy that is most spread out or approximate to uniform distribution under a set of constraints (Phillips et al. 2006; Elith et al. 2011).
- In geology, these covariates are the ore-controlling variables, evidential variables, predictors, proxies for critical parameters, or input variables

MAXIMUM ENTROPY (CONCEPT)

- In this study MaxEnt (model) applies the principles of maximum entropy to investigate the relationships between known deposits and available ore-controlling variables by performing a series of iterations on the basis of the most important features until no further improvements can be made.

- The interpretation is that MaxEnt can be applied to recognize areas with similar ore-controlling conditions where mineral deposits are most likely to be present.

ORE-CONTROLLING VARIABLES APPLIED IN THE MODEL

- Five datasets, including gold deposits, a fault system, lithostratigraphic contacts, age of lithology, shear zones and aeromagnetic data, were used and integrated by the MaxEnt model to map gold prospectivity.
- A total of 236 gold deposits were collected as training data for the MaxEnt model. The ore-controlling variables or derivative variables from these datasets were processed using ArcGIS 10.5,
- **Ore-controlling variables**

✓ Lithology

✓ Geological factors

✓ Geological Structures

✓ Age of lithology

✓ Contacts

✓ Shear Zones

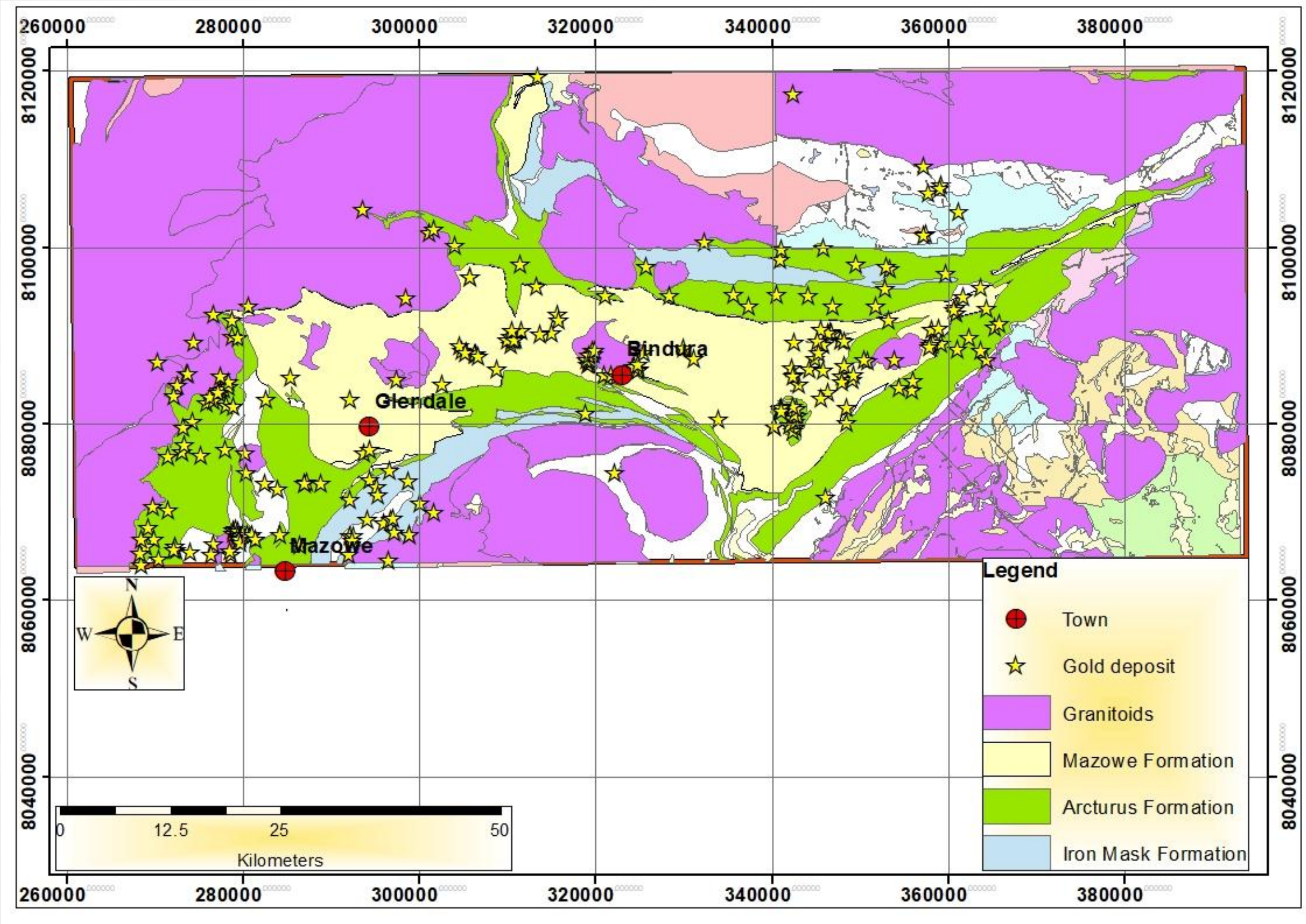
Predicting spatial distribution of potential orogenic gold mineralization

- Nine predictor variables were generated from the data digitized from the various sources (research articles, ZGS publications (bulletins).
- The generated files were initially converted to raster files before being transformed to Ascii file format for use in MaxEnt.
- These were then masked to the study area in ArcMap 10.5 using the Extraction tool in Spatial Analyst.
- MaxEnt modelling was then applied to estimate the regions of the study area that have the highest potential to host orogenic gold mineralization in the Harare-Shamva greenstone belt.

Predictor variables used in MaxEnt modeling

Predictor Variable	Source of information	Anticipated results
Lithology	Geology reports, bulletin 78, 97.	Association between gold deposit mineralization and lithological units
Lithology age	Geochronology reporting. Research articles (Jelsma & Dirks, 2000), Blenkisop et al., 2000	Discriminatory occurrence of gold based on temporal time domains in geology
Fault-NE	Geology reports, bulletin 78, 97 (ZGS). Structural map of Zimbabwe (ZGS) Research articles (Jelsma & Dirks, 2000)	Preferential occurrence of gold deposits linked to specific fault systems
Fault-NW	Geology reports, bulletin 78, 97 (ZGS). Structural map of Zimbabwe (ZGS) Research articles (Jelsma & Dirks, 2000)	Preferential occurrence of gold deposits linked to specific fault systems
Fault-NS	Geology reports, bulletin 78, 97 (ZGS). Structural map of Zimbabwe (ZGS) Research articles (Jelsma & Dirks, 2000)	Preferential occurrence of gold deposits linked to specific fault systems
Fault-EW	Geology reports, bulletin 78, 97 (ZGS). Structural map of Zimbabwe (ZGS) Research articles (Jelsma & Dirks, 2000)	Preferential occurrence of gold deposits linked to specific fault systems
Shear Zone	Geology reports, bulletin 78, 97 (ZGS). Structural map of Zimbabwe (ZGS) Research articles (Jelsma & Dirks, 2000)	

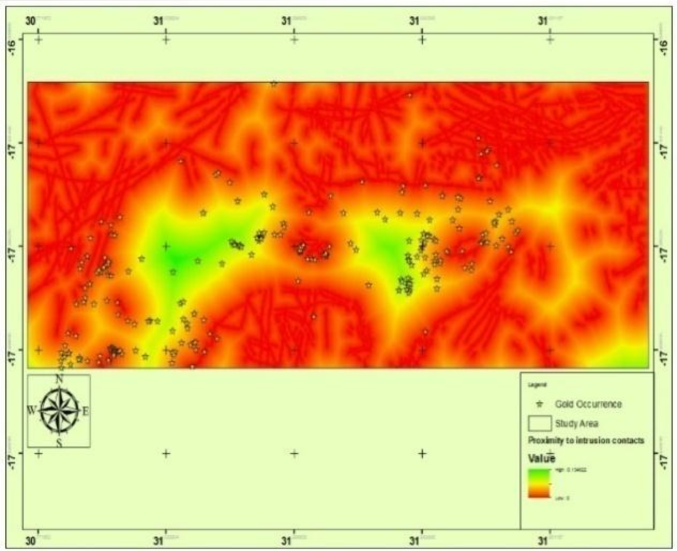
Association of gold mineralization with lithology in the Harare-Shamva greenstone belt.



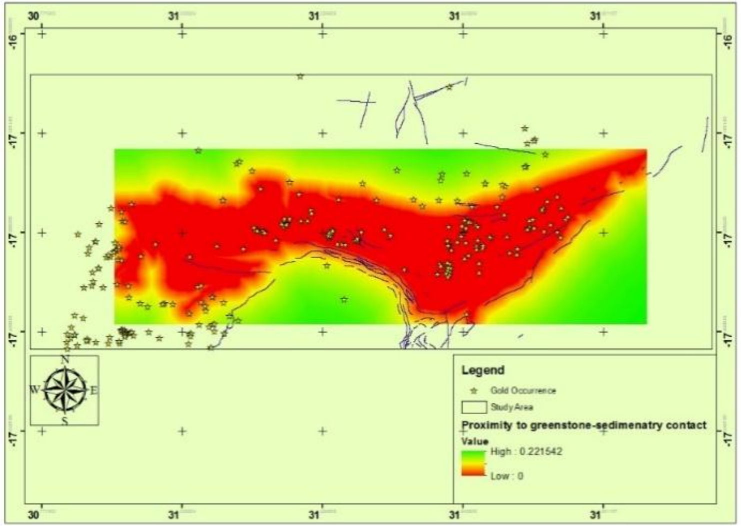
Extract of temporal distribution of gold mineralization within Harare-Shamva greenstone belt.

Geological Supergroup	Geological Formation	Age of geological formation	Major gold deposit
Bulawayo Supergroup	Arcturus Iron Mask	2900 Ma	Ndarama, Oceola, Amatolla, Surprise, Tafuna Hills cluster. Chifefe, Blue Bird, Moneybox
Shamvain Supergroup	Mazowe	2700 Ma	Shamva cluster
Granitoids	Bindura Granodiorite Jumbo Granodiorite	2649 ± 6 Ma 2664 ± 15 Ma	R.A. N cluster (Kimberley, Hastie, Topsman, Bonzo) Mazowe, Bernheim, Storis, Flying Bowl, Ogilvy.
	Quartz Diorite		Freda cluster (Promoter, Botha, Rebecca, Mona)

: Location of gold deposits in relation to intrusion contacts (a) and greenstone-sedimentary contacts (b).

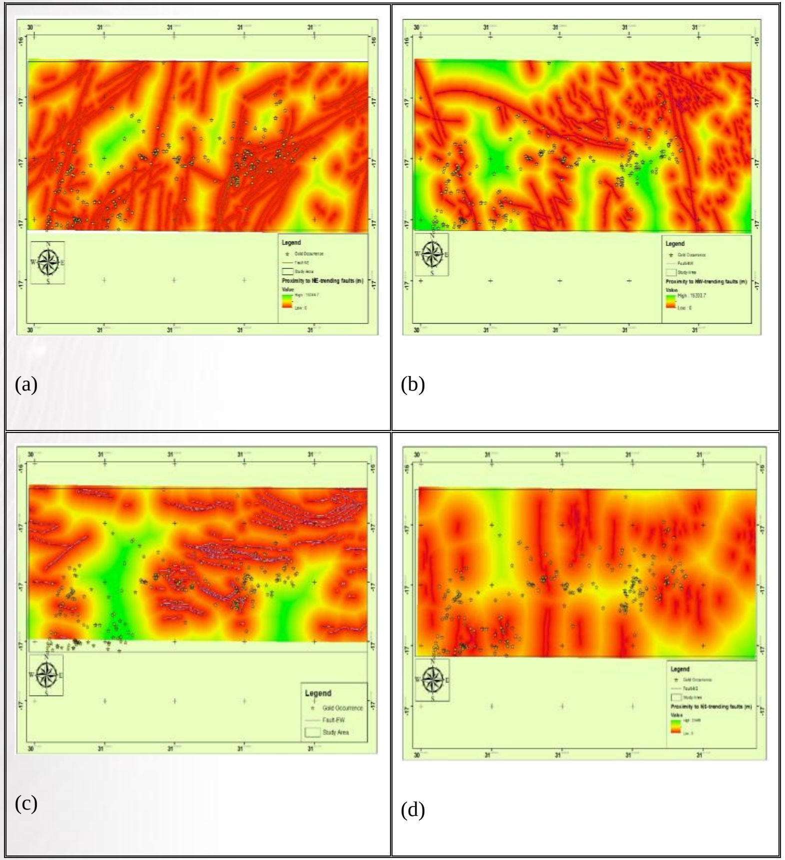


(a)



(b)

Predictor maps for fault systems

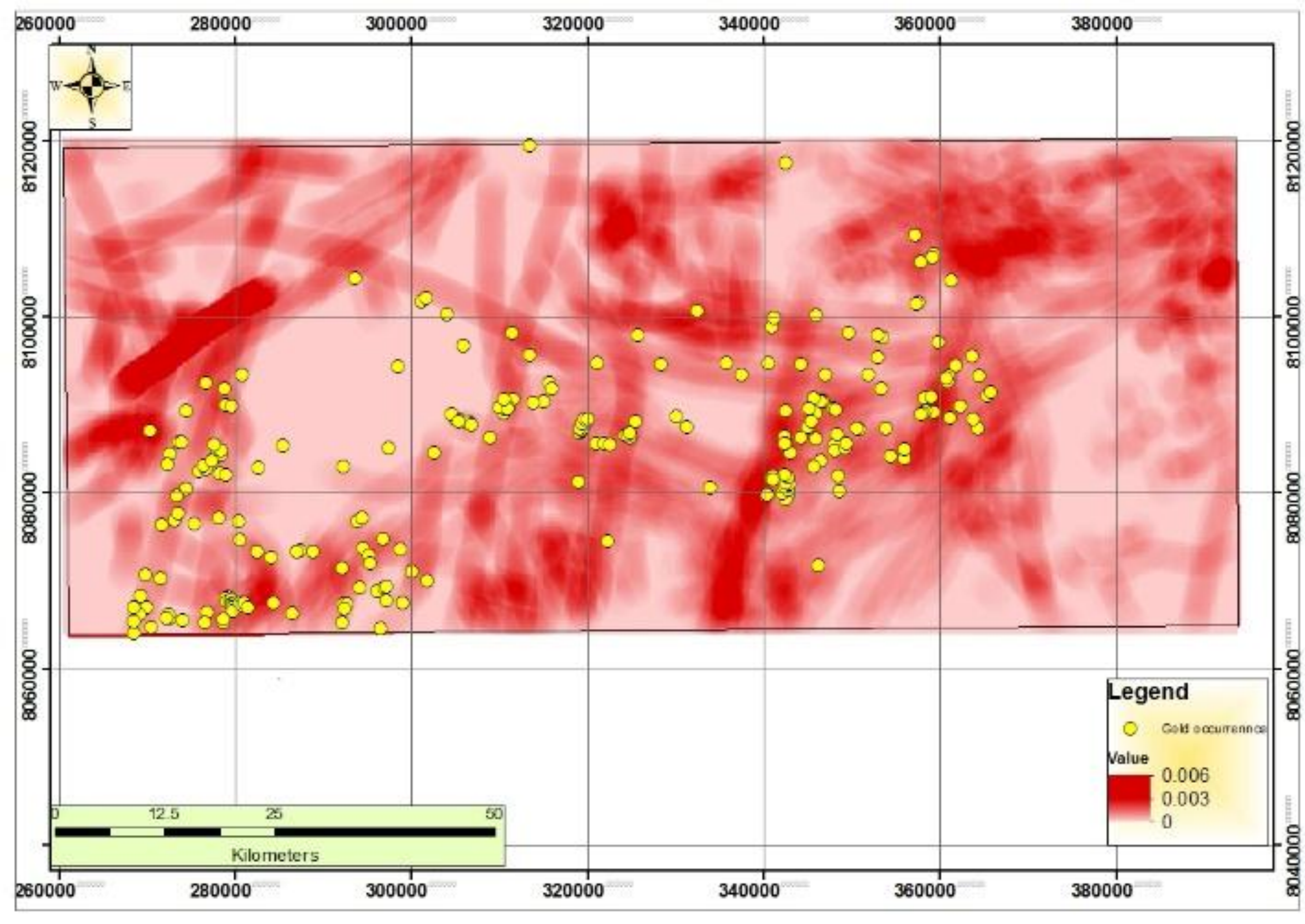


(a) (b) (c) (d)

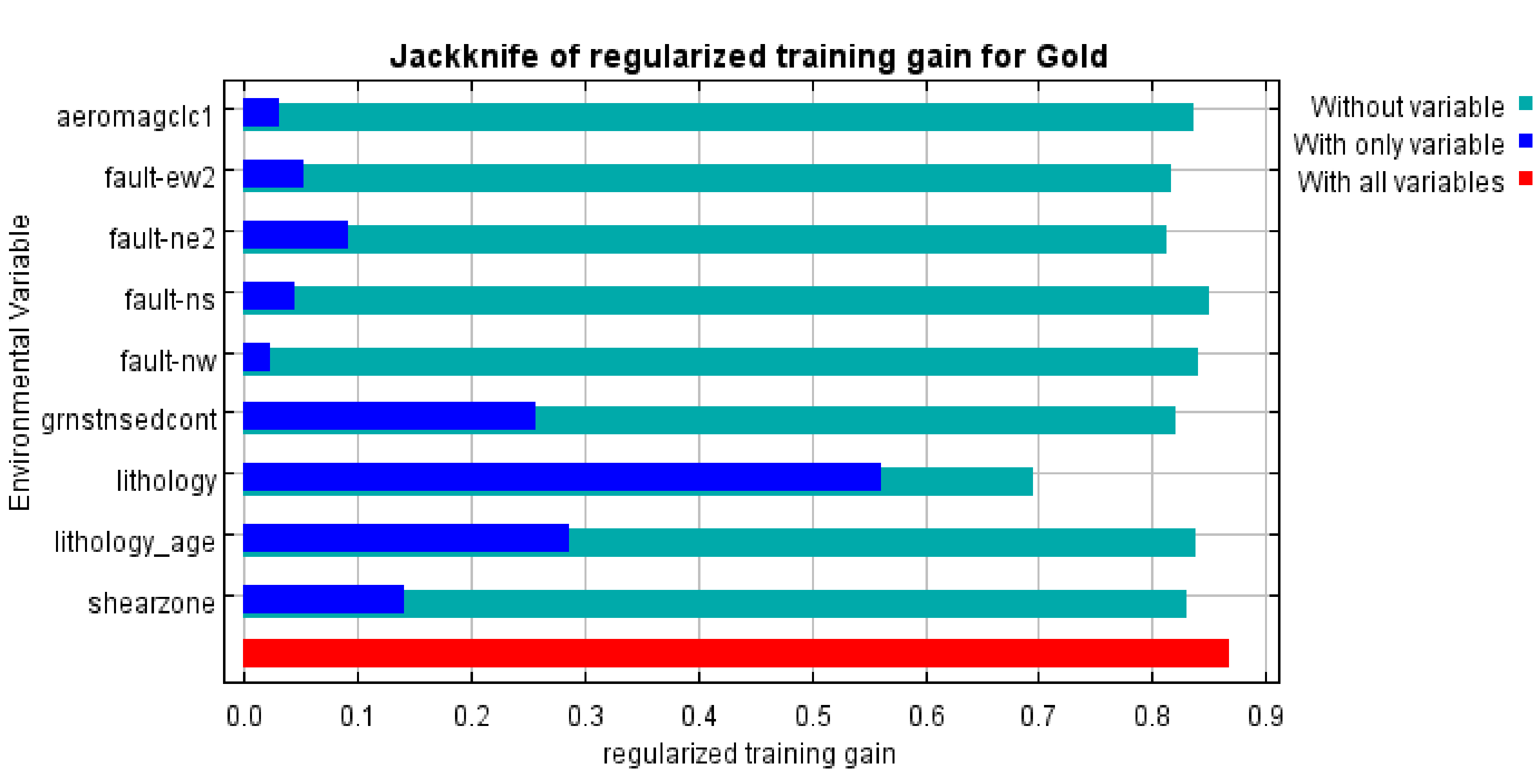
Results

- of the 236 gold occurrences in the study sample about 90% are well within the proximity of the NE-trending fault system.
- approximately 85% of the gold deposits are located within Euclidean distances of less than 2500m.
- Of these approximately 40% are within Euclidean distance of less than 1500m of the NE-trending faults.
- Fault-NS ranks the lowest interest variable with a percent contribution of 2.5%. This is in line with the Euclidean distance calculator in which this predictor variable returned a maximum distance of 23 498m for the furthest occurrences of gold deposits from the North-South-trending fault.

Fault density and location of gold deposit



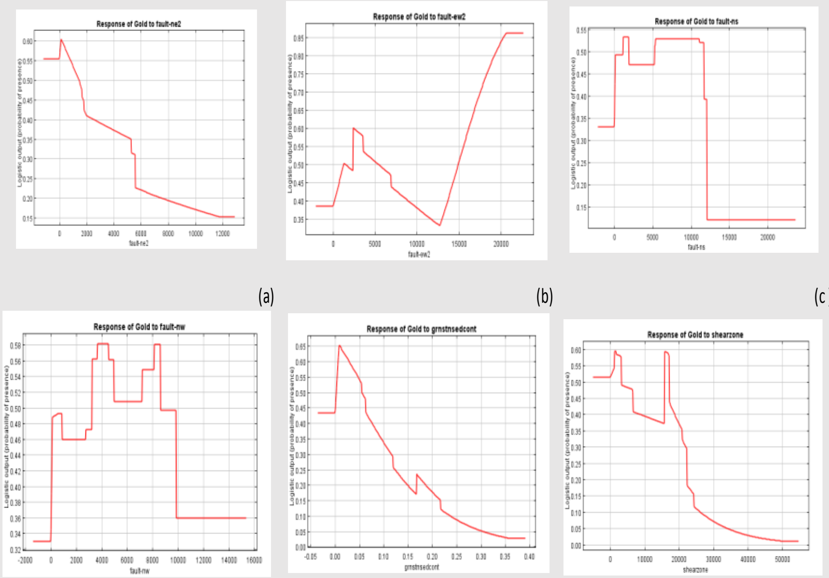
Jackknife of regularized training for gold prediction in Harare-Shamva GB



Contribution of ore-controlling variables to prediction of gold occurrence in Harare-Shamva greenstone belt

Variable	Percent contribution	Permutation importance
lithology	28.6	28.1
grnstnsedcont	23	13.9
lithology_age	14.7	11.2
fault-ne2	9.8	13.1
shearzone	9	9.3
fault-ew2	6.3	8.3
aeromagclc1	3.3	8
fault-nw	2.8	4.8
fault-ns	2.5	3.

Response Curves for predictor variables



(a) (b) (c)

(d) (e) (f)

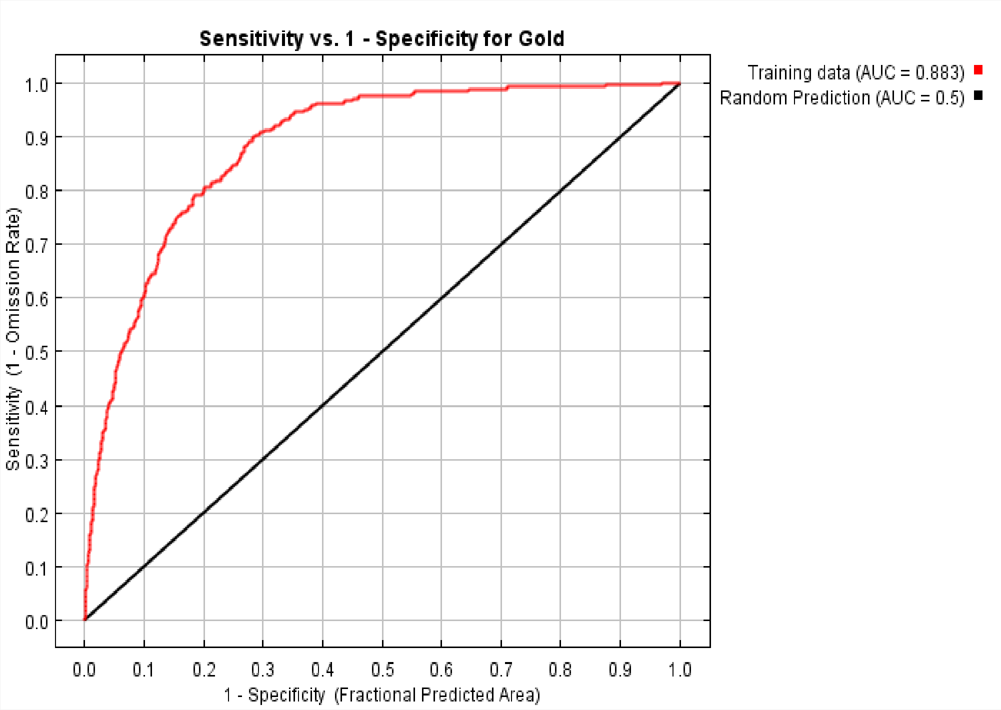
(g)

Response curves of predictor variables (a) proximity to NE-trending faults (b) proximity to EW-trending faults (c) proximity to NS-trending faults (d) proximity to NW-trending faults (e) proximity to greenstone-sedimentary contact (f) proximity to shear zone

- Proximity to NE-trending faults (Fault-NE), proximity to greenstone-sedimentary contact and proximity to shear zones response curves suggest that as distance from these features increase (that is increase in x-axis values) this eventually leads to a sharp decrease in the logistic probability of gold deposit occurrences (Figures (a), (e) (f)). When y-axis values are higher, the logistic probability of an occurrence is also higher.

- The logistic probability of gold occurrences is therefore higher within the proximity of Fault-NE, greenstone-sedimentary contact and shear zones. It is favourable at less than 5550m for Fault-NE with a peak logistic probability of 0.6 at less than 100m distance from the fault before the response curve flattens out to a maximum of 12000m with a logistics probability of less than 0.05

Receiver operating characteristic (ROC) curve for gold prediction in Harare-Shamva GB

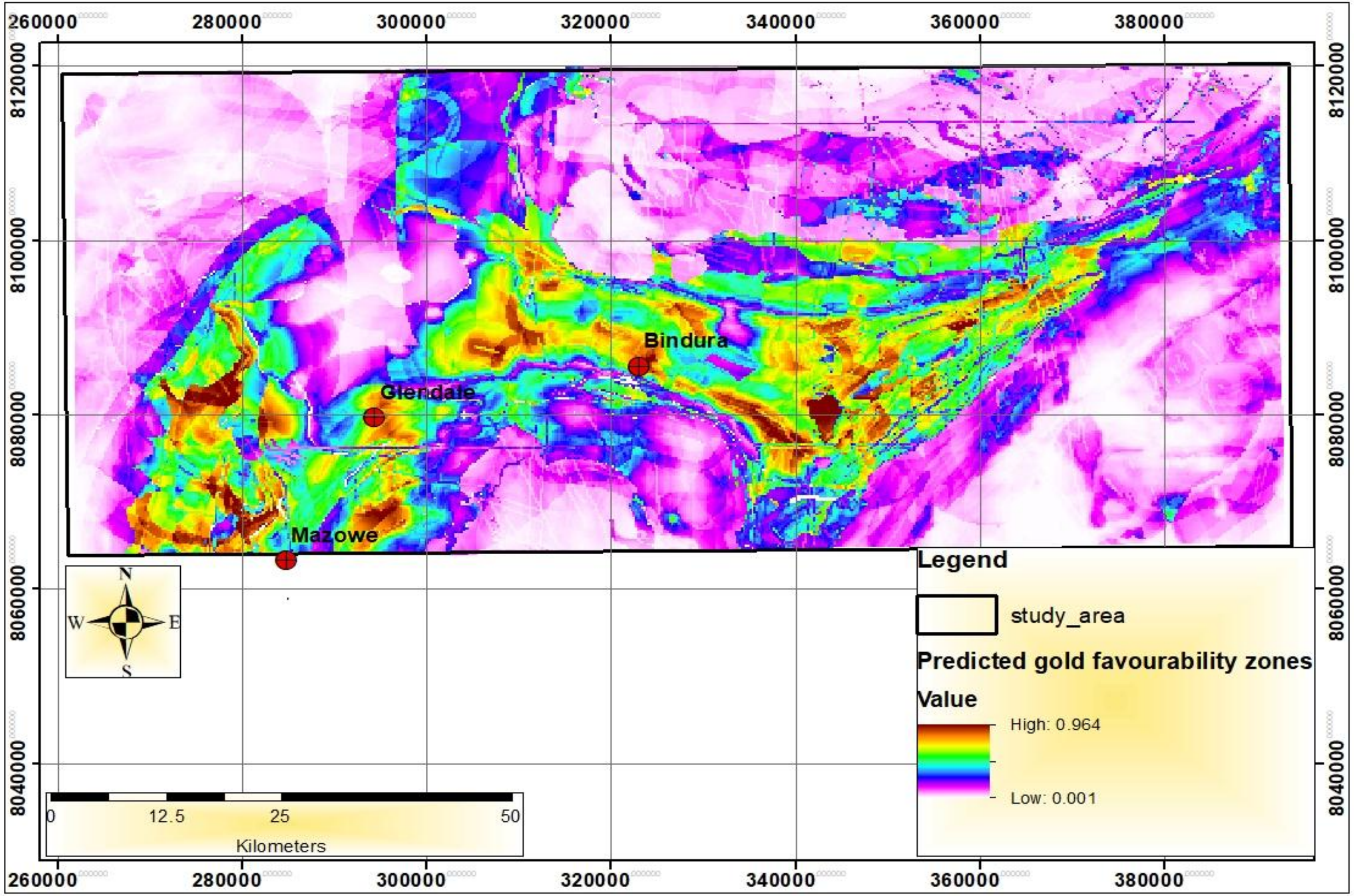


- results suggest good capability in distinguishing between favourable and less favourable regions for the occurrence of gold mineralization in the Harare-Shamva greenstone belt.

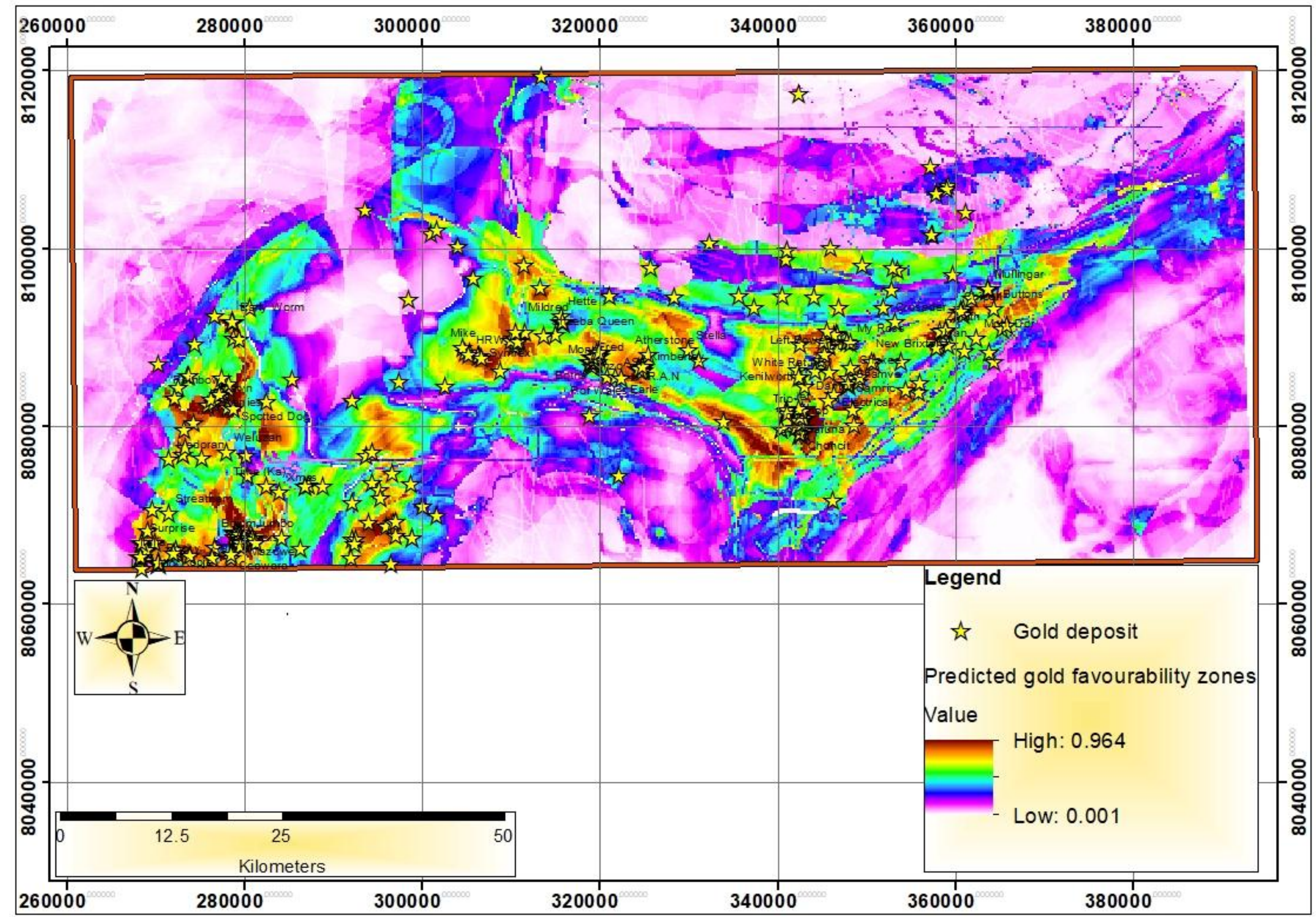
Performance Evaluation

- The receiver operating characteristic (ROC) curve is useful to examine the overall model performance by plotting sensitivity (true positive rate) against 1-specificity (false positive rate) at various threshold settings.
- The area under the ROC curve (AUC) represents the quality of the probabilistic model to reliably predict the occurrence or non-occurrence of deposits that can be calculated from all possible probability thresholds.
- The AUC explains how well the model classifies the true positive and true negative cases. Commonly, the AUC between 0.5 and 0.7 implies poor, between 0.7 and 0.9 implies moderate, and larger than 0.9 implies high performance of the model.

Favourability map for prediction of orogenic gold mineralization in Harare-Shamva GB



Prospectivity map showing MaxEnt predicted zones with overlay of gold mineralization in the Harare-Shamva greenstone belt.



Discussion of Results

LITHOLOGY

- These predictor variables contribute 85.1% of the total prediction for gold in the study and accounted for 79.6% of known gold occurrences in the study area with regions favourable to orogenic gold mineralization making up an estimated 23.6% of the study area. An estimated 95% of gold deposits in the study sample occur within the predicted regions.
- In this study gold mineralization was found to be associated with five lithological units, namely the volcano-sedimentary unit of the Mazowe Formation, the Archean granitoids (Bindura and Jumbo Granodiorite), the Arcturus volcanic greenstone belt rocks (meta-basalts, meta-andesites and dacites).
- Orogenic gold deposits tend to be associated with thermal events linked to crustal growth with no association to local lithology. Granitoids emplacement is believed to have been the kiln providing the sources of heat.
- Gold mineralization in the Mazowe and Arcturus Geological Formations and Granite-Granodiorite are consistent with assertions by Cassidy (1994) that orogenic gold deposits occupy a consistent spatial and temporal position. The gold deposits are hosted in rocks of different ages from Archean to Phanerozoic (3500 to 1.6Ma).

TIMING FOR GOLD MINERALIZATION

Discussion of Results

- Relative ages of the major geological formations comprising the Shamvain and Bulawayan Supegroups and isotopic ages of intrusions have been used to split between orogenic gold mineralization in older geological settings (Bulawayan) and younger geological settings (Shamvaian). Gold mineralization in the Harare-Shamva greenstone belt is hosted within geological sequences of specific temporal domains.
- Mineralization is restricted to the Shamvaian (2700Ma), Bulawayan Supergroup rocks (2900Ma) and Archean Granitoids. The major mineralized geological units of the Shamvaian Supergroup being the Mazowe Geological Formation (MGF), the Passaford and Murowodzi End Member. The MGF is essentially wholly volcaniclastic sediments consisting of greywackes, amphibolite and granitic constituents. The sediments are presumed to be the major sources of ore-bearing hydrothermal fluids as per the conclusions of Phillips and Powell (1996), Gaboury (2019) and Groves et al., (1997).
- Three major granitoid stocks host gold-bearing deposits within the study area and these comprise Jumbo Granodiorite ((2664 ± 15 Ma), Bindura Grandiorite (2649 Ma) and Glendale tonalite (2618 ± 19 Ma). Two major gold mines namely Mazowe and Fred Rebecca cluster of gold deposits are hosted on Jumbo and Bindura granodiorites respectively.

Summary

- The response curves show that ore-controlling variables like proximity to structural controls, for example faults or shear zones and proximity to intrusion contacts such as greenstone-sedimentary contacts may show ascending or descending relationships with known gold deposits.
- The spatial association of selected ore-controlling variables with the occurrence of gold deposit or mineralization was investigated using Response curves and Jackknife analysis to establish the relative importance of each ore-controlling variable. Consequently, lithology was the most significant ore-controlling variable (28.6%), followed by greenstone-sedimentary contact (23%), age of lithology (14.7%), Fault-NE (9.8%) and Shear zones (9%).
- Regions that are prospective to gold deposit occurrence or mineralization were defined by the favourability map (Figure 4 1). These regions are consistent with known gold deposit localities and other gold mineralization patterns in the study area, suggesting that MaxEnt modelling offers alternative tool for collective analysis of multisource geospatial data to enhance conceptual mineral systems modelling of geologic, geophysical, geochemical and structural controls on gold mineralization.
- The resultant predicted favourability map shows that regions that are favourable to orogenic gold mineralization make up an estimated 23.6% of the study area. An estimated 95% of gold deposits in the study population occur within the predicted regions. These favourable regions are coincident with spatial distribution of contributing ore-controlling variables, for example lithology (Mazowe sedimentary formation hosting Shamva gold mines, Jumbo Granodiorite hosting Mazowe cluster of mines, Bindura Granodiorite hosting the R.A.N cluster of gold mines, and Freda Rebecca cluster of mines and Arcturus meta-basalt). The model predicted 79.6% of gold deposits/occurrences, with high potential zone accounting for 6% of the total study area.
- Beside predicting the locations of known gold deposits, the favourability map also showed a number of regions which are not known for hosting gold deposits at the moment. These regions therefore represent new opportunities for gold mineralization since the regions are defined by favourable geological conditions as determined by the model.
- The response curves of Fault-NE, greenstone-sedimentary contact and shear zones showed higher logistic

Conclusions

- One of the most significant outcomes of the research was to demonstrate how a process-based mineralization system drawn from understanding the interplay between ore-controlling factors and ore-forming processes can be useful at generating exploration targets at a local scale by using limited regional data. This is critical in enhancing opportunities for discovery of new gold deposits by constraining prospective regions through focusing budgetary resources.

- Consequently, the MaxEnt model is, based on this result, a reliable and accurate prediction tool whose application can be expanded into applied geology.

Geological Time Scale

EON	ERA	PERIOD	MILLIONS OF YEARS AGO	KEY EVENTS
Phanerozoic	Caenozoic	Quaternary		Humans evolve
		Tertiary	1.6	
	Mesozoic	Cretaceous		
		Jurassic	138	Extinction of Dinosaurs
		Triassic		
	Paleaozoic	Permian	240	
		Carboniferous	330	Permian mass extinction
		Devonian		
		Silurian	410	
		Ordovician		Invertebrates become common
		Cambrian	500	
Proterozoic		Also known as Precambrian		
Archean			3500	
Hadean				Earliest life