Tectonic Environments of South American Porphyry Tin Magmatism Through Time Revealed Though Spatiotemporal Data Mining

GEOL3888 Group Assingment - Final Project

GEOL3888 Economic Geology Interdiciplinary Project Python Group Project : Week 13 : South American Tin Deposists

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Abstract

The chemical element tin is a widely used metal material, the majority of which is sourced from the crust as cassiterite. Tin has many functions in society, including its main function as an alloy for many products, and also as a component of solder. Porphyry ore deposits of tin are commonly associated with granulite intrusive deposits found near convergent boundaries such as the long-term subduction of the Nazca plate underneath the Peru-Chile boundary. As with any natural resource, there are associated risks with continuous mining and usage. It is possible, and therefore valuable, through computer science and machine learning to analyze the distribution, abundance, and age of tin ore deposits in South America, where some primary deposits of tin are located. Greater understandings of where this precious rare-earth material can be found will allow society and researchers to map our consumption of this natural resource and increase prospects of economic viability for future tin mining. From this analysis using data from the EarthChem source, it is evident that the South American Margin is a vast source of tin ore. The collisional tectonics of the convergence zone at the Nazca and South American Plate boundary is strongly coupled with the location and distribution of tin ore deposits. There is also a strong relationship between the age of the lithosphere where the tin ore is located, and the time period in which significant collision and subduction occurred, which suggest they are linked. Machine learning mechanisms such as random forests and support vector machines distinguished the important parameters of the relationship between the tectonics and the deposits.

Introduction

The chemical element tin is one of the oldest mined materials, dating back to its first use as a bronze alloy coating for implements and weapons during ~3,500 B.C. (Anderson, n.d.; Gagnon, n.d.). Although it has been used for centuries, tin is not a commonly found element in the crustal region of the Earth, as it only comprised 0.001% of the crust, which roughly equates to 2 ppm (Anderson, n.d.; Gagnon, n.d.). Compared to the element iron that accounts for approximately 5% of the crusts composition, roughly 50,500 ppm, tin is considered a rare earth element (Sawe, 2019). However, tin is still a widely used material, solder accounting for the largest global share of tin use (International Tin Association, 2018) (Figure 1). With any natural resource, including tin, there are risks associated with over-extraction,

including large-scale depletion of the global reserves and consequently, higher demand and market prices. It is possible through computer science and machine learning to analyze the distribution, abundance and age of tin ore deposits across the globe, ore more specifically within South America where primary tin deposits are located. Greater understandings of where this precious metal can be found will allow society and researchers to map our consumption of this natural resource. From increased knowledge on the use and abundance of tin, regulation surrounding tin resources and management policies can be effectively implemented to combat the escalating demise of the Earth's natural tin resources.

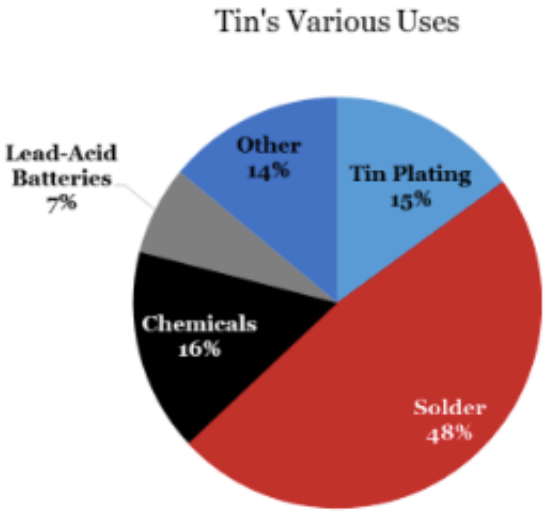

Figure 1. Chart of the various current uses of tin. Image Source: International Tin Association, 2018.

Metals are not often found distributed in a uniform fashion around the world, however, regions of significant occurrences do exist, and are termed 'metallogenic provinces' (Taylor, 1982). Tin ore is commonly a residual deposit from eluvial or alluvial processes that alter pre-existing rock through dissolution. This process results in large constituents of the rock being lost, leaving raw layers of tin ore in sedimentary conditions (Olade, 1980). However, primary tin deposits are often also associated with granitic intrusive deposits (Olade, 1980). The world's largest reserves of tin are situated in China, with over 1.1 million reserves. China is also credited for incidentally having the highest mine production of tin for 2017 and 2018 (USGS, 2019). The International Tin Association (ITA, formerly the International Tin Research Institute) forecasted a likely shortfall of tin beginning in 2018, and stated that tin reserves globally have uncertain futures and generally, the most economically viable reserves are currently being depleted (ITA, 2015). New mines, outside of the industrial-scale mines currently active in the tin-rich hubs of China and Indonesia, face financial challenges due to economic unviability of their tin deposits (ITA, 2015). It is therefore critical to continue tin exploration for potentially more economically viable deposits to avoid rising prices in the tin market. As a critical material increasingly used in technology such as mobile phones and computers, the strain on the search for tin will only increase as our world becomes more and more dependent on such technologies.

The Inner Arc of the Central Andes, however, also hosts significant reserves of tin, which have been categorised into two distinct ages of formation or "metallogenic episodes": a episode from the late Triassic–early Jurassic (mostly only in Northwestern Bolivia), and a "much more significant, late Oligocene to Miocene episode, which encompassed the entire length of the province" (Mlynarczyk and Williams-Jones, 2005, p.656), both of which contained rich tin and tungsten (Sn-W) reserves (Mlynarczyk and Williams-Jones, 2005). As a major boundary of convergence and subduction, South America hosts a

series of sub-parallel ore deposit agglomerations moving west to east, from the subduction trench that lies along the Pacific Ocean inwards. In addition to the tin belt (Sn-W-Bi-Sb-Ag-Au in the Eastern Cordillera (mountain range), there are also distinct copper-rich belts (Cu-Mo-Au-Fe in the Western Cordillera, and Cu-Pb-Zn-Ag-Au in the Altiplano region), however these are more extensive and widespread around the continent than the well-defined tin belt (Lehmann et al., 1990). While relatively geographically small, this tin belt, also known as the Bolivian tin belt, extends for 900 km and is still economic to mine, producing approximately 15% of total global historical tin production (Lehmann et al., 1990). The mineralisation of tin in the tin belt has been found as three separate forms with differing mechanisms of origin; porphyry tin, vein tin and polymetallic deposits which usually also contain high concentrations of silver (Fontboté 2018).

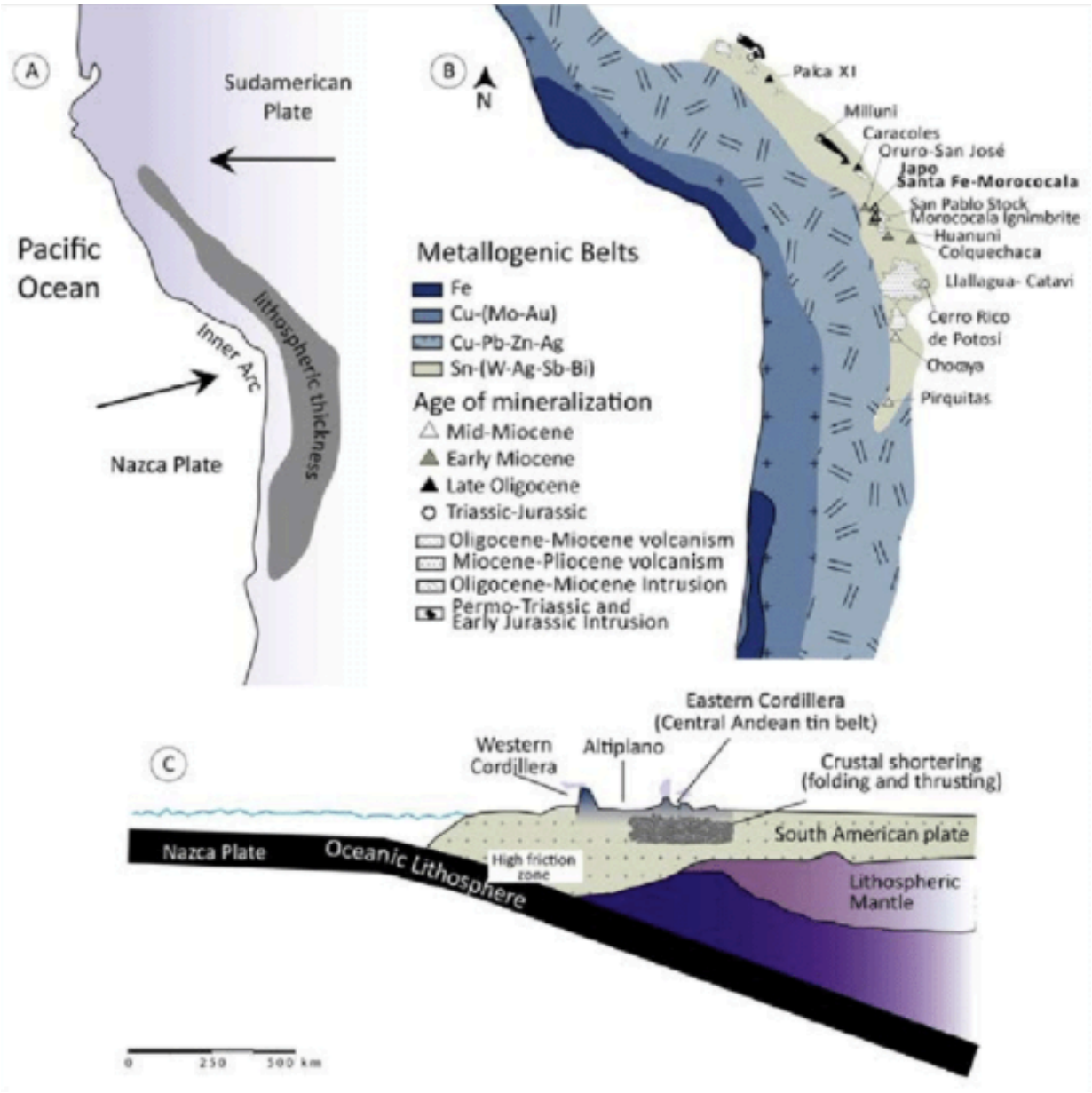

Figure 2: "Principal metallogenic belts and ore deposits of the Central Andean Tin belt (after Mlynarczyk and William-Jones, 2005). A. Plate tectonics, volcanism and lithospheric thickness; B. Relevant ore deposit with time in the Central Andean tin belt; C. Schematic cross-section of the Andean continental margin, showing the relationships" (Jiménez Franco et al., 2018, p.411).

In the Central Andes, the concentrations and the occurrence of tin that has been supplied to the tin belt have been linked to the oxidation-reduction (redox) conditions occurring in the magmatism (Fontboté 2018). Usually occurring as 'cassiterite' (a tin oxide mineral and the main form of tin ore), the tin was able

to be carried and transported so as to concentrate into a deposit through the maintenance of these reducing conditions, which are known to have been caused by the “interaction of magmas and hydrothermal activity with the carbonaceous Ordovician sedimentary units” (Fontboté 2018, p.258).

The characteristics of the long-term subduction of the Nazca plate underneath the Peru-Chile boundary include rapid convergence, a relatively young oceanic crust under-thrusting the compressional overriding continental plate, and a sub-horizontal dip of the subducting plate and relatively large earthquakes (Uyeda and Kanamori 1979). Some other parameters that control the tectonic setting and geometry of the Andean subduction zone are: trench normal convergence velocities (Maloney, Clarke et al. 2013), direction of mantle flow, absolute motion of the overriding plate, and slab retreat (Ramos 2010).

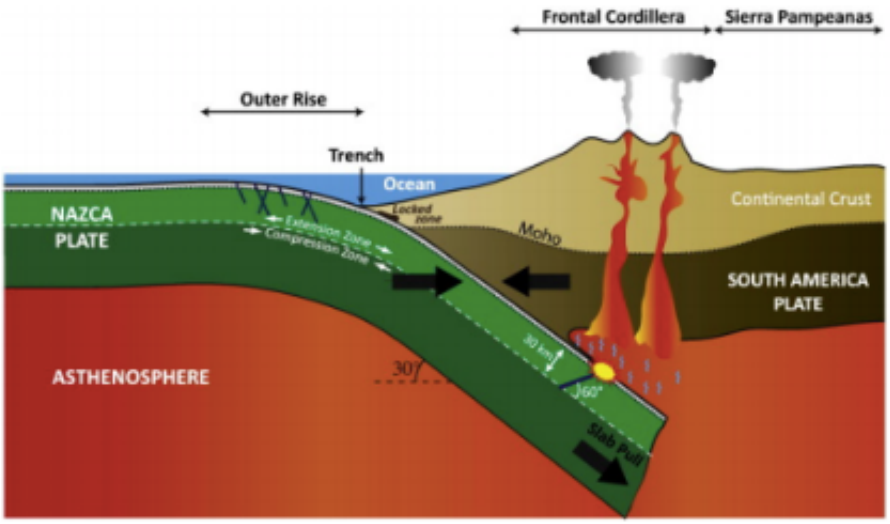

Figure 3. Tectonic setting of the Chile-Peru trench and subduction zone, and the Cordillera (mountains). Image Source: Lubecka, 2015.

In order to explore and analyse the abundance and distribution of tin deposits and their characteristics, particularly in South America and particularly the Central Andes, Machine Learning concepts and methods were utilised. Machine Learning involves increase in machine performance (P) at some task (T), through experience (E). In this case, the E was data repositories of global tin deposits recovered from EarthChem, while P and T were variables and methods that were specified through python coding, with final data produced via a Jupyter notebook. By utilising machine learning mechanisms to understand the tin data, visual data, such as maps, tables, and graphs, were able to be produced, resulting in more comparisons being able to be made between a multitude of parameters, and thus a more efficient understanding of the tin deposits. Specifically, Random Forests and Support Vector Machines (SVM) were utilised as core components of our machine learning functions. Random Forests involve tree-based formations, with each tree depending on a group of random variables, with the goal of the process being to find a function that can predict certain variables (Zhang and Ma, 2012). Support Vector Machines (SVM) are a technique for data classification, whereby data is separated into ‘testing’ and ‘training’ sets, with the goal being to produce a “model (based on the training data) which predicts the target values of the test data given only the test data attributes” (Hsu et al., 2003, p.1). Both of these machine learning methods allowed for the definition of dataset parameters that had likely causal or correlation links to other parameters. In this sense, parameters that directly related to the characteristics of the tin metallogenic deposits could be defined and explored further as key variables. Understanding the processes associated with the formation of tin deposits through machine learning algorithms would thus be able to contribute to current data associated with tin exploration.

Data Review

The data was sourced from EarthChem, a data collaboration cite established in 2005 that operates multiple data systems which assist geosciences in their quest to access, share, and use geochemical, petrological, and geochronological data. EarthChem is apart of Interdisciplinary Earth Data Alliance (IEDA) Data Facility, which is funded by the National Science Foundation (NSF), making it a notable and reliable source for data sourcing. In order to uphold the integrity of the data, data managers from EarthChem ensure that the data contributed by investigators and data that is extracted from the published literature is properly documented with respect to analytical data quality (method, precision, standard measurements), sample description (rock type, texture, age, modal composition, alteration), sample provenance (geospatial coordinates, location names, tectonic setting), sampling process (technique, date, cruise), and more.

The EarthChem Portal is a sub-section of the Data Mining & Analysis profile on the EarthChem website. The EarthChem Portal is a widely developed source for geochemical data that gives users the ability to search federated databases including PetDB, SedDB, NAVDAT, Met PetDB, the USGS National Geochemical Database, GEOROC, and GANSEKI simultaneously. EarthChem Portal includes a polygon function that allows any region to be isolated from a global map that is used in a sorting engine to source data for particular regions or types (Figure 4). The South American Margin (SAM) data on EarthChem was largely sourced from the GEOROCK and the United States Geological Survey (USGS) databases. PetDB and SedDB are two other sources that contributed data from that region.

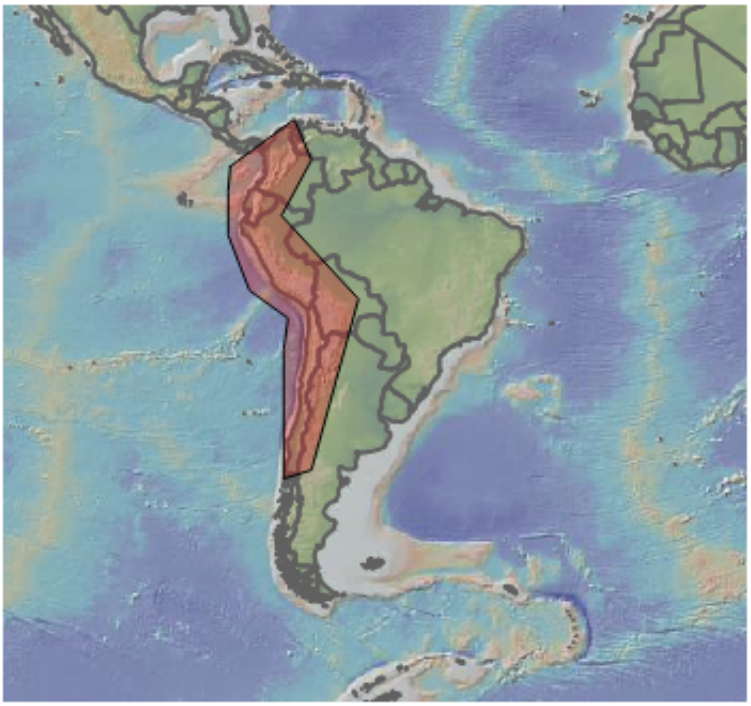

Figure 4. EarthChem Portal search query polygon builder to used to define South American Andes as subject area for data source inquiry (EarthChem.org, 2019; Oswald, 2019).

Although the data source is very recent, the data was cleaned, filtered, and subject to change in units before it was made available for the report. The data contained 21 variables that could have been analysed through machine learning, but for the purposes of this report only four were used; seafloor age (Ma), distance to trench edge (km), convergence normal rate (km/Ma), and subduction obliquity signed (radians). The data used in the notebook was a part of a 3-dimensional data set, meaning when the shape was printed, it showed the number of rows, columns, and the slice. There were 313 rows, 230

columns, and, depending on the shape file or array printed, there were 18 to 20 slices present. The data used for the Support Vector Machines tested 133 points, and the shape of the grid was (65, 100). The data shape sometimes varied throughout the analysis as the different parameters were analyzed through different forms of machine learning. The data was initially a global compile of tin-comprised ore deposits that dated as far back as 230 Ma, but by confining that data to the South American region it was possible to reduce the size of the overall dataset used. This reduced initial time to load and wrangle the raw data into the notebook.

Methods

In order to understand the abundance and distribution of tin (Sn) in the central Andes, a series of code commands were used to create informative age maps and plots. The tin chem data was sourced from the EarthChem SedDB (Earthchem.org/seddb) database and loaded into a "Jupyter Notebook", formerly an IPython Notebook. The initial step was to populate the interactive namespace from numpy and matplotlib and to import a series of libraries including shapefile and scipy. Pygplates, a module that advanced the usage of GPlates for python, with reconstructed tectonic plates which advanced understanding in the subduction kinematics that occur within South America (Butterworth et al., 2016), was then imported. This allowed for the correlation of plate movement with dated magmatic events, and using the plate reconstructions, this correlation was traced back to 230 Ma.

The notebook has two subsequent parts: Part 1 loads and wrangle the data into an appropriate format for machine learning algorithms (ML), and the Part 2 is the applied machine learning and results. To make the editing process more convenient, a coregLoop.py script was created to coregister different datasets. CoregLoop is one way to reconstruct and add data and shapefiles to their original birth time and the coregister those points with another set of points from another shapefile or a raster file. The input consisted of a latitude and longitude list as well as a list of ages and plate IDs corresponding to each point of latitude and longitude. This outputted a coregistered array of latitude and longitude points with multiple properties.

Each tin ore deposit was coupled with age data for the Andes region from Bertrand et al. (2014), and then reconstructed to its geographical position is correspondence with the time of its' metallogenesis. It was then necessary to coregister the kinematics of each tin ore deposits based upon the time and location of the metallogenesis, and prior to 20 Ma, to capture the evolution of the kinematics that lead to the formation of the tin ore deposits. Pseudo-random sets of 'tin deposits' to test against tectonic parameters that do not result in ore deposits were then created.

Initially the data was developed further from its original text file format, and shape files were instructed to create raster layers that would appear in the plots after the machine learning was completed. The shape files are also a key component of the geographical setting of the data. Data was sourced from both Muller et al. (2008), and Bertrand et al., (2014) and therefore needed to be serialized to a Python structure. The data set obtained already included access to python objects that were previously serialized into a character stream, making it possible for use in any python script, thus the pickle files were able to be imported from the connected data file using a file path list that is associated with the individual's computer. The andes shape files were printed, showing the clean and serialized data set.

Extra parameters were then added to further restrict the andes shapefile data. Numpy.arctan was used to account for subduction obliquity by finding the inverse of the tangent to locate where the result was stored in the shapefile and return a freshly allocated array. Numpy.zeros was used to see the new shape

of the array. Then it is possible to cumulate the distance along the track within the andes shapefile by using the numpy.cumsum, which computes the cumulative sum along an axis and was repeated (numpy.repeat) for each chemical element deposits along the same axis. In this scenario the chemical element deposits were limited to only present the tin ore deposits. Numpy.reshape was then applied to make the shape just created compatible with the original shape.

The newly created array that contains tin deposit data for 230 Ma in South America was matched to points along the distance of the trench for present day, and the function numpy.r was used as a simple way to build this coupling into a new array. Numpy.zeros was applied to return the new array with zeros so it was possible to store the index of the data. The looping function applied the data through space and time and the data was saved based on the distance along the track. Following this, the subduction obliquity angle data and the ore deposit formation flag data were added. This was also applied to the pseudo-random data set that was initially loaded in. The random and ore deposits data sets were then combined using numpy.concatenate which joins a sequence of arrays along an existing axis.

With the data loading and wrangling finally completed, the construction of figures identities then began, creating Part 2 of the notebook. The cartopy and matplotlib libraries were both important to first set up the figure and secondly add defining map characteristics. Cartopy made it possible to plot the data on globes, and the Longitude and Latitude Formatter modules provided latitude and longitude scales on each axis. Matplotlib.pty is a basic plotting module used with many functions such as axis and titles. A simple map plot was created to show the identified ore deposits and their age in correspondence the distance along the Nazca and South American plate boundary. The merged dataset, showing the cumulative sum of distance along the original profile is known by the ore deposit data and printed to show that each ore deposits was closest to its associated point along the trench, which the next figured demonstrated. The age and location of the data points were plotted along the South American Margin (SAM) and the present day trench was also plotted against time to produce a figure showing the location and time of tin ore formation.

The combined data sets were plotted against time and age with each partition segment saved to decipher whether it was an ore deposit or not. This was plotted on a color map that demonstrated the age of the subducting lithosphere. Initially, an empty array was created for the partitioned data set, and then the deposit date of both the ore and non ore types were plotted to make an array that would organize the points into color groups based on if they were ore deposit or not. Following this, the random and ore-heavy deposits were plotted and subsequently categorized by color. Spatio-temporal bin parameters were set, which take the reigns of data and divide the entire range of values into a series of intervals belonging to both space and time. To change resolution of intervals and impose space-time restrictions two loops were created; one through the 6500 km length of the Andean Margin in 500 km increments, and another through all time in 10 Ma increments. Seeing the data sourced for this report, the time was restricted to 230 Ma. The portions of data important to this study were extracted to check if the domain had a deposit or not, and were then partitioned based on a condition: if they had 1 or did not have a 0. The partition data from this was converted into a numpy.array for easier manipulation and plotting through machine learning.

Machine learning aids the understanding of how what tectonomagmatic parameters are related to ore formation. Support Vector Machines and Random Forest classification methods are used. Two methods of data analysis were used: looking for the general area of ore formation and considering each ore formation point individually. The partitioned data was used for the area of formation analysis where the data was initially split into testing and training sets. Within the training set it was learnt which parameters are important, while the testing set tested the validity of that method. The data was required to be in a specific format to obtain specific parameters that were included in the machine learning (ML). Four

parameters, seafloor age (Ma), distance to trench edge (km), convergence normal rate (km/Ma), and subduction obliquity (degrees), were selected from the variables list printed as one of the first steps of the notebook. The classification vectors and features were recombined and saved, along with the temporal-spatial parameters using numpy.c, which translated slice objects to concentration along the second axis so they could be used for future plotting.

Random forests were created and trained and and then applied to our gridded data to determine the probabilities at each of the points. The grid was saved against the timestamps, which made it possible to loop through each timestep to output each time slice individually. First, the initial time was pulled out and the probabilities of the remaining time steps were found, including the latitude and longitude, which were all saved out into a numpy.txt. Next, the scatter plot was created, containing both the non deposit and deposit data to show the random forest which predicted the probability of ore deposits based on age and location along the trench. In addition, Support Vector Machines (SVM) were used to learn which parameters were important. A classifier was created and trained for fitting the parameters (features) to known results (targets/classes). The classifier was saved and then, using the subsets of the data, a cross-fold validation score was obtained and printed.

Typical results of SVM included vectors of predicted and actual results that were used to create a time-space map showing when and where along the margin an ore deposit may have formed. The testing and training data were both plotted on a grid style map which predicted the probability of porphyry magnetism in relation to time and correspondence to the trench. Next, the random forest was classified, which helped determine which parameters preferentially optimised the test score. The importance of the four parameters in locating points and areas of deposits were plotted on a histogram. Using the same vectors, or the predicted and actual results, a time-space map was created showing when and where along the margin an ore deposit may have formed. This plotted each of the result vectors, the testing data, and the training data onto one grid style map that showed the magnetism of the porphyry tin deposits based on age and location along the trench.

The point of formation analysis used the same methods as above, however the data was formatted slightly different, meaning the functions needed to be re-written. The data was split into testing and training sets where "training" sets made it possible to learn which parameters are important, and then test the validity of this with the "testing" set. A time-erected dataset was used to make a cross validation data set, followed by reclassification of the vectors. This produced the number of positive and negative examples. A SVM was plotted by creating a classifier and training it to fit the parameters (features) to the know results (targets). To plot the results, a simple time-space map showing when and where along the margin an ore deposit may have formed was created, along with a grid that mapped the ML results.

Lastly the random forest was classified. The random forest first need not be created and trained to result in a cross validation core to be used in creating figures. Features of importance were plotted, which included the four parameters of the report, onto a histogram showing the significance of parameters. Similarly to the SVM, a time-space map was created, showing when and where along the margin an ore deposit may have formed, using a grid to implement the ML results, which returned a plot of porphyry magnetism. It was important to lastly check for the accuracy of the random testing but picking both positive and negative points to produce and accuracy percentage of the points and parts.

Data Analysis

To initiate the analytical process, a graph is produced to asses the deposition of tin deposits along the trench over time (Figures 6 and 7). The majority of deposits fall in the first 40 Ma and around the 3000 km mark along the trench, but there are several deposits approximately 150 Ma in age and sitting around this mark. This partitioned data is simply focusing on the location and time of the deposit, however tectonomagmatic parameters should be applied in order to properly plot the deposits in relation to spatio-temporal attributes.

To plot the point of formation of the porphyry tin deposits, the combined dataset and the seafloor age data is presented on a colour map that shows the correlation between the location of the deposit relative to the trench, the age of the deposit, as well as the age of subducting lithosphere. An empty array is used to store each segmented dataset, as well as an array that is used for colouring the points of the ore deposit locations. A random dataset simulates conditions where tectonic parameters are thought not to create ore deposits - this is done so by assigning the random formation ages between 0 and 230 Ma to each present day latitude-longitude location of known deposits in the dataset (Butterworth et al., 2016). From here, these nondeposit locations formulated are reconstructed to their random formation age and the tectonomagmatic properties associated with the formation of the nondeposit are recorded.

Essentially, this creates the spatial location for areas in which it makes sense geologically for a deposit to form, however, the conditions at the time were inappropriate for porphyry tin magmatism production (Butterworth et al. 2016). This is essential for the machine learning systems as it is important that they are aware of the parameters associated with both the deposition and non-deposition of ore (Butterworth et al., 2016). This method underrepresents some regions of the South America Margin and representing areas with known deposits as being non-deposits in order to balance the number of deposits with non-deposits (Akbani et al., 2004; Butterworth et al., 2016). Non-deposit random data and the ore deposit data are deposited on the colour map, as well as setting the spatio-temporal bin parameters - this sets the time (temporal domains) and distance (spatial domains) at the increments desired. This is looped throughout 230Ma of plate reconstructions, separated by 10 Ma increments, across 6500 km length of the Andean Margin, which is separated in 500km increments. Isolating the Age (Variable Four) and Distance along margin (Variable Eighteen), the code runs to check if the domain as a deposit and marks appropriately according to whether or not there is data stored there, or, if there is a deposit.

For South America, there is a staggering amount of non-deposits compared to the amount of deposits. There majority of non-deposits fall roughly around 3000 km along the trench, as well as being pulled from the start (0 km) along the trench. The Ore deposits are predominantly found within the first 50 Ma, falling between 3000 km and 4000 km and correlating with subducting lithosphere that is older, around 40 to 100 Ma of age.

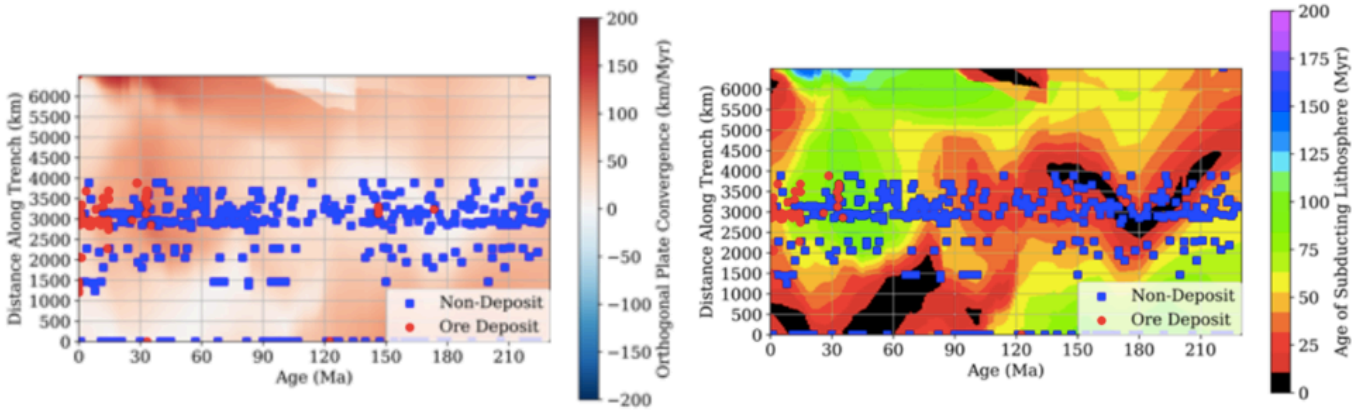

Figure 5: The porphyry deposit formation locations in a spatio-temporal model with the associated

subduction parameters of orthogonal convergence rate (left) and age of seafloor lithosphere (right). The red circles are ore deposits, or positive cases, and the blue squares are non-deposits. When the deposit/s fall in a grid square, a bin separated into 500 km and 10 Ma intervals, it is considered as a deposit. If it does not fall in the grid square, it is considered a non-deposit.

Point of Formation

In order to determine the association between tectonomagmatic parameters and the deposit location, the data points are considered separate events. Porphyry deposits typically are around 2 km in thickness and 5 km in width (Butterworth et al., 2016; Singer et al., 2008), and the minimum distance between each porphyry analysed is around 10 km. Our dataset contained plate models between 0 and 230 Ma, however all the data was deposited prior to around 160 to 170 Ma. This method created 18 deposits and 281 non-deposits. Convergence that occurs along the trench occurs at various rates, and the deposits, as shown in Figure 5, demonstrate formation that the deposits formed during slower convergence rates, roughly between a few km/Ma to 50 km/Ma. There is also a suggestion for the correlation of age of the seafloor between around 40 Ma and 100 Ma with porphyry magmatism.

Machine Learning Analysis

Both Random Forest and Support Vector Machine are statistical analysis methods that, when incorporated with machine learning methods, points of strength amongst the data are found, while also ascertaining which parameters associate with the production of porphyrys. By running both non-linear classifier methods, one can view the advantageous and disadvantageous qualities of each system in a way that will provide more insight to our analysis. Essentially, both methods work to ascertain training and testing points within the data, which allows the machine learning methods to learn which of the parameters link to each deposit and non-deposit incidence. This eventuate in a prediction which can be used to compare to the actual data that has been produced (Butterworth et al., 2016).

Random Forest

Random Forest are non-linear classifiers that train a collection of decision trees on a subset of features, tectonic parameters in our case, and training samples with replacement (Breiman, 2001; Butterworth et al., 2016). For prediction, the class of the query point is determined by the main ruling of the decision tree predictions. This randomization process is called ‘bagging’, and Random Forests use this on data and data features which makes it simple to ascertain to the most important features required of prediction. This machine learning technique is advantageous when working with the unbalanced class data that is in use for this study (Butterworth et al., 2016). Simply put, the Random Forest algorithm takes a set number of random entries – in this case, 128 estimators were used – and builds a decision tree which are then included, depending on the amount specified. Each tree predicts which category – in this case, deposit or non-deposit – will be assigned a new record, which is then officially signed to the category in which the majority of decision trees predicted.

By using this machine learning system, an unbiased and stable system is implemented that produces substantial results. It usefully scales well and is able to use data and produce results regardless of whether the data has missing values. The probabilities drawn from this method are ‘determined as an “out-of-bag accuracy”’ (Breiman, 2001; Butterworth et al., 2016). The Random Forest method allows us to gain a quantitative measure of the features most important to the porphyry genesis, following the

decisions trees and ascertaining which of them provide us with the highest “out of bag currency” (Breiman, 2001; Butterworth et al., 2016). The features, or rather, the parameters, appear to be rather balanced in terms of significance.

Support Vector Machine

Support Vector Machine is another machine learning technique utilising non-linear classifiers - a kernel machine that uses support vectors in order to determine classification (Butterworth et al., 2016). This system projects the tectonic parameters to a “high…dimensional space (the kernel space)” (Butterworth et al., 2016 p. 2855), which separates the data into positive and negative classes. Using binary class labels (here, deposits and non-deposits), the support vector machine slots the data vector classifications (tectonic parameters) into these class labels. Due to the small size of the testing data set, nonlinear radial basis kernel is used as it is more powerful and will try and separate the classes with a hyperplane that is described by a set of vectors (Akbani et al., 2004; Butterworth et al., 2016). The scikit-learn python package is used, as it was with the Random Forest classification, set with default radial basis function kernels and parameters (Pedregosa et al., 2011; Butterworth et al., 2016). The probabilities found using this method are determined through the Platt scaling method which assign probabilities through a comparison of the trained support vectors created (Butterworth et al., 2016; Platt, 1999).

Each dataset has been analysed both with parameters and individually, and in some cases, the data has been analysed in combination with the parameters that were set. In some cases there are over interpretations of the data, and this must be removed in order to increase significance of the data and analysis we receive. This was achieved by ranking the parameters by feature importance, and testing each of them systematically, which brought forward those features that were consistent and significant.

Our workflow was simple – our model was trained by subduction parameters, then by viewing the most consistent and thus important parameters of a dataset this allowed prediction of porphyry tin deposits and non-deposits. This is why only seafloor Age (Ma), distance to trench edge (km), convergence normal rate (km/Ma) and subduction obliquity (degrees) have been explored, as they are the most consistently important features (Butterworth et al., 2016). From here spatial-temporal maps are drawn in order to analyse the likelihood of porphyry magmatism throughout the subduction history of South America trench.

Results

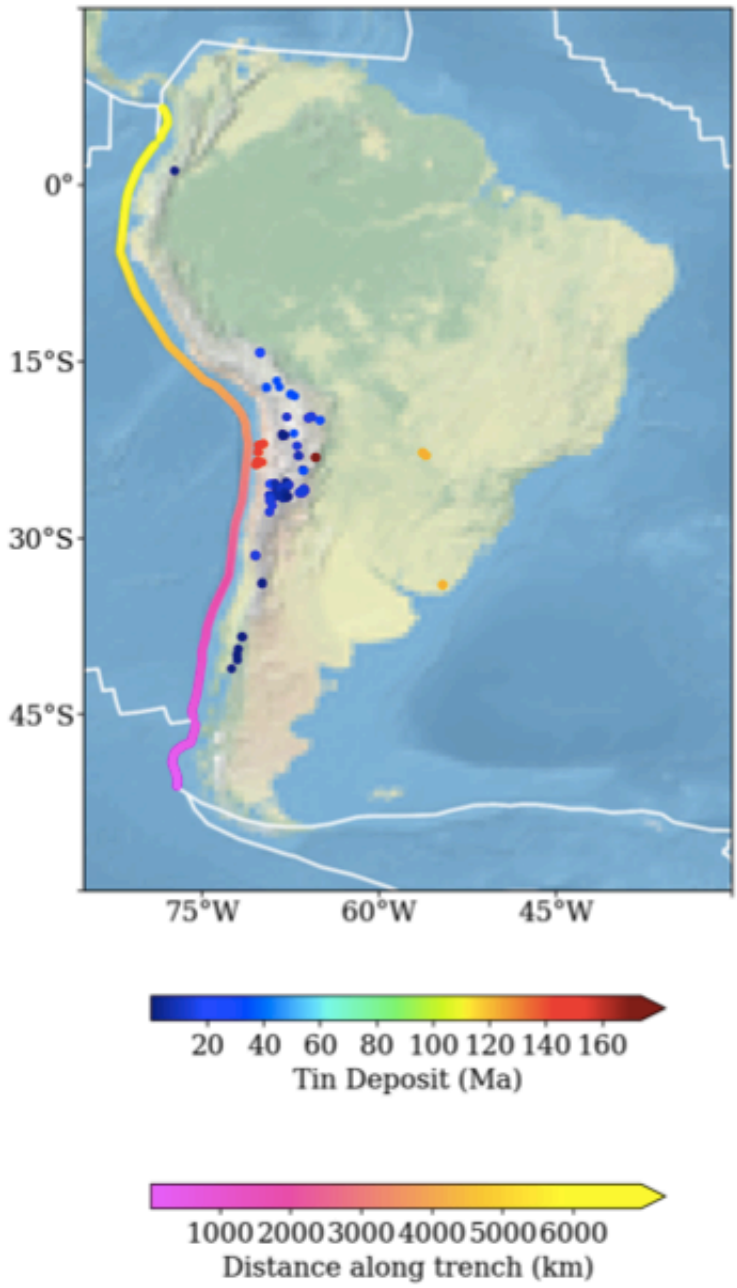

Figure 6. Map of South American tin deposits and their associated ages of point formation up to 160 million years. The distance along the trench from the southernmost point of South America northward is also illustrated. Source: EarthChem (2019), Benjamin et al. (2019).

The vast majority of the tin deposits in South America have an age of formation of between 10-40 Ma (in the Quaternary) and occur relatively parallel to the subduction-zone trench, and mostly occur between 2000-4000 km along the trench (Figures 6 and 7). The other few deposits close to the present-day trench (shown in orange-red in Figure 1) are Jurassic in age, and the yellow-coloured deposit points further east (away from the trench) are Cretaceous in age.

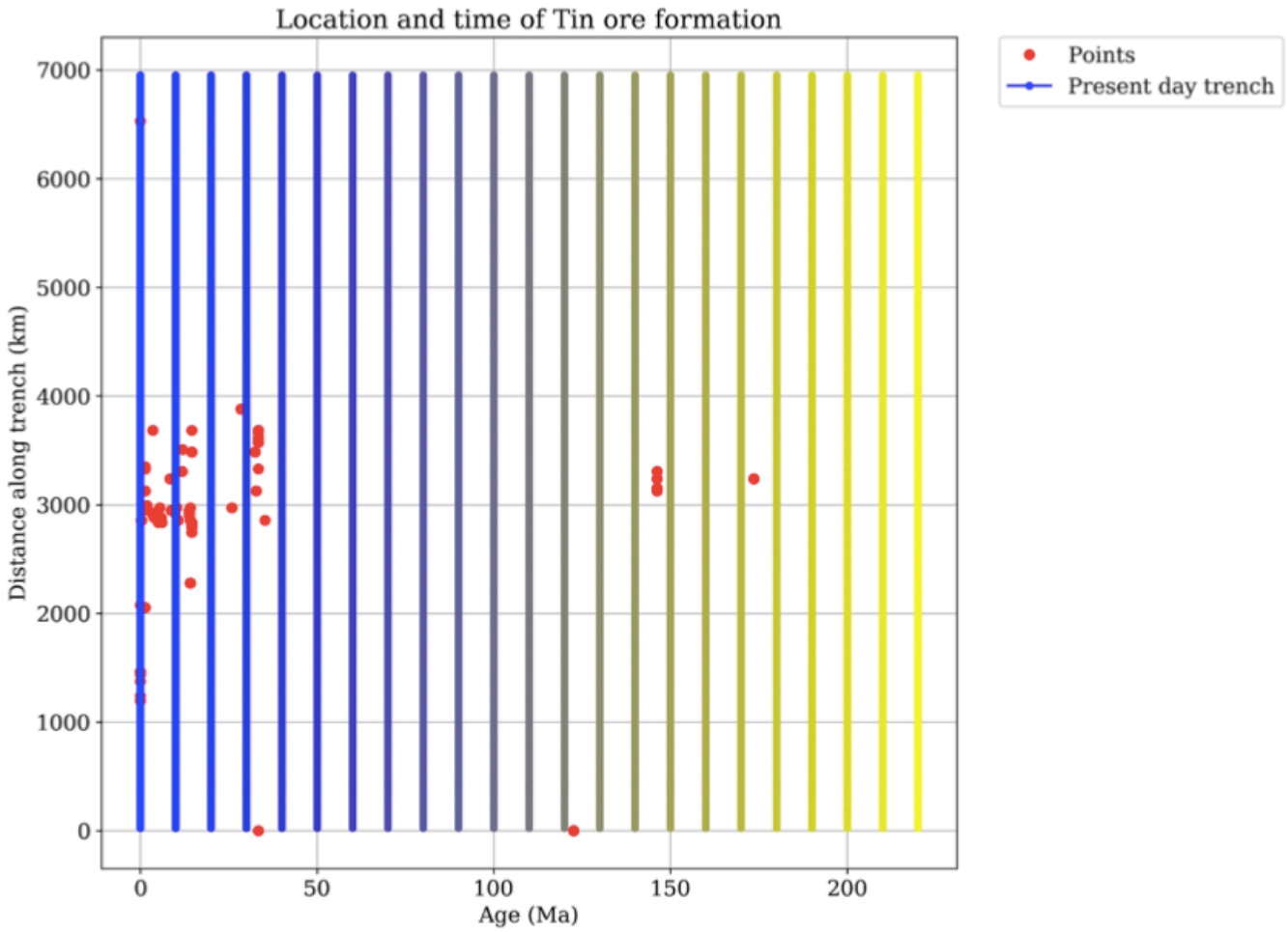

Figure 7. Tin deposit points plotted against the location (distance along trench) and time (Ma) of their formation, partitioned into 10 Ma segments. Source: EarthChem (2019), Benjamin et al. (2019).

From Figure 7, it is again evident that the large majority of tin deposits have formed in the range of 2000-4000 km distance along the trench, and most of the ages of the points of formation are clustered around 10-40 Ma.

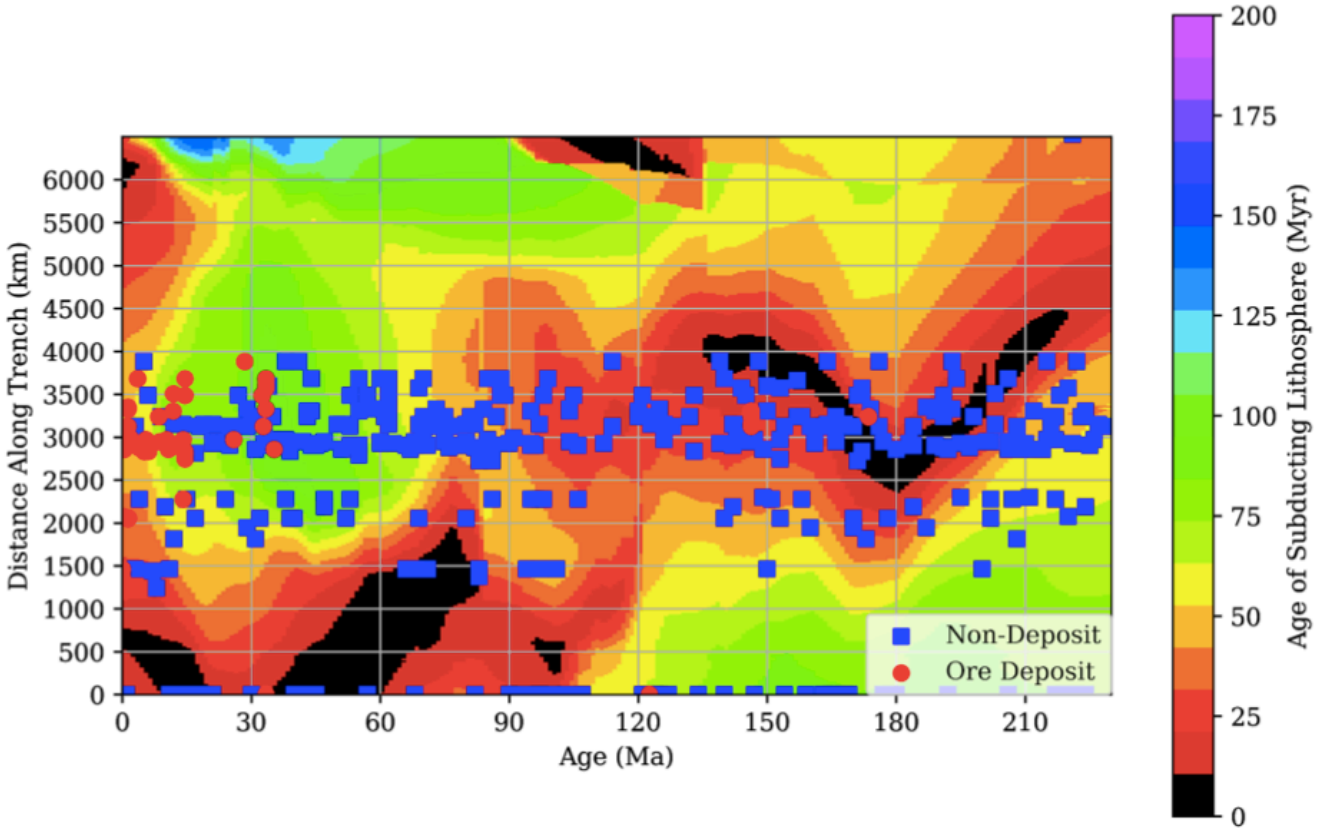

Figure 8. Deposits divided into non-ore and ore deposits plotted against their Age (Ma), Distance Along Trench (km) and the Age of Subducting Lithosphere (Ma). Source: EarthChem (2019), Benjamin et al. (2019).

Figure 8 demonstrates the deposits of tin which are classified as ore deposits (shown as red circles), and the non-ore deposits (shown are blue squares). The ore deposits are heavily concentrated around subducting lithosphere that is around 40-100 Ma in age.

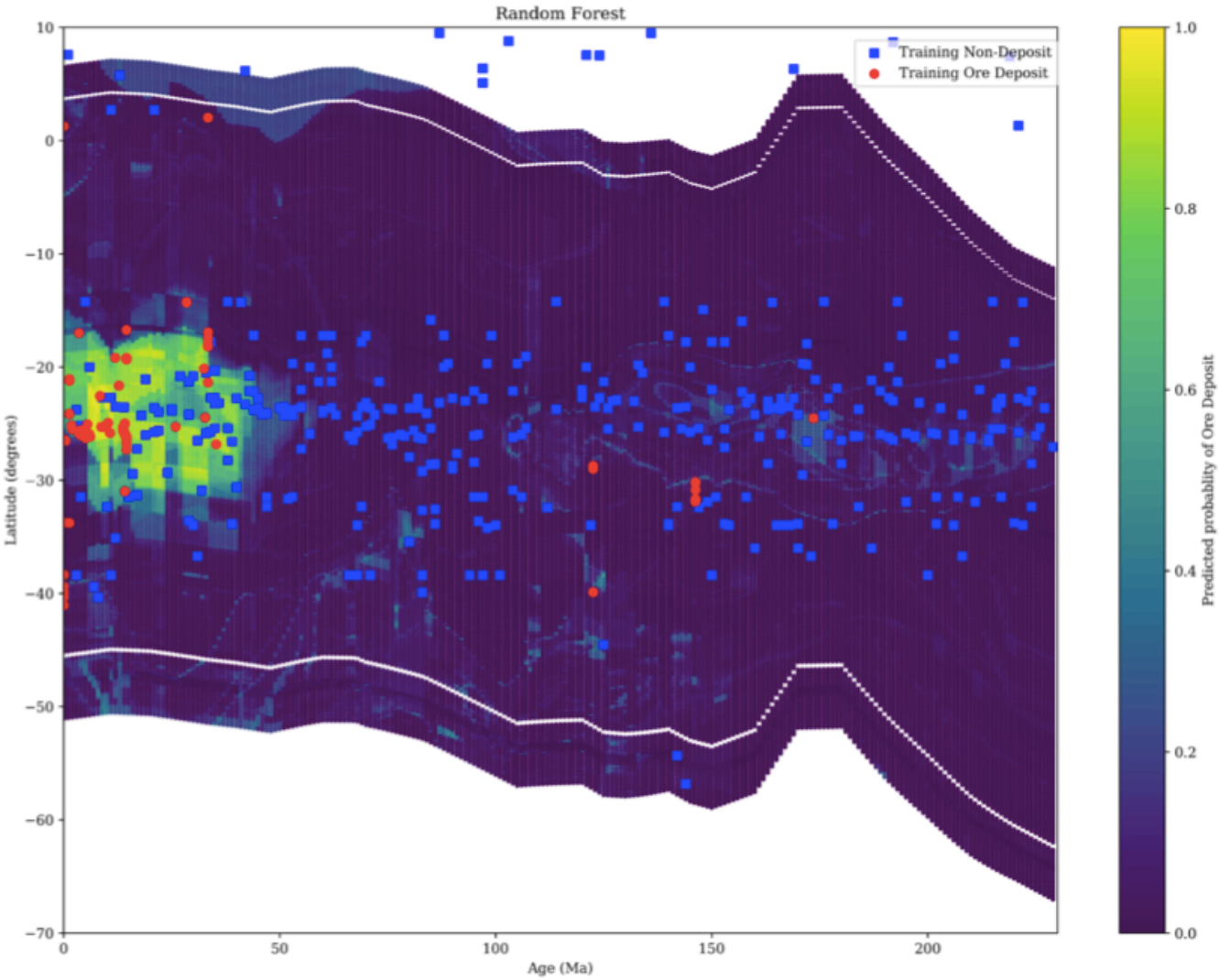

Figure 9. Random Forest - trained data, illustrating the predicted probability of each point across latitude and age as being an ore deposit. Source: EarthChem (2019), Benjamin et al. (2019).

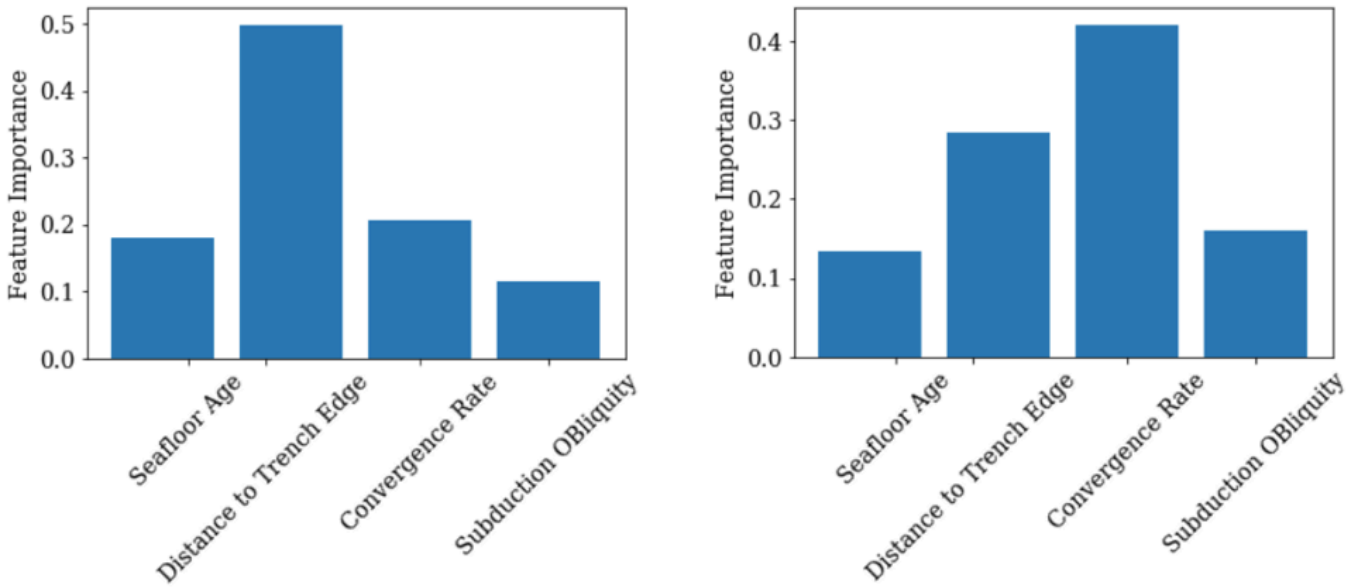

Figure 10. (left): Most significant parameters for determining the area of formation of tin ore deposits. Source: EarthChem (2019), Benjamin et al. (2019).

Figure 11. (right): Most significant parameters for determining the point of formation of tin ore deposits. Source: EarthChem (2019), Benjamin et al. (2019).

According to Figures 10 and 11, the most significant parameters vary when determining the area of formation and the point of formation of tin ore deposits. For the are of formation, the most significant parameter above all others is the Distance to Trench Edge, while for the point of formation, the most significant parameter is the Convergence Rate, closely followed by Distance to Trench Edge.

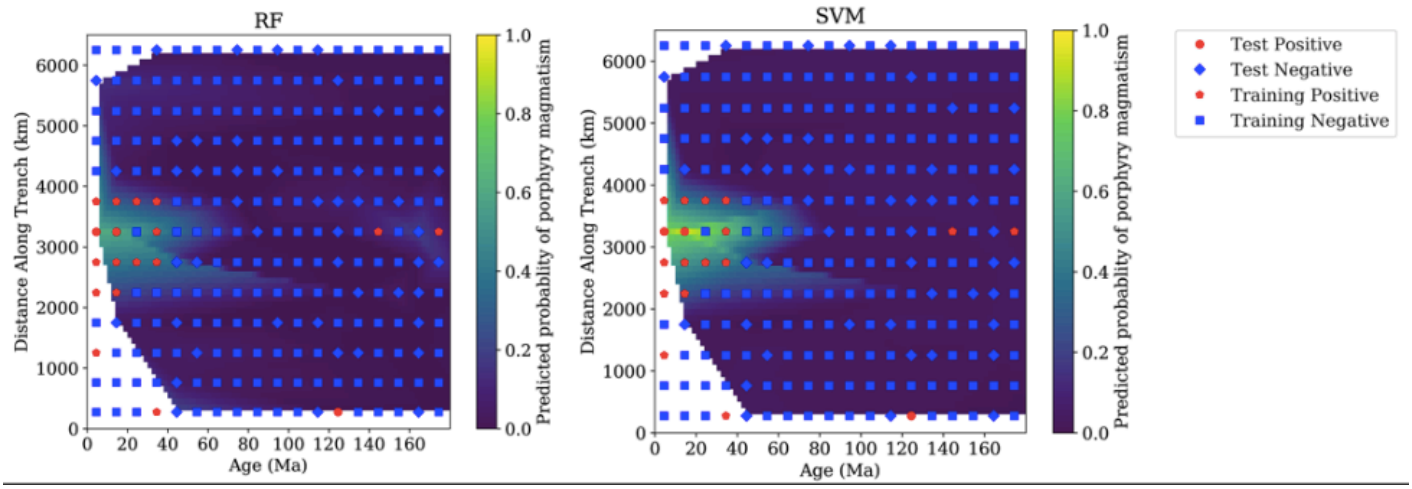

Figure 12. Prediction results of the Random Forest method: porphyry magmatism occurring through time and space. This is the partitioned data that is not restricted by time. Source: EarthChem (2019), Benjamin et al. (2019).Prediction results of the Support Vector Machine method: porphyry magmatism occurring through time and space. This is the partitioned data that is not restricted by time. Source: EarthChem (2019), Benjamin et al. (2019).

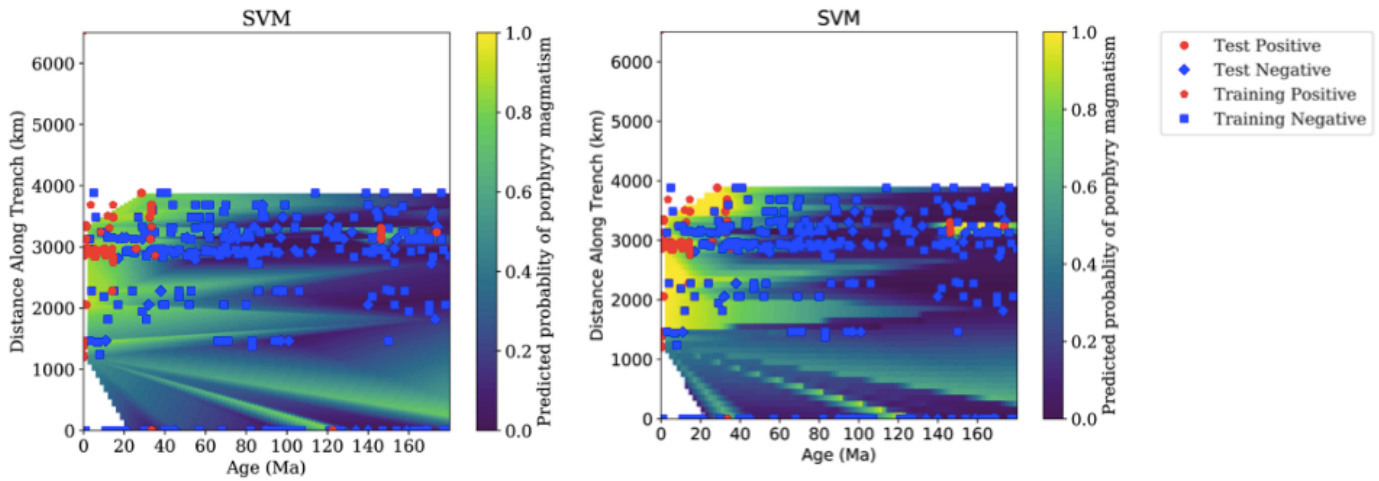

Figure 13: Prediction results of the Support Vector Machine method: porphyry magmatism occurring through time and space. This is the point data that is not restricted by time. Source: EarthChem (2019), Benjamin et al. (2019). Prediction results of the Support Vector Machine method: porphyry magmatism occurring through time and space. This is the point data that is not restricted by time. Source: EarthChem (2019), Benjamin et al. (2019).

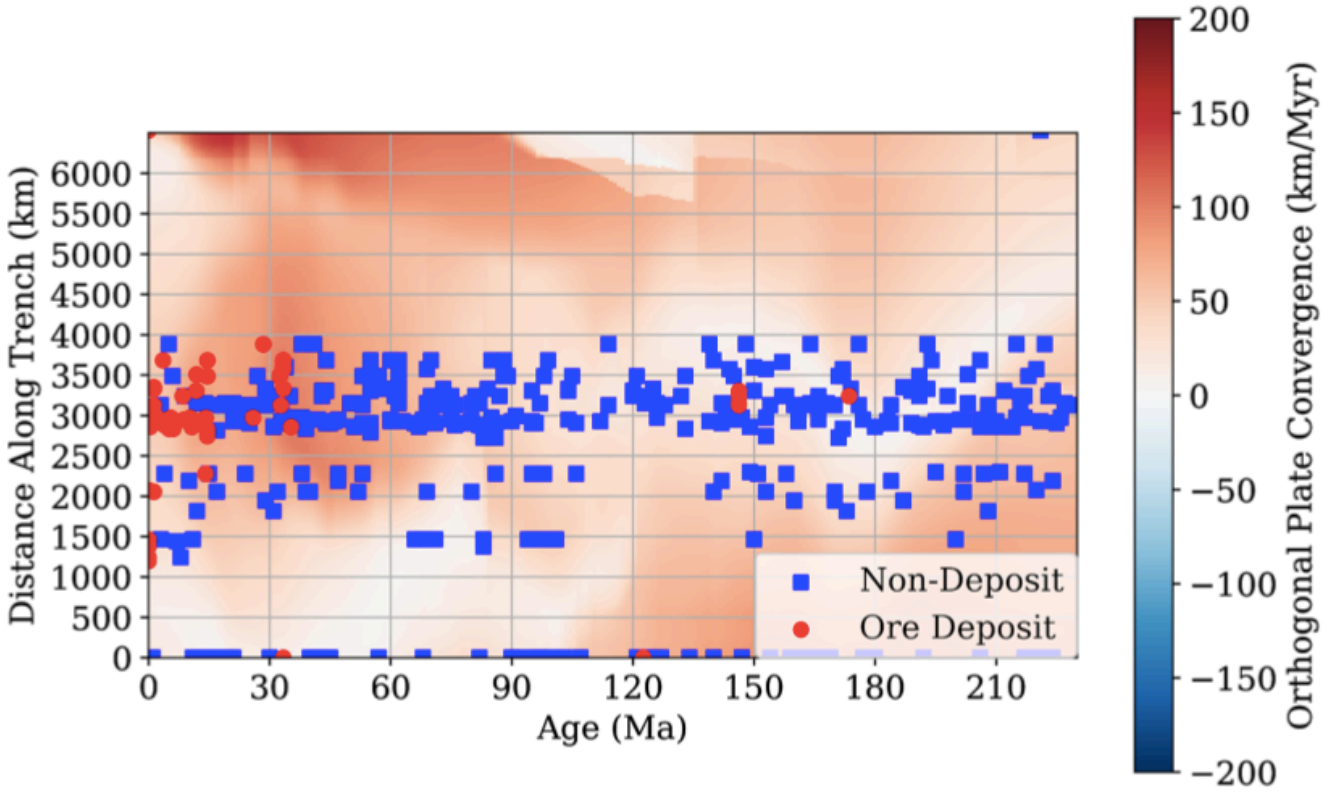

Figure 14: Plate Convergence Rate (km/Myr) plotted against the ages of non-ore and ore deposits and their Distance Along Trench (km).

Discussion

Porphy tin magmatism of the South American Bolivian Tin Belt can be evaluated on both spatial and temporal scales using computer science and machine learning. Initially there was a relationship between the tectonic environment and the deposits located in the Andes Mountains. The tin belt is located in the primary region of the Nazca Plate subduction zone (Figure 6). This is also where it is not uncommon to find other ore deposits including copper and lithium (EarthChem, 2019). The majority of the deposits in the Bolivian Tin Belt are no older than 40 Ma, which would be in the oligocene and miocene time periods. Each deposits is also centrally located between 2000 km and 4000 km along the trench, meaning there is a region of the South American Plate and Nazca Plate that is more highly active than other areas of contact. This is most likely due to the direction of plate movement, as the Nazca Plates most north-east section moves down and away towards the more central region of South America. This would increase the stress within the central region, thus having greater tectonic impacts. The location and time of tin ore formation (Figure 6) presented that the formations of tin were young and closest to the present day trench, while only five deposits existed between the 100 Ma and 200 Ma time period. It is unknown if these deposits were related to previous tectonic events or are the residual deposits from eluvial or alluvial processes. These methods of computer science to plot the age and location of the tin ore deposits proved worthwhile in determining the relation of the deposits to tectonic events. It is clear that the convergence of the Nazca Plate under the South American Plate has resulted in collisional tectonics.

The age of the subducting lithosphere was analysed (Figure 7) in respect to the deposits age and location along the trench. The plot concluded that the ore deposits which were aged between 0 Ma and 40 Ma where located within lithosphere aged no younger than 50 Ma and no older than 100 Ma. The younger deposits are associated with the lithospheric age associated with the oligocene time period.

The temporal relationship of the ore deposits was controlled by large-scale tertiary tectonics from the olgicoene time period (Mlynarczyk and Jones, 2005). The progressive breakup of the Farallon Plate into the Cocos Plate and Nazca Plate (20 Ma - 25 Ma) rapidly resulted in a orthogonal plate convergence that produced major tectonic and magmatic events in southeastern Peru and Bolivia (Mlynarczyk and Jones, 2005). These tectonic events initiated the increase of the trenchward velocity which provides support that there is a relationship between orogeny and ore-related magmatism (Mlynarczyk and Jones, 2005). The collision resulted in a focused horizontal compressional stress that created large scale failure in the region (Mlynarczyk and Jones, 2005).

Tin deposits were found to be most concentrated at the widest part of the Andes between 2000 km and 4000 km along the trench, mainly in the region of the western part of the eastern Cordillera. This part of the Andes is associated with a shallow subduction slab and an unusually thickened continental lithosphere and high heat flow (Romanyuk, 2009). A sub-Andean thrust fault formed (19 Ma) under the eastern Cordillera, causing rapid thickening of the crust in the eastern Andes (Romanyuk, 2009). Subsequent thinning of the overlying crust initiated migration of the deformation front and this process was accompanied by diverse magmatic activity, mainly ignimbrite complexes and basaltic flows, and destruction of the continental lithosphere is thought to contribute to ore mineralization in the Bolivian Tin Belt (Romanyuk, 2009).

The special relationship is obvious, as the central main feature of the the mountain range is the Central Andean tin belt (Mlynarczyk and Jones, 2005). The region is characterized by its low measure of volcanic activity and high mountains. Although the volcanism is low in the region, there is a relatively high heat flow caused by the subduction towards the west (Mlynarczyk and Jones, 2005). The inner arc, where fewer ore deposits are found is mainly sedimentary. However, there are still less significant tin ore deposits located in the inner arc from fluvial processes (Mlynarczyk and Jones, 2005). The tin belt is located in the belt region of the Andes which is a result of extreme compression which produced horizontal shortening and vertical thickening, which explains the great thickness of the lithosphere in the area (Mlynarczyk and Jones, 2005).

The initial tectonomagmatic parameters that were used in our analysis were seafloor age, segment length, slab length, distance to trench edge, subducting plate normal velocity, subducting plate parallel velocity, overriding plate normal velocity, overriding plate parallel velocity, convergence normal rate, convergence parallel rate, subduction polarity, subduction obliquity, and distance along margin. Of these, the four main parameters that were found to be the most robust predictors of tin deposit location where seafloor age, distance to trench edge, convergence normal rate and subduction obliquity. Individual parameters are not sufficient on their own as robust indicators of tin metal deposition locations, but the combination of the four most dominant parameters acting simultaneously prove to be more accurate locators of deposition sites.

Although some older deposits associated with relatively young seafloor were located, the majority of the tin deposits in our analysis appear to be of older oceanic lithospheres, between 50 Ma old and 60 Ma old, of the down-going slab. The thickening of the oceanic lithosphere as it gets older or further away from the spreading center and the relatively thick layer of sediments accumulated on the subducting plate may contribute more metals and volume to the melt generated by subduction of the oceanic lithosphere (Butterworth, 2016; Steinberg et al. 2016), (Sacks, 1983). The age of the Nazca subducting plate is limited to around 50 Ma to 60 Ma, compared with other sea floors exceeding 100 Ma old in other parts of the world (Müller, 2008; Sdrolias et al. 2008). This means the application of seafloor age, in this study, as indication of deposit location must be restricted to subducting plates of ages less than about

60 Ma, though it seems that sufficient volume of sediments and minerals contributing to the magma melt is a good result in tin porphyry deposition (Butterworth, 2016; Steinberg et al. 2016). It would be useful to do a similar analysis on older subducting slabs.

Other explanations for correlations with age may be the temperatures of the subducting slab, buoyancy differences between younger or older slabs (Sacks, 1983), increased flexure of older slabs (Butterworth, 2016; Steinberg et al. 2016; Capitanio, Morra et al. 2009) and dip angle of the subducting plate (Butterworth, 2016; Quevedo et al. 2012) There appears to be a strong correlation between distance from the trench edge and tin deposit locations. This parameter showed the highest importance rating. This may be explained by relationships between subducting slab angle and age and temperature of the subducting plate resulting in optimal depths reached by the oceanic lithosphere in the mantle resulting in the flux melting creating magmatism at some distances from the trench edge (Butterworth, 2016; Steinberg et al. 2016; Cross and Pilger, 1982; Schurr and Asch et al. 2003).

Increase in melt formation with increased normal convergence rate is likely to produce more ore deposits associated with magmatism (Butterworth, Steinberg et al. 2016; Ramos 2010). On the other hand, the more orthogonal the angle the slab approaches the convergence zone, the deeper the melt forms. This results in more likelihood of ore formation especially when coupled with high convergence rate (Butterworth, 2016; Steinberg et al. 2016). Therefore, subduction obliquity is a more key parameter of ore formation than normal convergence rate.

Our methods for classifying our dataset using two machine learning algorithms were successful, as shown by our five-fold cross validation scores. The Machine Learning algorithms we used, RF and SVM, together classified the parameters that were most correlated with ore formation. Although each parameter on its own is not sufficient to provide predictions on ore formation through magmatism, the combination of the four parameters most likely to predict ore formation simultaneously proves to be a more robust link between tectonomagmatic processes and ore formation location.

Conclusion

To conclude, machine learning and computer science were able to help in the process of comprehending a hefty compilation of data of the South American ore environment. There is a strong coupling between the tectonic events and ore deposits at the Nazca and South American Plate margin and the timestamp of the lithosphere and porphyry deposits support this analysis. Random forest and SVM of both the area and point related plots showed similar results overall, but had rated the parameters importance different in regards to their effect on tectonic related ore deposit formation. This was not surprising, as the area will have a different priority to an individual point depending on the location and age of the deposits.

It is clear form reviewed literature and this analysis that tin ore deposits are strongly related to tectonic events. Therefore, tin is even more precious than originally characterised, as large collisional events don't happen regularly within a human generation, but on a geological scale the last tectonic collision event is relatively middle aged. This poses a concern, as deposits existing now will most likely be the only deposits sene for millions of years. Although large tectonic events would also have great impacts on society and coastal regions many South Americans call home. This is why it is key to analyse the remaining natural resources left within the Earth's crust and manage the mining and use of those resources to plan accordingly for the furniture. Fortunately we live in an age with access to information and learning to allow other types of management that can aid in the consumption of natural resources, but society as a whole should not rely on these measures, as they have not proven to be completely integrated into society.

Further studies and analysis should include the comparison of tin ore to other related ore deposits in the same region. It might also be beneficial to compare the short term effectiveness of tectonic created ore deposits over alluvial tin ore deposits, and what process might effectively benefit society in the short term rather than on a million year scale.

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GEOL3888 Group Assignment - Final Project - Notebook Code

Tectonic Environments of South American Porphyry Iron Magmatism Through Time Revealed by Spatiotemporal Data Mining

Detailed below is the workflow followed in order to achieve the results explored and analysed within the formal technical report.

In [98]:
```
import sys
sys.path.append('/Users/Emily/geol3888/pygplates_rev12_python27_MacOS64')
```

In [99]:
```
#Last Updated 20180523
#Changed Appendix 3 Butterworth et al. 2016
#Tectonic environments of South American porphyry-copper magmatism through time revealed
#by spatio-temporal data mining
#Nathaniel Butterworth, Daniel Steinberg, Dietmar Müller, Simon Williams, Andrew Merdith,
#Stephen Hardy

#Use pylab to show figures
%pylab --no-import-all inline

#Import a few different tools and libraries. See Utils_coreg for more detail.
from Utils_coreg import *

#Import the tools for machine learning
from sklearn.model_selection import train_test_split
from sklearn.model_selection import cross_val_score
#from sklearn import cross_validation
from sklearn.svm import SVC
from sklearn.ensemble import RandomForestClassifier
from sklearn import preprocessing

#Import data processing tools
import pickle
import matplotlib.mlab as ml
```

```
Populating the interactive namespace from numpy and matplotlib
```

Each ore deposit with age in the Andes set is from Bertrand et al. (2014) is reconstructed to its geographical position at the time of its metallogenisis. We then 'coregister' the kinemtics associated with each ore deposit at that time in that location. We further reconstruct the ore deposits for 20 Myr prior to metallogenisis to capture the evolution of the kinematics that may lead to ore formation. We are then left with a matrix of parameters linked to each ore deposit through time (as listed below).

This notebook demonstrates how we take our data and apply machine learning (ML) algorithms to it. The notebook is split in two parts. Part I loads the data and wrangles it into an appropriate form for ML. Part II is the actual ML implementations and the results of the ML.

Data Wrangling

Here we developed the data. Using digitised pophyry copper deposits from Bertrand et al., 2014, we ran a coregistration, setting the pathway in Utils_coreg.py. We then loaded a pseudo-random set of 'copper deposits' to test against. We then read the data.

List of Variables

0 Present day longitude (degrees)

1 Present day latitude (degrees)

2 Reconstructed longitude (degrees)

3 Reconstructed latitude (degrees)

4 Age (Ma)

5 Time before mineralisation (Myr)

6 Seafloor age (Myr)

7 Segment length (km)

8 Slab length (km)

9 Distance to trench edge (km)

10 Subducting plate normal velocity (km/Myr)

11 Subducting plate parallel velocity (km/Myr)

12 Overriding plate normal velocity (km/Myr)

13 Overriding plate parallel velocity (km/Myr)

14 Convergence normal rate (km/Myr)

15 Convergence parallel rate (km/Myr)

16 Subduction polarity (degrees)

17 Subduction obliquity (degrees)

18 Distance along margin (km)

19 Subduction obliquity signed (radians)

20 Ore Deposits Binary Flag (1 or 0)

In [100]:
```
andeanIN=open('/Users/Emily/mineralexplorationcourse/Week10/Muller_
pickles/Muller_Bertrand_coregistered.pkl', 'rb')
#andeanIN=open('/Users/Emily/mineralexplorationcourse/Week10/Muller
_pickles/Muller_Bertrand_coregistered_random.pkl','rb')
#use a random case here for sanity check
andes=pickle.load(andeanIN)
andeanIN.close()

andeanIN=open('/Users/Emily/mineralexplorationcourse/Week10/Muller_
pickles/Muller_Bertrand_coregistered_random.pkl','rb')
andesRand=pickle.load(andeanIN)
andeanIN.close()

print andes.shape
print andesRand.shape

#Read in the present day subduction zone to trace back in time.
andeanIN=open('/Users/Emily/mineralexplorationcourse/Week10/Muller_
pickles/Muller_Bertrand_coregistered_sampleMuller0.pkl','rb')
andesPresent=pickle.load(andeanIN)
andeanIN.close()

print andesPresent.shape

print "loaded datasets"
```

```
(377, 1, 18)
(377, 1, 18)
(313, 230, 18)
loaded datasets
```

In [101]:
```
#Remove data that has zeros for everyhting (or just where the longi
tude 0)

clean=numpy.where(andes[:,0,1]!=0)
andesClean = cleanCondition(clean,andes)

clean=numpy.where(andesRand[:,0,1]!=0)
andesRandClean = cleanCondition(clean,andesRand)

#Muller 13Ma and 41Ma have issues along the trench,
#take the average of known good values for any points that did not
coregister.
for i in xrange(len(andesPresent[0,:,2])):
    for j in xrange(len(andesPresent[:,0,2])):
        if andesPresent[j,i,3]==0:
            andesPresent[j,i,:]=(andesPresent[j,i+1,:]+andesPresent
[j,i-1,:])/2
        #If there are nans, just replace them with the next closest
timestep
        for k in xrange(len(andesPresent[0,0,:])):
            if numpy.isnan(andesPresent[j,i,k]):
                print andesClean.shape, andes.shape
                print andesRandClean.shape, andesRand.shape
                print andesPresent.shape
```

```
(321, 1, 18) (377, 1, 18)
```

(344, 1, 18) (377, 1, 18)
(313, 230, 18)
(321, 1, 18) (377, 1, 18)
(344, 1, 18) (377, 1, 18)
(313, 230, 18)
(321, 1, 18) (377, 1, 18)
(344, 1, 18) (377, 1, 18)
(313, 230, 18)
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In [102]:

```
#Now add extra parameters to the datasets
print andesPresent.shape

#Add subduction obliquity
theta=numpy.arctan(andesPresent[:,:,15]/andesPresent[:,:,14])
print theta.shape
andesPresent2 = numpy.zeros((andesPresent.shape[0],andesPresent.sha
pe[1],andesPresent.shape[2]+2))
andesPresent2[:,:,:-2] = andesPresent
andesPresent2[:,:,-1]=theta
print andesPresent2.shape

#Add the distance along the track
distAlongTrack=numpy.cumsum(andesPresent[:,0,7])
tempDist=numpy.repeat(distAlongTrack,andesPresent2.shape[1])
tempDist=numpy.reshape(tempDist,(andesPresent2.shape[0],andesPresen
t2.shape[1]))

andesPresent2[:,:,-2]=tempDist

print andesPresent2.shape
```

```
(313, 230, 18)
(313, 230)
(313, 230, 20)
(313, 230, 20)
```

In [103]:

```
#Make an array that contains the list of points that match up with
the distance along
#the trench of the present day day

#Make an array of lonlats that we want to search in
lonlat = numpy.r_['1,2,0',andesPresent2[:,0,0],andesPresent2[:,0,1]
]

#The size of the region to find the closest point (in degrees)
region=10
```

```
##########################################
##Make this append to the andesClean data
#Make an emtpy array that stores the indexes of
indexArray=numpy.zeros((len(andesClean[:,0,0]),len(andesClean[0,:,0
])))

d = numpy.zeros((andesClean.shape[0],andesClean.shape[1],andesClean
.shape[2]+1))
d[:,:,:-1] = andesClean

#Loop through all the data in space and time
for ind,val in enumerate(andesClean[:,0,0]):
    for jind,valj in enumerate(andesClean[ind,:,0]):
        lonBirth=andesClean[ind,jind,0]
        latBirth=andesClean[ind,jind,1]

        #Now look up the nearest neighbor for each point
        index=coregPoint([lonBirth,latBirth],lonlat[:],region)

        if index=='inf':
            pass
        else:
            #and save the index and distance along the track
            indexArray[ind,jind]=index
            d[ind,jind,-1]=distAlongTrack[index]

#Add the subduction obliquity angle data and the ore deposit format
ion flag data
thetad=numpy.arctan(d[:,:,15]/d[:,:,14])
d2 = numpy.ones((d.shape[0],d.shape[1],d.shape[2]+2))
d2[:,:,:-2] = d
d2[:,:,-2]=thetad


##### Random data

##########################################
##Make this append to the andesRandClean data
#Make an emtpy array that stores the indexes of
g = len(andesRandClean[:,0,0])
v = len(andesRandClean[0,:,0])
print g
print v

indexArray=numpy.zeros((g,v))
print indexArray

d = numpy.zeros((andesRandClean.shape[0],andesRandClean.shape[1],an
desRandClean.shape[2]+1))
d[:,:,:-1] = andesRandClean

# print andesPresent2[:,0,7]
# print distAlongTrack
#Loop through all the data in space and time
for ind,val in enumerate(andesRandClean[:,0,0]):
    for jind,valj in enumerate(andesRandClean[ind,:,0]):
```

```
        lonBirth=andesRandClean[ind,jind,0]
        latBirth=andesRandClean[ind,jind,1]

        #Now look up the nearest neighbor for each point
        index=coregPoint([lonBirth,latBirth],lonlat[:],region)

        if index=='inf':
            pass
        else:
            #and save the index and distance along the track
            indexArray[ind,jind]=index
#             print ind,jind,index
            d[ind,jind,-1]=distAlongTrack[index]

#Add the subduction obliquity angle data and the ore deposit format
ion flag data
thetad=numpy.arctan(d[:,:,15]/d[:,:,14])
d2Rand = numpy.zeros((d.shape[0],d.shape[1],d.shape[2]+2))
d2Rand[:,:,:-2] = d
d2Rand[:,:,-2]=thetad


##############################################
#Combine to Random and Ore Deposit datasets
d3=numpy.concatenate([d2,d2Rand])

print andesClean.shape, d2.shape
print andesRandClean.shape, d2Rand.shape

print numpy.shape(d3)
```

```
344
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 [0.]
 [0.]
 [0.]]
(321, 1, 18) (321, 1, 21)
(344, 1, 18) (344, 1, 21)
(665, 1, 21)
```
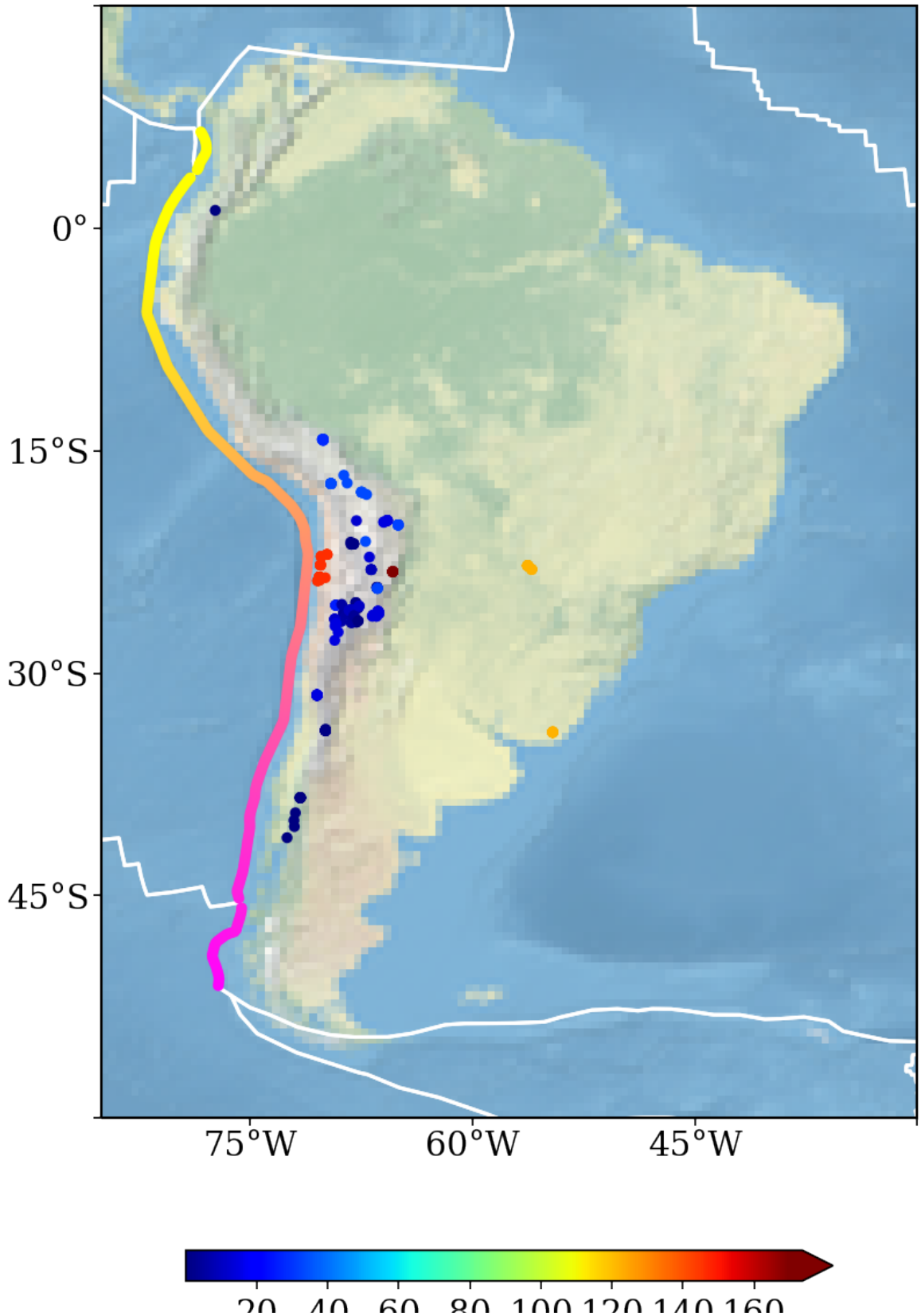

In [172]:

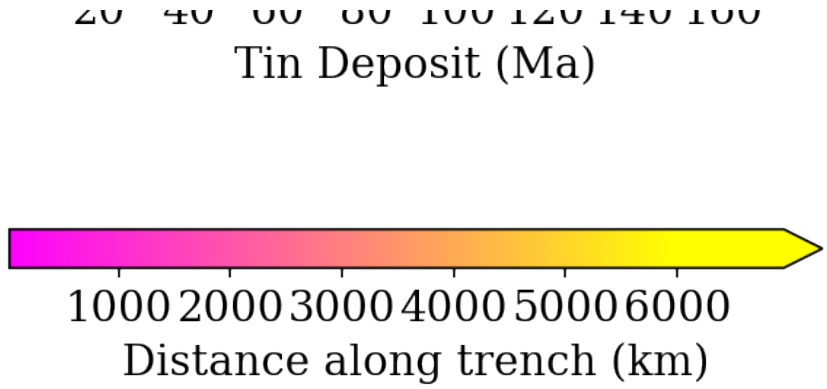
```
import cartopy.crs as ccrs

###Set up the figure
fig = plt.figure(figsize=(16,12),dpi=150)

ax = plt.axes(projection=ccrs.PlateCarree())
ax.stock_img()
ax.set_extent([-85, -30, -55, 10])
#ax.coastlines('50m', linewidth=0.8)


###Add the map grid lines and format them
gl = ax.gridlines(crs=ccrs.PlateCarree(), draw_labels=True,
                  linewidth=2, color='gray', alpha=0.5, linestyle='
-')

from cartopy.mpl.gridliner import LONGITUDE_FORMATTER, LATITUDE_FOR
MATTER
```

```
import matplotlib.ticker as mticker
from matplotlib import colorbar, colors

gl.xlabels_top = False
gl.ylabels_left = True
gl.ylabels_right = False
gl.xlines = False
gl.ylines = False
gl.xlocator = mticker.FixedLocator([-75,-60, -45,-30])
gl.ylocator = mticker.FixedLocator([-60, -45, -30, -15, 0,15])
ax.set_xticks([-75,-60, -45,-30])
ax.set_xticklabels([''])
ax.set_yticks([-60, -45, -30, -15, 0,15])
ax.set_yticklabels([''])
gl.xformatter = LONGITUDE_FORMATTER
gl.yformatter = LATITUDE_FORMATTER
#gl.xlabel_style = {'size': 15, 'color': 'gray'}
#gl.xlabel_style = {'color': 'black', 'weight': 'normal'}

print("Made base map")


print("Added topo")

###Plot shapefile polygon outlines
#Load in plate polygons for plotting
topologyFile='/Users/Emily/geol3888/pygplates_rev12_python27_MacOS6
4/Week10/Muller_export/topology_platepolygons_0.00Ma.shp'
[recs,shapes,fields,Nshp]=readTopologyPlatepolygonFile(topologyFile
)
for i, nshp in enumerate(range(Nshp)):
    if nshp!=35 and nshp!=36 and nshp!=23:
    #These are the plates that cross the dateline and cause
        #banding errors
        polygonShape=shapes[nshp].points
        poly=np.array(polygonShape)
        xh=poly[:,0]
        yh=poly[:,1]
        ax.plot(xh, yh, c='w',zorder=1)

print("Added shapes")

xh=andesPresent[:,0,0]
yh =andesPresent[:,0,1]
l2 = ax.scatter(xh, yh, 50, marker='.',c=distAlongTrack,cmap=plt.cm
.spring,zorder=3)
cbar=fig.colorbar(l2, ax=ax, orientation="horizontal", pad=0.1, fra
ction=0.06, shrink=0.3,extend='max')
cbar.set_clim(0, 6000)
cbar.set_label('Distance along trench (km)')

xh=andesClean[:,0,0]
yh =andesClean[:,0,1]
l2 = ax.scatter(xh, yh, 50, marker='.',c=andesClean[:,0,4],cmap=plt
.cm.jet,zorder=3)
cbar=fig.colorbar(l2, ax=ax, orientation="horizontal", pad=0.1, fra
ction=0.06, shrink=0.3,extend='max')
```

```
cbar.set_clim(0, 170)
cbar.set_label('Tin Deposit (Ma)')

print("Added deposit probability")

plt.show()
```

```
Made base map
Added topo
Added shapes
Added deposit probability
```





In [105]:
```
np.shape(andesPresent2)
```

Out[105]:
```
(313, 230, 20)
```

The following demonstrates this merged dataset, showing the cumulative sum of ditance along the orignial profile is known by the ore deposit data - each ore deposits needs to find its closest associated point along the trench.

In [107]:
```
#This is the dataset
d3[d3[:,0,-1]==1,0,18]
```

Out[107]:
```
array([2925.48178, 2925.48178, 2947.88818, 2947.88818, 2992.70211,
       3881.33212, 3881.33212, 3881.33212, 3881.33212, 3881.33212,
       3881.33212, 3881.33212, 3881.33212, 3881.33212, 3881.33212,
       3881.33212, 3127.15281, 3127.15281, 3127.15281, 3127.15281,
       3127.15281, 3127.15281, 3149.56253, 3149.56253, 3149.56253,
       3149.56253, 3149.56253, 3149.56253, 3149.56253, 3149.56253,
       3149.56253, 3149.56253, 3149.56253, 3149.56253, 3149.56253,
       3149.56253, 3149.56253, 3127.15281, 3127.15281, 3149.56253,
       3149.56253, 3149.56253, 3149.56253, 3149.56253, 3149.56253,
       3149.56253, 3149.56253, 3239.22521, 3239.22521, 3239.22521,
       3239.22521, 3239.22521, 3239.22521, 3306.48145, 3306.48145,
       3306.48145, 3306.48145, 3306.48145, 3306.48145, 3306.48145,
       3306.48145, 3306.48145, 2858.26488, 2858.26488, 2858.26488,
       2903.07576, 2903.07576, 2903.07576, 2903.07576, 2903.07576,
       2903.07576, 2903.07576, 2903.07576, 2903.07576, 2903.07576,
       2858.26488, 2858.26488, 2880.67013, 2880.67013, 2903.07576,
       2903.07576, 2925.48178, 2925.48178, 2970.29496, 3328.67191,
       3328.67191, 3328.67191, 3328.67191, 3351.03377, 3328.67191,
       3328.67191, 3328.67191, 3328.67191, 3328.67191, 3239.22521,
       3239.22521, 3239.22521, 3239.22521, 3239.22521, 3239.22521,
       3239.22521, 3239.22521, 3239.22521, 3239.22521, 3239.22521,
       1462.5077 , 1462.5077 , 1462.5077 , 1462.5077 , 1462.5077 ,
       1462.5077 , 1462.5077 , 1462.5077 , 1462.5077 , 1462.5077 ,
       1462.5077 , 1462.5077 , 1462.5077 , 1462.5077 , 1462.5077 ,
       1462.5077 , 2925.48178, 2925.48178, 2925.48178, 2925.48178,
       2925.48178, 2925.48178, 2925.48178, 2947.88818, 2947.88818,
       2947.88818, 2947.88818, 2947.88818, 2947.88818, 2903.07576,
       2947.88818, 2947.88818, 2947.88818, 2947.88818, 2947.88818,
       2947.88818, 2903.07576, 2947.88818, 2947.88818, 2947.88818,
       2903.07576, 2925.48178, 2903.07576, 2925.48178, 2925.48178,
       2925.48178, 2925.48178, 2925.48178, 2903.07576,    0.     ,
          0.     ,    0.     ,    0.     ,    0.     ,    0.     ,
```

```
   0.     ,    0.     ,    0.     ,    0.     ,    0.     ,
   0.     ,    0.     ,    0.     ,    0.     ,    0.     ,
   0.     , 2277.84282, 2277.84282, 2277.84282, 2277.84282,
2277.84282, 2277.84282, 2277.84282, 2277.84282, 2277.84282,
2277.84282, 2277.84282, 2277.84282, 2277.84282, 2277.84282,
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2277.84282, 2277.84282,    0.     ,    0.     ,    0.     ,
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   0.     ,    0.     ,    0.     ,    0.     ,    0.     ,
   0.     , 3239.22521, 3239.22521, 3239.22521, 3239.22521,
3239.22521, 2970.29496, 2970.29496, 2970.29496, 2970.29496,
2970.29496, 2835.86002, 2880.67013, 2903.07576, 2880.67013,
2992.70211, 2947.88818, 2858.26488, 2947.88818, 2858.26488,
2903.07576, 2903.07576, 2903.07576, 2903.07576, 2925.48178,
2925.48178, 2947.88818, 2835.86002, 2835.86002, 2903.07576,
2903.07576, 2858.26488, 2858.26488, 2858.26488, 2858.26488,
2970.29496, 2970.29496, 3127.15281, 3127.15281, 3127.15281,
3127.15281, 3127.15281, 3127.15281, 3127.15281, 3127.15281,
3127.15281, 3127.15281, 1195.8403 , 1240.55808, 2076.36222,
1440.16946, 1373.99822, 2053.97803, 2053.97803, 2053.97803,
2053.97803, 2053.97803, 2053.97803, 2053.97803, 2053.97803,
2053.97803, 2053.97803, 2053.97803, 2053.97803, 2053.97803,
6531.93433, 3574.31261, 3574.31261, 3574.31261, 3596.33241,
3596.33241, 3574.31261, 3328.67191, 3574.31261, 3618.35615,
3485.36702, 3485.36702, 3485.36702, 3485.36702, 3485.36702,
3485.36702, 3485.36702, 3485.36702, 3662.4238 , 3306.48145,
3507.54008, 3684.4676 , 3684.4676 , 3684.4676 , 3684.4676 ,
3684.4676 , 3684.4676 , 3684.4676 , 3684.4676 , 3684.4676 ,
3684.4676 , 3684.4676 ,    0.     ,    0.     , 2746.42098,
2791.05147, 2813.45555, 2835.86002, 3485.36702, 3485.36702,
3485.36702, 3485.36702, 3485.36702, 3485.36702, 3485.36702,
3485.36702])
```
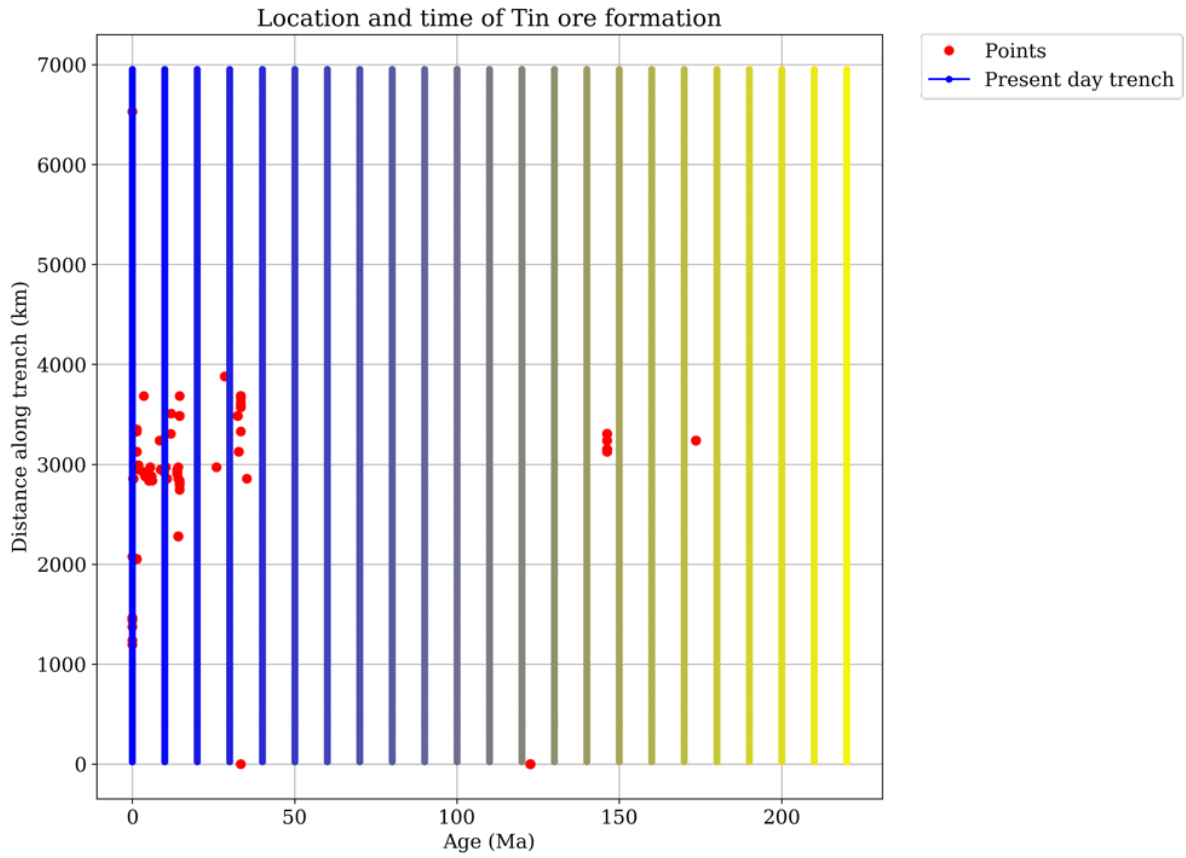

In [190]:

```
#Make a figure demonstrating this
fig = plt.figure(figsize=(10,10),dpi=300)
ax = fig.add_subplot(111)

#plot all the age and location along SAM of all the data points
ax.plot(d3[d3[:,0,-1]==1,0,4]+d3[d3[:,0,-1]==1,0,5],d3[d3[:,0,-1]==
1,0,18],'ro')

#Plot the present day trench through time
for i in xrange(0,230,10):
    mycolor=[(i)/230.0,(i)/230.0,1-(i)/230.0]
    plt.plot(andesPresent2[:,i,4]+andesPresent2[:,i,5],andesPresent
2[:,0,18],\
    #plt.plot(andesPresent[:,i,4]+andesPresent[:,i,5],range(len(and
esPresent[:,i,4])),\
             color=mycolor,markersize=10, markeredgecolor='None',ma
rker='.')

#Add details to plot
plt.legend(["Points","Present day trench"],
           bbox_to_anchor=(1.05, 1), loc=2, borderaxespad=0.,numpoi
nts=1)

plt.title('Location and time of Tin ore formation')
plt.ylabel('Distance along trench (km)')
plt.xlabel('Age (Ma)')

#plt.xlim([0,230])
#plt.ylim([0,6500])
#ax.set_xticks(np.arange(0,230,10))
#ax.set_yticks(np.arange(0,6500,500))
plt.grid()

plt.show()
```



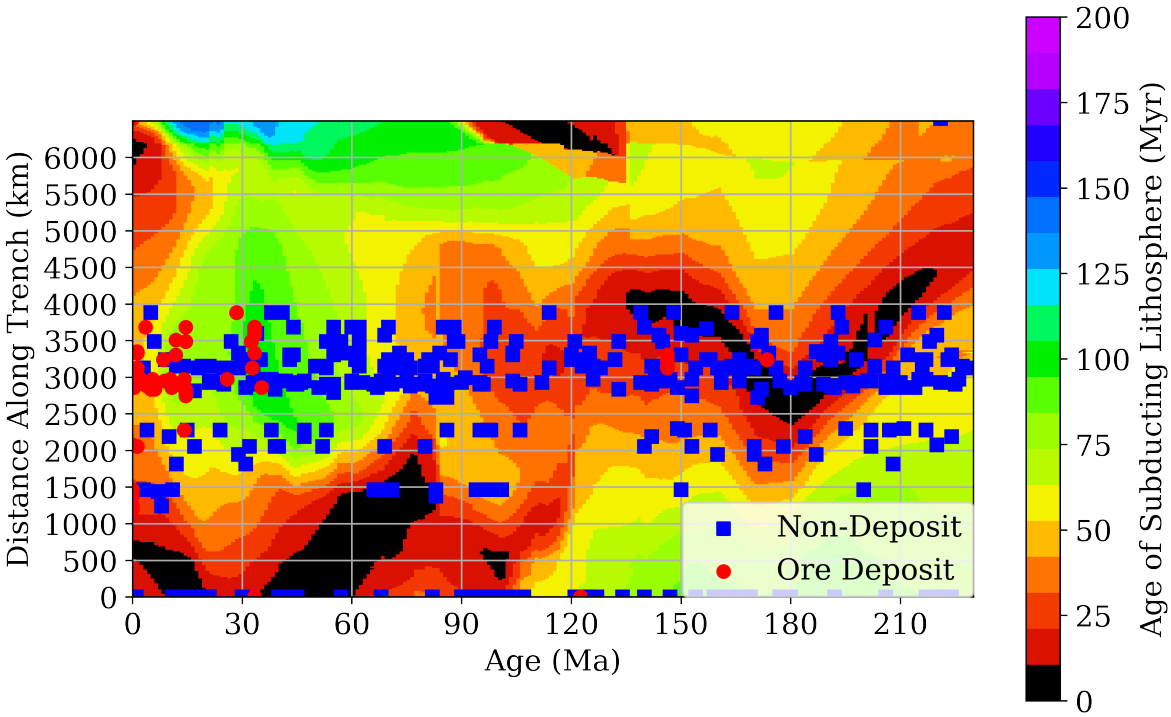
This demonstrates the data partitioned. We split the data into 500km by 10 Myr (these numbers are based on estimates for the sizes of porphyry deposits). Here, we focus on the tectonomagmatic parameters of each space and see if it produces an ore deposit.

In [176]:
```
#Plot the combined datasets through all time and space. And (more i
mportantly) save each
# partioned  segment of the data, stating whether there is an ore d
eposit or not

#Initiliase the figure
fig = plt.figure(figsize=(9,6),dpi=600)
ax = fig.add_subplot(111)

#Retrieve a colour map
age_cmap=colormap_age()

#Plot the dataset, change the dataset you want to show
plt.imshow(andesPresent2[:,0:230,6],\
           #extent=[0,170,andesPresent2[-1,0,18],andesPresent2[0,0,
18]],aspect=0.02,\
           extent=[0,230,6500,0],aspect=0.02,\
           cmap=age_cmap,vmin=0,vmax=200) #Seafloor age 6
#            cmap=plt.cm.RdBu_r,vmin=-200,vmax=200) #Convergence Ra
te 14
#            cmap=plt.cm.PuOr,vmin=-90,vmax=90) #Subduction Obliqui
ty 17 degs, 19 rads
           #cmap=plt.cm.rainbow) #Distance from Plate Boundary 9


#plt.clim(0,70)
```

```
plt.gca().invert_yaxis()
cbar=plt.colorbar()
cbar.location='bottom'
cbar.set_label('Age of Subducting Lithosphere (Myr)') #6
# cbar.set_label('Orthogonal Plate Convergence (km/Myr)') #14
# cbar.set_label('Subduction Obliquity (degrees)') #17 degs 19 sign
ed rads
# cbar.set_label('Distance to trench edge/plate boundary (km)') #9


#Make an empty array to store each segmented dataset
partionedData=[]

#Now plot where all the Ore deposits fall
#make an array for coloring the points
k=0

#Plot the non-deposit, 'random' data
data1=d3[d3[:,0,20]==0,0,4]+d3[d3[:,0,20]==0,0,5]
data2=d3[d3[:,0,20]==0,0,18]

for i in xrange(0,len(data1),1):
    #mycolor=[0.6,0.9,(i+0.1)/float(len(data1))]
    ax.plot(data1[i],data2[i],\
             color='b',marker='s',linestyle='None',lw=0.)

#Plot the ore deposit data
data1=d3[d3[:,0,20]==1,0,4]+d3[d3[:,0,20]==1,0,5]
data2=d3[d3[:,0,20]==1,0,18]

for i in xrange(0,len(data1),1):
    #mycolor=[(i+0.1)/float(len(data1)),(i+0.1)/float(len(data1)),(
i+0.1)/float(len(data1))]
    ax.plot(data1[i],data2[i],\
             color='r',marker='o',linestyle='None',lw=0.)

    #print d3[i,0,6], mycolor #Check with parameter colouring



##THIS IS WHERE THE SPATIO-TEMPORAL BIN PARAMETERS ARE SET

print "Number of spatial domains: ", len(xrange(0,6500,500))
print "Number of temporal domains: ",len(xrange(0,230,10))
print "Number of total domains: ", len(xrange(0,6500,500))*len(xran
ge(0,230,10))

#Change the extent of the next 2 for-loops and iterators to change
resolution of intervals and impose space-time restrictions
#Loop through the 6500km length of the Andean Margin in 500km incre
ments #max length is actually 6107km
for i in xrange(0,6100,500):
    j=i+500

    #Loop through all time in 10Myr increments, change here to rest
rict time
    for t1 in xrange(0,230,10):
```

```
        t2=t1+10

        #Extract just the parts of the data we want
        bin1=numpy.where(d3[:,0,18]>=i)
        andesTemp1 = cleanCondition(bin1,d3)
        bin2=numpy.where(andesTemp1[:,0,18]<j)
        andesTemp2 = cleanCondition(bin2,andesTemp1)
        bin3=numpy.where(andesTemp2[:,0,4]>=t1)
        andesTemp3 = cleanCondition(bin3,andesTemp2)
        bin4=numpy.where(andesTemp3[:,0,4]<t2)

        andesData = cleanCondition(bin4,andesTemp3)

        bin1=numpy.where(andesPresent2[:,0,18]>=i)
        andesTemp1 = cleanCondition(bin1,andesPresent2)
        bin2=numpy.where(andesTemp1[:,0,18]<j)
        andesTemp2 = cleanCondition(bin2,andesTemp1)

        andesProfile = andesTemp2[:,t1:t2,:]

        andesProfile = numpy.nanmean(numpy.nanmean(andesProfile,axi
s=0),axis=0)

        #Check if that domain has or deposit or not.
        if len(andesData) > 0:
            #If it does store a 1
            if andesData[0][0][-1]==1:
                partionedData.append(numpy.append(andesProfile,1))
            #If it does not store a 0
            else:
                partionedData.append(numpy.append(andesProfile,0))

        #If it does not store a 0
        else:
            partionedData.append(numpy.append(andesProfile,0))



#Label the plot
plt.ylabel('Distance Along Trench (km)')
plt.xlabel('Age (Ma)')
plt.xlim([0,230])
#plt.ylim([-50,10])
plt.ylim([0,6500])
ax.set_xticks(np.arange(0,230,30))
ax.set_yticks(np.arange(0,6500,500))
plt.grid()

#Make a legend
Z = [[-10,-10],[-10,-10]] #With dummy variables
p1=ax.scatter(Z[0],Z[1],marker='s',c='b')
p2=ax.scatter(Z[0],Z[1],marker='o',c='r')
ax.legend([p1,p2],["Non-Deposit","Ore Deposit"],
           bbox_to_anchor=(1, 0), loc=4, borderaxespad=0.,numpoints
=1)

plt.show()
```

```
Number of spatial domains:  13
Number of temporal domains:  23
Number of total domains:  299
```



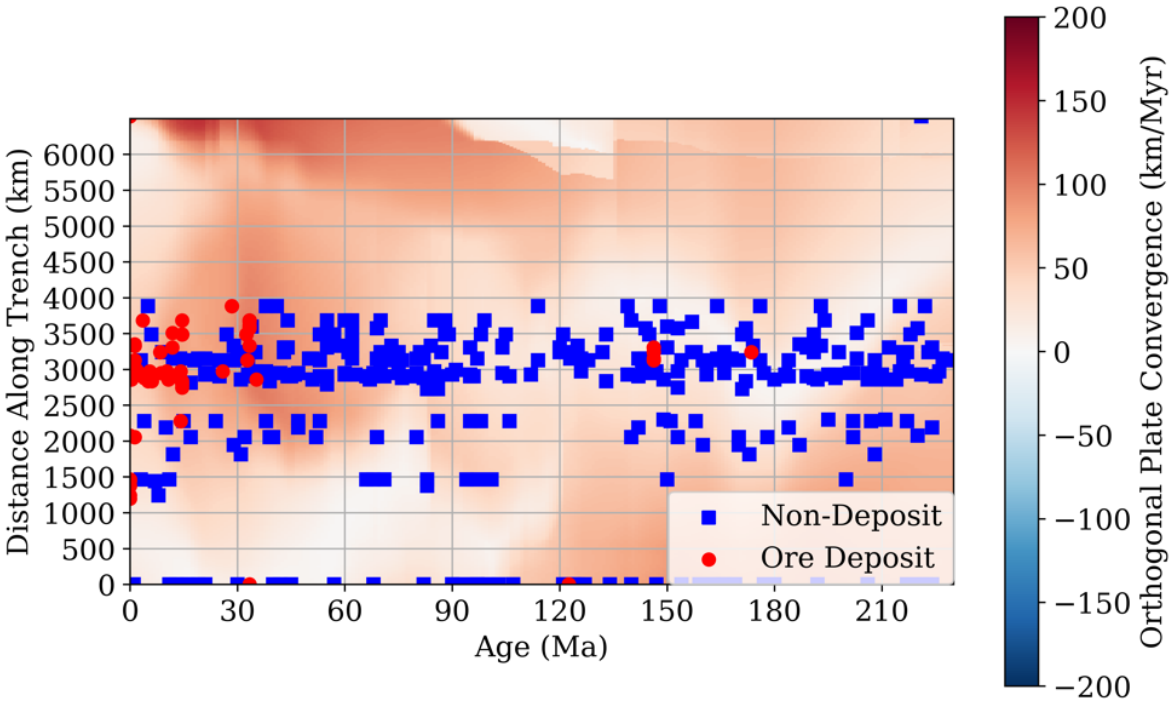
In [191]:

```
#Plot the combined datasets through all time and space. And (more i
mportantly) save each
# partioned  segment of the data, stating whether there is an ore d
eposit or not

#Initiliase the figure
fig = plt.figure(figsize=(9,6),dpi=600)
ax = fig.add_subplot(111)

#Retrieve a colour map
age_cmap=colormap_age()

#Plot the dataset, change the dataset you want to show
plt.imshow(andesPresent2[:,0:230,6],\
           #extent=[0,170,andesPresent2[-1,0,18],andesPresent2[0,0,
18]],aspect=0.02,\
           extent=[0,230,6500,0],aspect=0.02,\
          # cmap=age_cmap,vmin=0,vmax=200) #Seafloor age 6
        cmap=plt.cm.RdBu_r,vmin=-200,vmax=200) #Convergence Rate 14
#            cmap=plt.cm.PuOr,vmin=-90,vmax=90) #Subduction Obliqui
ty 17 degs, 19 rads
           #cmap=plt.cm.rainbow) #Distance from Plate Boundary 9


#plt.clim(0,70)
plt.gca().invert_yaxis()
cbar=plt.colorbar()
cbar.location='bottom'
#cbar.set_label('Age of Subducting Lithosphere (Myr)') #6
cbar.set_label('Orthogonal Plate Convergence (km/Myr)') #14
# cbar.set_label('Subduction Obliquity (degrees)') #17 degs 19 sign
```

```
ed rads
# cbar.set_label('Distance to trench edge/plate boundary (km)') #9


#Make an empty array to store each segmented dataset
partionedData=[]

#Now plot where all the Ore deposits fall
#make an array for coloring the points
k=0

#Plot the non-deposit, 'random' data
data1=d3[d3[:,0,20]==0,0,4]+d3[d3[:,0,20]==0,0,5]
data2=d3[d3[:,0,20]==0,0,18]

for i in xrange(0,len(data1),1):
    #mycolor=[0.6,0.9,(i+0.1)/float(len(data1))]
    ax.plot(data1[i],data2[i],\
             color='b',marker='s',linestyle='None',lw=0.)

#Plot the ore deposit data
data1=d3[d3[:,0,20]==1,0,4]+d3[d3[:,0,20]==1,0,5]
data2=d3[d3[:,0,20]==1,0,18]

for i in xrange(0,len(data1),1):
    #mycolor=[(i+0.1)/float(len(data1)),(i+0.1)/float(len(data1)),(
i+0.1)/float(len(data1))]
    ax.plot(data1[i],data2[i],\
             color='r',marker='o',linestyle='None',lw=0.)

    #print d3[i,0,6], mycolor #Check with parameter colouring



##THIS IS WHERE THE SPATIO-TEMPORAL BIN PARAMETERS ARE SET

print "Number of spatial domains: ", len(xrange(0,6500,500))
print "Number of temporal domains: ",len(xrange(0,230,10))
print "Number of total domains: ", len(xrange(0,6500,500))*len(xran
ge(0,230,10))

#Change the extent of the next 2 for-loops and iterators to change
resolution of intervals and impose space-time restrictions
#Loop through the 6500km length of the Andean Margin in 500km incre
ments #max length is actually 6107km
for i in xrange(0,6100,500):
    j=i+500

    #Loop through all time in 10Myr increments, change here to rest
rict time
    for t1 in xrange(0,230,10):
        t2=t1+10

        #Extract just the parts of the data we want
        bin1=numpy.where(d3[:,0,18]>=i)
        andesTemp1 = cleanCondition(bin1,d3)
        bin2=numpy.where(andesTemp1[:,0,18]<j)
```

```
        andesTemp2 = cleanCondition(bin2,andesTemp1)
        bin3=numpy.where(andesTemp2[:,0,4]>=t1)
        andesTemp3 = cleanCondition(bin3,andesTemp2)
        bin4=numpy.where(andesTemp3[:,0,4]<t2)

        andesData = cleanCondition(bin4,andesTemp3)

        bin1=numpy.where(andesPresent2[:,0,18]>=i)
        andesTemp1 = cleanCondition(bin1,andesPresent2)
        bin2=numpy.where(andesTemp1[:,0,18]<j)
        andesTemp2 = cleanCondition(bin2,andesTemp1)

        andesProfile = andesTemp2[:,t1:t2,:]

        andesProfile = numpy.nanmean(numpy.nanmean(andesProfile,axi
s=0),axis=0)

        #Check if that domain has or deposit or not.
        if len(andesData) > 0:
            #If it does store a 1
            if andesData[0][0][-1]==1:
                partionedData.append(numpy.append(andesProfile,1))
            #If it does not store a 0
            else:
                partionedData.append(numpy.append(andesProfile,0))

        #If it does not store a 0
        else:
            partionedData.append(numpy.append(andesProfile,0))



#Label the plot
plt.ylabel('Distance Along Trench (km)')
plt.xlabel('Age (Ma)')
plt.xlim([0,230])
#plt.ylim([-50,10])
plt.ylim([0,6500])
ax.set_xticks(np.arange(0,230,30))
ax.set_yticks(np.arange(0,6500,500))
plt.grid()

#Make a legend
Z = [[-10,-10],[-10,-10]] #With dummy variables
p1=ax.scatter(Z[0],Z[1],marker='s',c='b')
p2=ax.scatter(Z[0],Z[1],marker='o',c='r')
ax.legend([p1,p2],["Non-Deposit","Ore Deposit"],
           bbox_to_anchor=(1, 0), loc=4, borderaxespad=0.,numpoints
=1)

plt.show()
```

```
Number of spatial domains:  13
Number of temporal domains:  23
Number of total domains:  299
```



In [177]:

```
#Convert to a numpy array for easier manipulation and plotting
aaa=numpy.array(partionedData)

print "Shape of data array: ", aaa.shape

#Number of 'positive' and 'negative' examples
print "Positive (deposits) examples: ",np.shape(aaa[aaa[:,20]==1,:]
)
print "Negative (non-deposits) examples: ",np.shape(aaa[aaa[:,20]==
0,:])

#Check for NAN..
print "Are there NANs?", numpy.isnan(numpy.sum(aaa))
```

```
Shape of data array:  (299, 21)
Positive (deposits) examples:  (18, 21)
Negative (non-deposits) examples:  (281, 21)
Are there NANs? False
```

PART II

Machine Learning

Now we use datasets to figure out what tectonomagmatic parameters are related to ore formation. Support Vector Machines and Random Forrest classification methods are used. We explore two methods of data analysis:

```
- Looking at the general area of ore formation
- Considering each ore formation point individually
```

Area of Formation (Partitioned Data)

Firstly, we split the data into testing and trainig sets.

```
- Within the training set we learn which parameters are important
- Within the testing set we test the validity of this
```

In [178]:

```
#Put the data into the correct format

#Get the parameters we want to include in the ML, indicies are from
the List of Variables
#as many as you want or as few as want - think about 2, maybe seafl
oor age/convergence
params=[6,9,14,17]
# params=[6,9,10,11,12,13,14,15,16,17]
datalength=len(params)

## Recombine the features and the classification vectors. #Save the
temporal-spatial parameters too for plotting purposes.
andesData = numpy.c_[preprocessing.scale(aaa[:,params]),aaa[:,5],aa
a[:,18],aaa[:,20]]

##OR

#Make a dataset for cross validation
#andesTraining = d3[:,0,:]
#Time Restricted Set
# andesTraining=d3[d3[:,0,4]<70,0,:]
#andesData = numpy.c_[preprocessing.scale(andesTraining[:,params]),
andesTraining[:,4],andesTraining[:,18],andesTraining[:,20]]

#Do a 80/20 split of the data  to be used to make an example fit of
the data
andesTrain, andesTest,  = train_test_split(\
       andesData, test_size=0.2, random_state=1)

print "Shape of data array: ", andesData.shape
```

```
Shape of data array:  (299, 7)
```

In [179]:

```
print 'Make the classifiers'
print 'RF...'
#create and train the random forest
#multi-core CPUs can use: rf = RandomForestClassifier(n_estimators=
100, n_jobs=2)
#n_estimators use between 64-128 doi: 10.1007/978-3-642-31537-4_13
rf = RandomForestClassifier(n_estimators=128, n_jobs=1,class_weight
=None).fit(andesData[:,0:datalength],andesData[:,-1])
print "Done RF"
scores = cross_val_score(rf, andesData[:,0:datalength],andesData[:,
-1], cv=10)
print "RF Scores: ",scores
print "SCORE Mean: %.2f" % np.mean(scores), "STD: %.2f" % np.std(sc
ores)


print 'SVC...'
clf = SVC(probability=True,class_weight=None).fit(andesData[:,0:dat
alength],andesData[:,-1])
print "Done SVC"
scores = cross_val_score(clf, andesData[:,0:datalength],andesData[:
,-1], cv=10)
print "SVM/SVC Scores: ",scores
print "SCORE Mean: %.2f" % np.mean(scores), "STD: %.2f" % np.std(sc
ores)
```

```
Make the classifiers
RF...
Done RF
RF Scores:  [0.93548387 0.93333333 0.96666667 0.93333333 0.9666666
7 1.
 0.93333333 0.96666667 1.         0.96551724]
SCORE Mean: 0.96 STD: 0.02
SVC...
Done SVC
SVM/SVC Scores:  [0.93548387 0.93333333 0.93333333 0.9        0.96
666667 1.
 0.93333333 1.         1.         0.96551724]
SCORE Mean: 0.96 STD: 0.03
```

In [180]:
```
andeanIN=open('/Users/Emily/mineralexplorationcourse/Week10/Muller_
pickles/Muller_Bertrand_coregistered_sampleMuller0.pkl','rb')


#This sets the output names, change for appropriate timestep
prefix="0"

andesPresent=pickle.load(andeanIN)
andeanIN.close()

#Now add extra parameters to the datasets
print andesPresent.shape

for i in xrange(len(andesPresent[0,:,2])):
    for j in xrange(len(andesPresent[:,0,2])):
        if andesPresent[j,i,3]==0:
            andesPresent[j,i,:]=(andesPresent[j,i+1,:]+andesPresent
[j,i-1,:])/2
        #If there are nans, just replace them with the next closest
timestep
        for k in xrange(len(andesPresent[0,0,:])):
            if numpy.isnan(andesPresent[j,i,k]):
                andesPresent[j,i,k]=andesPresent[j,i+1,k]


#Add subduction obliquity
theta=numpy.arctan(andesPresent[:,:,15]/andesPresent[:,:,14])
print theta.shape
andesPresent2 = numpy.zeros((andesPresent.shape[0],andesPresent.sha
pe[1],andesPresent.shape[2]+2))
andesPresent2[:,:,:-2] = andesPresent
andesPresent2[:,:,-1]=theta
print andesPresent2.shape

#Add the distance along the track
distAlongTrack=numpy.cumsum(andesPresent[:,0,7])
tempDist=numpy.repeat(distAlongTrack,andesPresent2.shape[1])
tempDist=numpy.reshape(tempDist,(andesPresent2.shape[0],andesPresen
t2.shape[1]))

andesPresent2[:,:,-2]=tempDist

print andesPresent2.shape
```

```
(313, 230, 18)
(313, 230)
(313, 230, 20)
(313, 230, 20)
```

In [181]:
```
aaa=andesPresent2.reshape(len(andesPresent2[:,0,0])*len(andesPresen
t2[0,:,0]),len(andesPresent2[0,0,:]))
print aaa.shape

andesSuite = numpy.c_[preprocessing.scale(aaa[:,params]),\
                      aaa[:,0],aaa[:,1],\
                      aaa[:,2],aaa[:,3],\
                      aaa[:,5],aaa[:,18]]
```

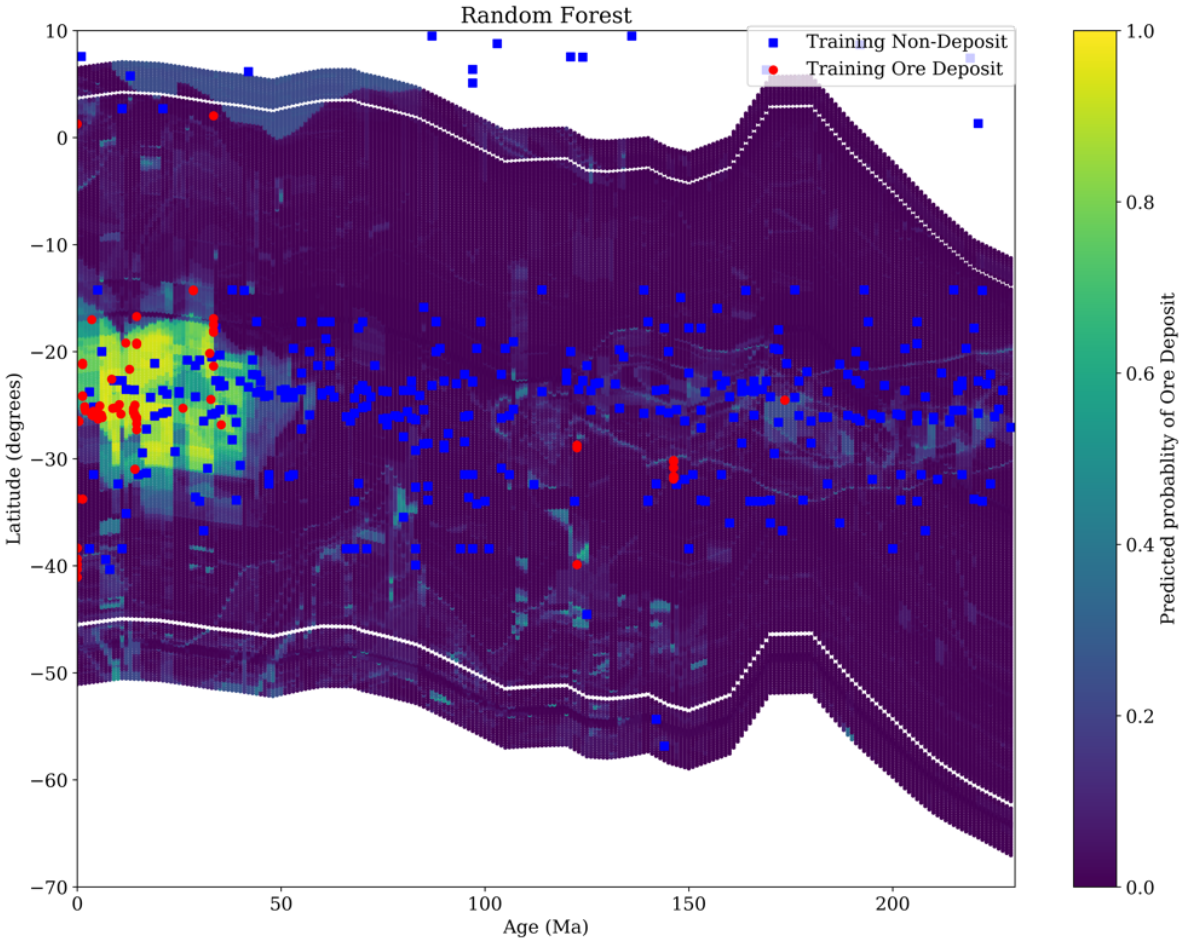
```
(71990, 20)
```

In [182]:
```
#Apply the trained ML to our gridded data to determine the probabil
ities at each of the points
print 'RF...'
pRF=numpy.array(rf.predict_proba(andesSuite[:,0:datalength]))
print "Done RF"

print 'SVC...'
pSVC=numpy.array(clf.predict_proba(andesSuite[:,0:datalength]))
print "Done SVC"
```

```
RF...
Done RF
SVC...
Done SVC
```

In [183]:
```
#Save out the grids for all of the timesteps.
#And make a figure
fig = plt.figure(figsize=(16,12),dpi=600)
ax = fig.add_subplot(111)

#Now because the data was formatted to a long list for the ML and w
e want individual timesteps
# we can loop through each timestep to output each timeslice indici
dually
for t in xrange(230):
    #Pull out just the current time
    firstInd=(andesSuite[:,-2] < (t+1))
    secondInd=(andesSuite[:,-2] > (t-1))
    finalInd=numpy.all([secondInd,firstInd],axis=0)

    andesTime=andesSuite[finalInd,:]

    #RF
    #Find the probability for these times
    proba = pRF[finalInd,1]
    #Save out lat, lon, and probability
    outputfile = "probgrids/probgrid"+prefix+"RF_"+str(t)+".xyz"
#     numpy.savetxt(outputfile,(numpy.c_[andesTime[:,-4],andesTime[
:,-3], proba]),delimiter=" ",fmt='%1.5f')

    #And plot it
    plt.scatter(andesTime[:,-2],andesTime[:,-3],c=proba,s=10,marker
='o',edgecolor='none')

    #SVC repeat as above
```

```
    proba = pSVC[finalInd,1]
    outputfile = "probgrids/probgrid"+prefix+"SVC_"+str(t)+".xyz"
#     numpy.savetxt(outputfile,(numpy.c_[andesTime[:,-4],andesTime[
:,-3], proba]),delimiter=" ",fmt='%1.5f')

#     plt.scatter(andesTime[:,-2],andesTime[:,-3],c=proba,s=10,mark
er='o',edgecolor='none')

    #scale the colour at each step for our plot
    plt.clim([0,1])


#Just for colorbar,
firstInd=(andesSuite[:,-2] < (t))
secondInd=(andesSuite[:,-2] > (t-2))
finalInd=numpy.all([secondInd,firstInd],axis=0)
andesTime=andesSuite[finalInd,:]
proba = pRF[finalInd,1]
plt.scatter(andesTime[:,-2],andesTime[:,-3],c=proba,s=10,marker='o'
,edgecolor='none')
cbar=plt.colorbar()
cbar.set_label('Predicted probablity of Ore Deposit')
plt.clim([0,1])


#Plot the non-deposit data
data1=d3[d3[:,0,20]==0,0,4]
data2=d3[d3[:,0,20]==0,0,3]

plt.scatter(data1,data2,c='b',marker='s')


#Plot the ore-deposit data
data1=d3[d3[:,0,20]==1,0,4]
data2=d3[d3[:,0,20]==1,0,3]

plt.scatter(data1,data2,c='r',marker='o')


#Add details to the plot
plt.title('Random Forest')
# plt.title('SVC/SVM')
plt.ylabel('Latitude (degrees)')
plt.xlabel('Age (Ma)')
plt.xlim([0,230])
plt.ylim([-70,10])


#Make a legend
Z = [[-10,-10],[-10,-10]] #With dummy variables
p1=ax.scatter(Z[0],Z[1],marker='s',c='b')
p2=ax.scatter(Z[0],Z[1],marker='o',c='r')
ax.legend([p1,p2],["Training Non-Deposit","Training Ore Deposit"],
           bbox_to_anchor=(1, 0.935), loc=4, borderaxespad=0.,numpo
ints=1)

plt.show()
```



SVM

Use Support Vector Machines to learn which parameters are important.

In [184]:

```
#Make the classifier
clf = SVC(probability=True,verbose=True,cache_size=1000,class_weigh
t=None)


#Now make a single classification for plotting and typicla results
#Train the classifier by fitting the parameters (features) to known
results (targets/classes)
clf.fit(andesTrain[:,0:-3], andesTrain[:,-1])

print "Prediction-testing set (expected result):"
print andesTest[:,-1]

print "Prediction of test (actual result):"
print clf.predict(andesTest[:,0:-3])

#Save the values of prediction
p=numpy.array(clf.predict_proba(andesTest[:,0:-3]))

#Get a single score out for the data
svmParams=clf.score(andesTest[:,0:-3], andesTest[:,-1])
print "Single result:"
print svmParams

# print clf.support_vectors_

###
#Now get a cross-fold validation score using all subsets of the dat
a
scores = cross_val_score(clf, andesData[:,0:-3], andesData[:,-1], c
v=5)

print "Cross fold validation results:"
print scores

#print clf.n_support_
```

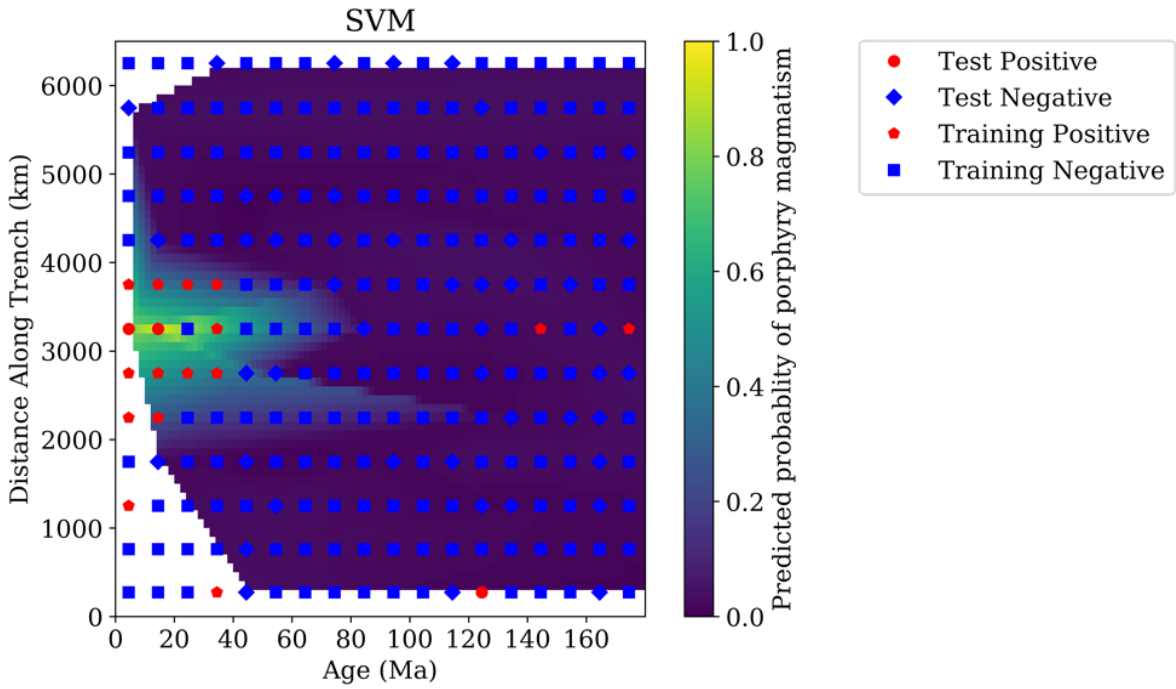
```
[LibSVM]Prediction-testing set (expected result):
[0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 1.
0. 0.
 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 1. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0.
 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 1.]
Prediction of test (actual result):
[0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0.
 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 1. 0. 0. 0. 0. 0. 0. 0. 0.
0. 0.
 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 1.]
Single result:
0.9833333333333333
[LibSVM][LibSVM][LibSVM][LibSVM][LibSVM]Cross fold validation resu
lts:
[0.93442623 0.95       0.98333333 0.96610169 0.96610169]
```

Support Vector Machines Typical Result

In [185]:
```
#Make some plots of typical results

#Create vectors of the prediced and actual results
subset=andesTrain[andesTrain[:,-1]==1]
subsetpredict=andesTest[andesTest[:,-1]==1]
subsetNegative=andesTrain[andesTrain[:,-1]==0]
subsetpredictNegative=andesTest[andesTest[:,-1]==0]

#Create a time-space map showing when and where along the margin an
ore deposit may have
#formed

#Create a grid to map the ML results to
grid_x, grid_y = np.meshgrid(np.linspace(0,200,100),np.linspace(0,6
500,65))
#Retrieve the ML scores
values = p[:,1].flatten()
print "Number of points used for testing: ", np.shape(values)

#Now grid the data
grid_z1 = ml.griddata(andesTest[:,-3].flatten(),\
                      andesTest[:,-2].flatten(),\
                      values, grid_x, grid_y,interp='linear')

print "Shape of grid:", np.shape(grid_z1)

#Plot the new grid
fig = plt.figure(figsize=(8,6),dpi=600)
plt.imshow(grid_z1,origin='lower',\
           extent=[0,200,0,6500],aspect=0.03)

font = {'family' : 'serif',
        'weight' : 'normal',
        'size'   : 14}

plt.rc('font', **font)

cbar=plt.colorbar()
cbar.set_label('Predicted probablity of porphyry magmatism')


#Plot each of the result vectors
#Plot the testing data
p1,=plt.plot(subsetpredict[:,-3],subsetpredict[:,-2],'ro')
p2,=plt.plot(subsetpredictNegative[:,-3],subsetpredictNegative[:,-2
],'bD')

#Plot the training data
p3,=plt.plot(subset[:,-3],subset[:,-2],'rp')
p4,=plt.plot(subsetNegative[:,-3],subsetNegative[:,-2],'bs')

#Create the legend
```

```
plt.legend([p1,p2,p3,p4],\
           ["Test Positive","Test Negative","Training Positive","Tr
aining Negative"],
           bbox_to_anchor=(2, 1), loc=1, borderaxespad=0.,numpoints
=1)

#Adjust the plot
plt.clim([0,1])
plt.xlim([0,180])
plt.ylim([0,6500])
ax = plt.axes()
ax.set_xticks(np.arange(0,180,20))
ax.set_yticks(np.arange(0,6500,1000))

plt.ylabel('Distance Along Trench (km)')
plt.xlabel('Age (Ma)')
plt.title('SVM')

plt.show()

print "Five-fold cross validation scores: ", scores
print 'SCORE Mean: %.2f' % np.mean(scores), 'STD: %.2f' % np.std(sc
ores)
```

```
Number of points used for testing:  (60,)
Shape of grid: (65, 100)
```




```
Five-fold cross validation scores:  [0.93442623 0.95        0.98333
333 0.96610169 0.96610169]
SCORE Mean: 0.96 STD: 0.02
```

Random Forest Classification

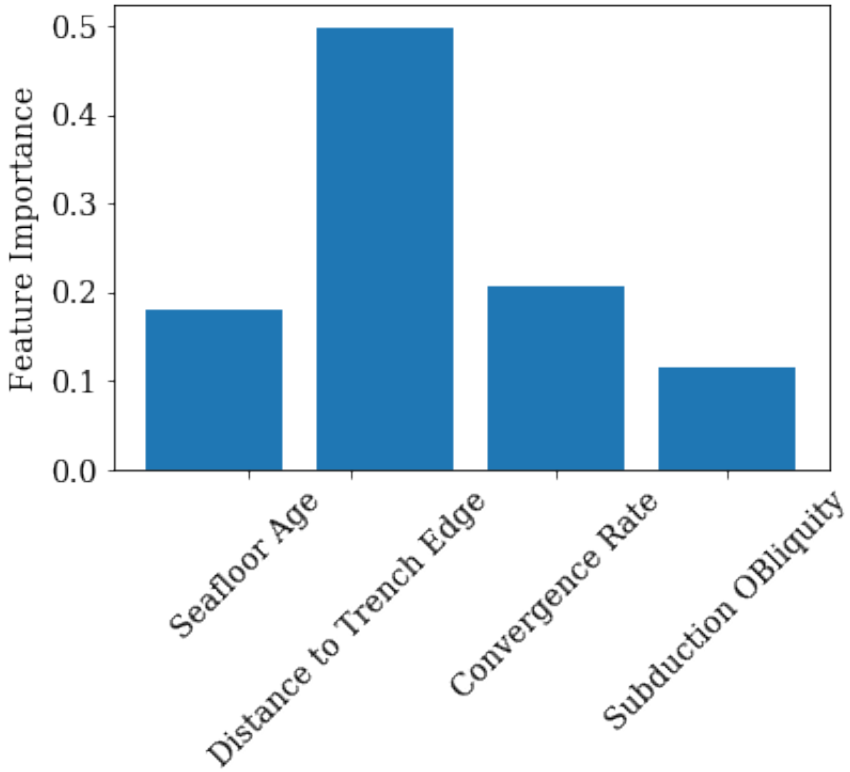
In [120]:

```
print 'Running...'
#create and train the random forest
#multi-core CPUs can use: rf = RandomForestClassifier(n_estimators=
100, n_jobs=2)
#n_estimators use between 64-128 doi: 10.1007/978-3-642-31537-4_13
rf = RandomForestClassifier(n_estimators=128, n_jobs=1,class_weight
=None)


#Now make a single classification for plotting and typical results
print 'Fitting...'
rf.fit(andesTrain[:,0:-3], andesTrain[:,-1])

#predicted_probs = [[index + 1, x[1]] for index, x in enumerate(rf.
predict_proba(testingSet))]

print 'Score of test data: ', rf.score(andesTest[:,0:-3], andesTest
[:,-1])
p=numpy.array(rf.predict_proba(andesTest[:,0:-3]))
#q=numpy.array(predicted_probs)

#The Random Forest method allows us to determine what parameters pr
eferentially optimised the test score.
print "Feature Importance: ", rf.feature_importances_

###
#Get a cross-fold validation score using all subsets of the data
scores = cross_val_score(rf, andesData[:,0:-3], andesData[:,-1], cv
=5)

print "Five-fold cross validation scores: ", scores
```

```
Running...
Fitting...
Score of test data:  0.9833333333333333
Feature Importance:  [0.21064221 0.50705508 0.16837191 0.1139308 ]
Five-fold cross validation scores:  [0.93442623 0.95       0.98333
333 0.96610169 0.94915254]
```

In [171]:

```
#Plot of feature importance
paramLabels=["Seafloor Age","Distance to Trench Edge","Subducting P
late Normal", "Subducting Plate Parallel",\
             "Overriding Plate Normal", "Overriding Plate Parallel"
,\
             "Convergence Rate","Convergence Parallel",\
             "Subduction Polarity", "Subduction OBliquity"]

paramLabels=["Seafloor Age","Distance to Trench Edge","Convergence
Rate", "Subduction OBliquity"]

fig, ax = plt.subplots()

#rects=ax.bar([0,1,2,3,4,5,6,7,8,9,10],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6,7,8,9],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6,7,8],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6,7],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4],rf.feature_importances_)
rects=ax.bar([0,1,2,3],rf.feature_importances_)

#print len(rf.feature_importances_)

#Set the location of the tick marks
# ax.set_xticks([-0.8,-0.8,0.2,1.2,2.2,3.4,4.8,5.4,6.6,7.4])
ax.set_xticks([0.2,0.8,2.0,3.0])

# plt.ylim([0,0.35])

ax.set_xticklabels(paramLabels,rotation=45)
ax.set_ylabel('Feature Importance')

font = {'family' : 'serif',
        'weight' : 'normal',
        'size'   : 14}
plt.rc('font', **font)

plt.show()

print "Feature Importance: ", rf.feature_importances_
```



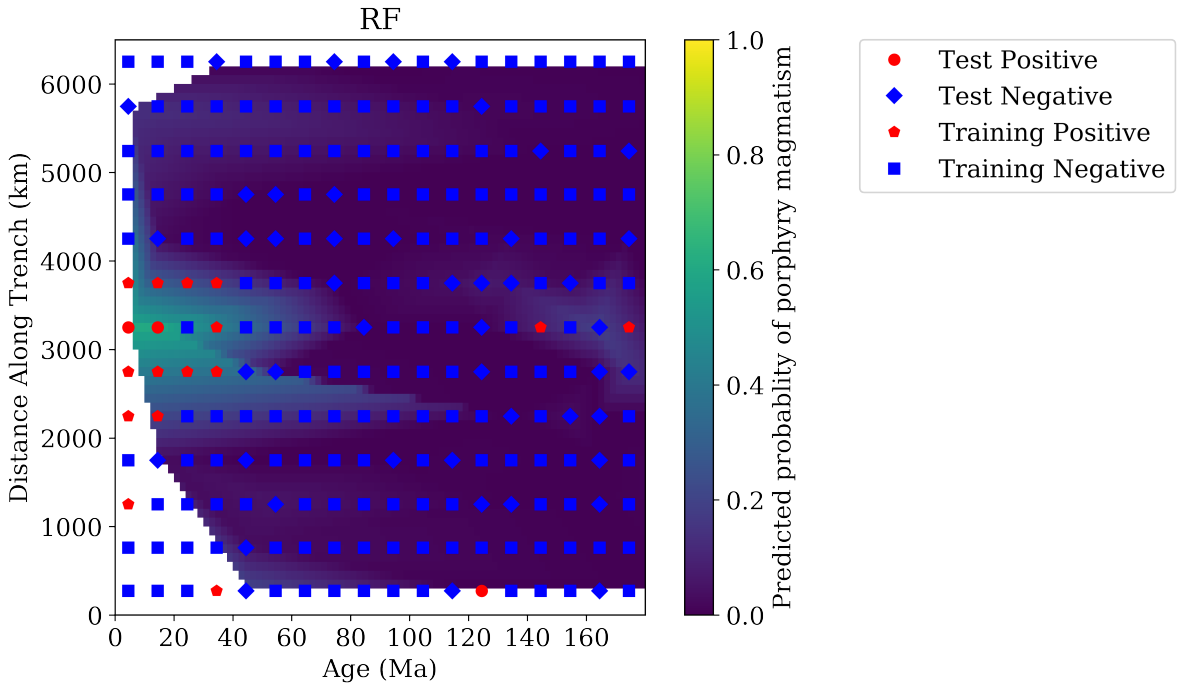

```
Feature Importance:  [0.17957099 0.49813178 0.20591702 0.11638022]
```

In [122]:

```
#Make some plots of typical results

#Create vectors of the prediced and actual results
subset=andesTrain[andesTrain[:,-1]==1]
subsetpredict=andesTest[andesTest[:,-1]==1]
subsetNegative=andesTrain[andesTrain[:,-1]==0]
subsetpredictNegative=andesTest[andesTest[:,-1]==0]

#Create a time-space map showing when and where along the margin an
ore deposit may have
#formed

#Create a grid to map the ML results to
grid_x, grid_y = np.meshgrid(np.linspace(0,200,100),np.linspace(0,6
500,65))
#Retrieve the ML scores
values = p[:,1].flatten()
print "Number of points with an ML score: ", np.shape(values)
print np.shape(andesTest[:,-3].flatten())
print np.shape(andesTest[:,-2].flatten())
#Now grid the data
grid_z1 = ml.griddata(andesTest[:,-3].flatten(),\
                      andesTest[:,-2].flatten(),\
                      values, grid_x, grid_y,interp='linear')

print "Shape of grid:", np.shape(grid_z1)

#Plot the new grid
fig = plt.figure(figsize=(8,6),dpi=600)
plt.imshow(grid_z1,origin='lower',\
           extent=[0,200,0,6500],aspect=0.03)
```

```
font = {'family' : 'serif',
        'weight' : 'normal',
        'size'   : 14}

plt.rc('font', **font)

cbar=plt.colorbar()
cbar.set_label('Predicted probablity of porphyry magmatism')


#Plot each of the result vectors
#Plot the testing data
p1,=plt.plot(subsetpredict[:,-3],subsetpredict[:,-2],'ro')
p2,=plt.plot(subsetpredictNegative[:,-3],subsetpredictNegative[:,-2
],'bD')

#Plot the training data
p3,=plt.plot(subset[:,-3],subset[:,-2],'rp')
p4,=plt.plot(subsetNegative[:,-3],subsetNegative[:,-2],'bs')

#Create the legend
plt.legend([p1,p2,p3,p4],\
           ["Test Positive","Test Negative","Training Positive","Tr
aining Negative"],
           bbox_to_anchor=(2, 1), loc=1, borderaxespad=0.,numpoints
=1)

#Adjust the plot
plt.clim([0,1])
plt.xlim([0,180])
plt.ylim([0,6500])
ax = plt.axes()
ax.set_xticks(np.arange(0,180,20))
ax.set_yticks(np.arange(0,6500,1000))

plt.ylabel('Distance Along Trench (km)')
plt.xlabel('Age (Ma)')
plt.title('RF')

plt.show()

print "Five-fold cross validation scores: ", scores
print 'SCORE Mean: %.2f' % np.mean(scores), 'STD: %.2f' % np.std(sc
ores)
```

```
Number of points with an ML score:  (60,)
(60,)
(60,)
Shape of grid: (65, 100)
```




```
Five-fold cross validation scores:  [0.93442623 0.95        0.98333
333 0.96610169 0.94915254]
SCORE Mean: 0.96 STD: 0.02
```

Point of formation data

Same methods as above, however the data is formatted slightly differently so we must rewrite the functions used.

Split the data into testing and training sets.

With the "training" set we learn which parameters are important, and we test the validity of this with the "testing" set.

In [195]:
```
#Make a dataset for cross validation
andesTraining = d3[:,0,:]
#Time Restricted Set
#andesTraining=d3[d3[:,0,4]<70,0,:]

print "Size of data set: ", andesTraining.shape

#Recombine the features and the classification vectors. #Save the t
emporal-spatial parameters too for plotting purposes.
params=[6,9,14,17] #indicies from List of Variables
# params=[6,9,10,11,12,13,14,15,16,17]
andesData = numpy.c_[preprocessing.scale(andesTraining[:,params]),a
ndesTraining[:,4],andesTraining[:,18],andesTraining[:,20]]

#Do a 80/20 split of the data  to be used to make an example fit of
the data
andesTrain, andesTest,  = train_test_split(\
       andesData, test_size=0.2, random_state=1)

print "Shape of data array: ", andesData.shape

#Number of 'positive' and 'negative' examples
print "Positive (deposits) examples: ",np.shape(andesTraining[andes
Training[:,20]==1,:])
print "Negative (non-deposits) examples: ",np.shape(andesTraining[a
ndesTraining[:,20]==0,:])

print "Are there NANs?", numpy.isnan(numpy.sum(andesData))
```

```
Size of data set:  (665, 21)
Shape of data array:  (665, 7)
Positive (deposits) examples:  (321, 21)
Negative (non-deposits) examples:  (344, 21)
Are there NANs? False
```

SVM

In [196]:

```
#Make the classifier
clf = SVC(probability=True,class_weight=None)

#Train the classifier by fitting the parameters (features) to know
results (targets)
clf.fit(andesTrain[:,0:-3], andesTrain[0:,-1])

print "Prediction-testing set (expected result):"
print andesTest[0:,-1]

print "Prediction of test (result):"
print clf.predict(andesTest[:,0:-3])

#Save the values of prediction
p=numpy.array(clf.predict_proba(andesTest[:,0:-3]))

#To get a score out for the data
svmParams=clf.score(andesTest[:,0:-3],andesTest[0:,-1])
print "Single result:"
print svmParams

#Get a cross-fold validation score using all subsets of the data
scores = cross_val_score(clf, andesData[:,0:-3], andesData[:,-1], c
v=5)

print "Cross fold validation results:"
print scores
```

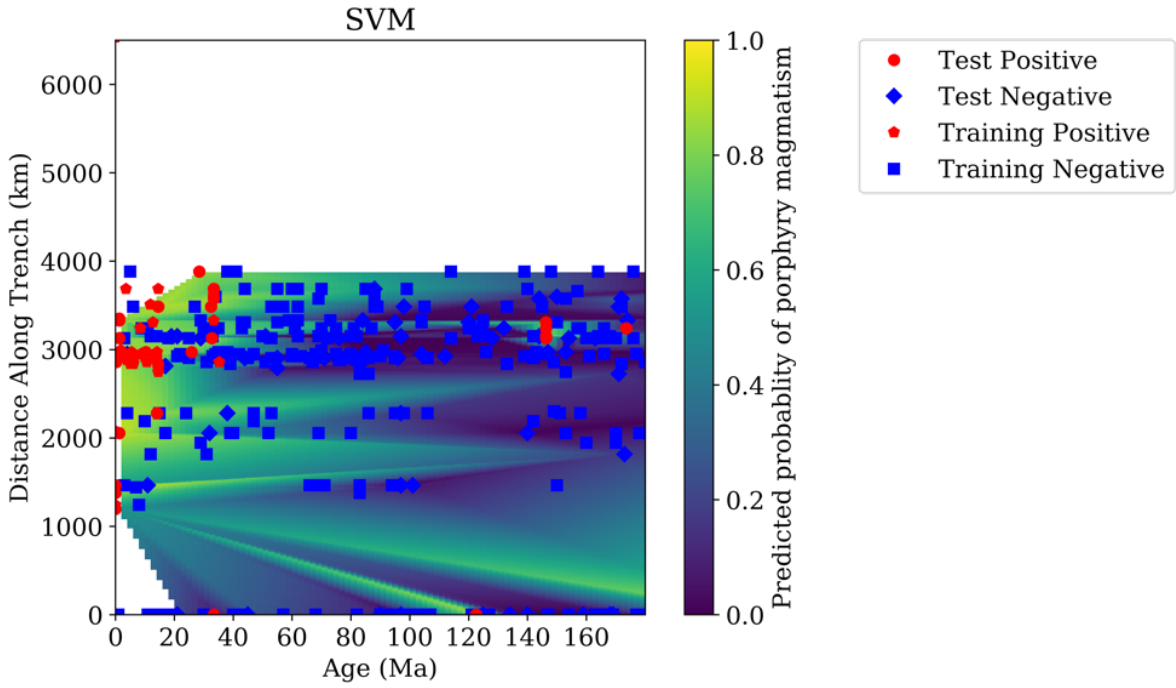
```
Prediction-testing set (expected result):
[0. 1. 1. 1. 0. 0. 1. 1. 0. 0. 0. 0. 1. 0. 0. 1. 1. 0. 0. 0. 1. 0.
1. 0.
 0. 1. 0. 0. 0. 1. 0. 0. 1. 0. 0. 0. 0. 0. 1. 0. 1. 1. 1. 0. 1. 0.
0. 1.
 0. 0. 0. 1. 1. 0. 0. 0. 1. 1. 1. 1. 0. 0. 0. 1. 1. 0. 0. 1. 0. 0.
1. 1.
 0. 0. 0. 0. 0. 1. 1. 0. 0. 0. 0. 0. 0. 0. 1. 1. 1. 1. 0. 1. 1. 0.
1. 1.
 1. 1. 1. 0. 0. 0. 1. 1. 1. 1. 1. 0. 0. 0. 0. 1. 1. 0. 0. 0. 0. 1.
0. 1.
 1. 0. 1. 0. 1. 1. 0. 0. 1. 1. 0. 0. 1.]
Prediction of test (result):
[0. 1. 1. 1. 0. 0. 1. 1. 0. 1. 0. 0. 1. 1. 0. 1. 1. 0. 0. 0. 1. 0.
1. 1.
 0. 1. 0. 0. 0. 1. 0. 0. 1. 0. 0. 0. 0. 0. 1. 0. 1. 1. 1. 0. 1. 1.
0. 1.
 0. 1. 0. 1. 1. 0. 0. 0. 1. 1. 1. 1. 0. 0. 0. 1. 0. 0. 0. 1. 0. 0.
1. 0.
 0. 0. 1. 0. 0. 1. 1. 0. 0. 1. 0. 0. 0. 1. 1. 1. 1. 1. 1. 1. 1. 0.
1. 1.
 1. 1. 1. 0. 0. 0. 1. 0. 1. 1. 1. 1. 1. 0. 0. 1. 1. 0. 1. 1. 0. 1.
1. 1.
 1. 0. 1. 0. 1. 1. 0. 0. 1. 1. 0. 0. 1.]
Single result:
0.8721804511278195
Cross fold validation results:
[0.58208955 0.79699248 0.76691729 0.85714286 0.82575758]
```

SVM Results

In [197]:
```
#Make some plots of typical results

#Create vectors of the prediced and actual results
subset=andesTrain[andesTrain[:,-1]==1]
subsetpredict=andesTest[andesTest[:,-1]==1]
subsetNegative=andesTrain[andesTrain[:,-1]==0]
subsetpredictNegative=andesTest[andesTest[:,-1]==0]

#Create a time-space map showing when and where along the margin an
ore deposit may have formed

#Create a grid to map the ML results to
grid_x, grid_y = np.meshgrid(np.linspace(0,200,100),np.linspace(0,6
500,500))
#Retrieve the ML scores
values = p[:,1].flatten()
print "Number of points with an ML score: ", np.shape(values)

grid_z1 = ml.griddata(andesTest[:,-3].flatten(),\
                      andesTest[:,-2].flatten(),\
                      values, grid_x, grid_y,interp='linear')

print "Shape of grid:", np.shape(grid_z1)

fig = plt.figure(figsize=(8,6),dpi=600)
plt.imshow(grid_z1,origin='lower',\
           extent=[0,200,0,6500],aspect=0.03)

font = {'family' : 'serif',
        'weight' : 'normal',
        'size'   : 14}

plt.rc('font', **font)

cbar=plt.colorbar()
cbar.set_label('Predicted probablity of porphyry magmatism')

#Plot each of the result vectors
#negative testing
p2,=plt.plot(subsetpredictNegative[:,-3],subsetpredictNegative[:,-2
],'bD')

#negative training
p4,=plt.plot(subsetNegative[:,-3],subsetNegative[:,-2],'bs')

#positive training
p3,=plt.plot(subset[:,-3],subset[:,-2],'rp')

#positive testing
p1,=plt.plot(subsetpredict[:,-3],subsetpredict[:,-2],'ro')

plt.legend([p1,p2,p3,p4],\
```

```
            ["Test Positive","Test Negative","Training Positive","Tr
aining Negative"],
            bbox_to_anchor=(2, 1), loc=1, borderaxespad=0.,numpoints
=1)



#Adjust the plot
plt.clim([0,1])
plt.xlim([0,180])
plt.ylim([0,6500])
ax = plt.axes()
ax.set_xticks(np.arange(0,180,20))
ax.set_yticks(np.arange(0,6500,1000))

plt.ylabel('Distance Along Trench (km)')
plt.xlabel('Age (Ma)')
plt.title('SVM')

plt.show()

print "Five-fold cross validation scores: ", scores
print 'SCORE Mean: %.2f' % np.mean(scores), 'STD: %.2f' % np.std(sc
ores)
```

```
Number of points with an ML score:  (133,)
Shape of grid: (500, 100)
```




```
Five-fold cross validation scores:  [0.58208955 0.79699248 0.76691
729 0.85714286 0.82575758]
SCORE Mean: 0.77 STD: 0.10
```

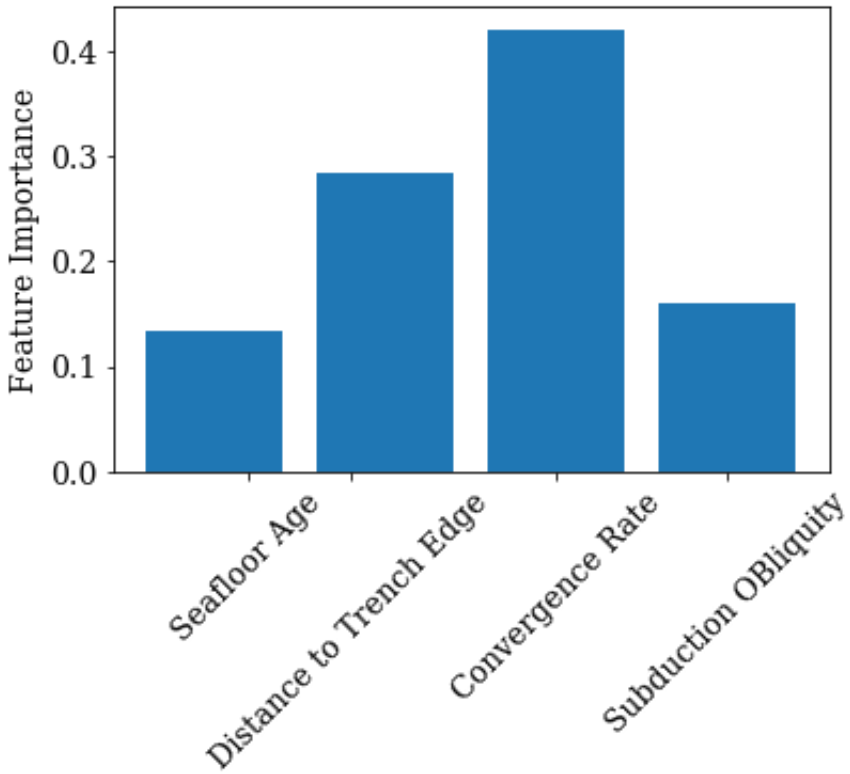
Random Forest Classification

In [126]:
```
print 'Running...'
#create and train the random forest
#multi-core CPUs can use: rf = RandomForestClassifier(n_estimators=
100, n_jobs=2)
#n_estimators use between 64-128 doi: 10.1007/978-3-642-31537-4_13
rf = RandomForestClassifier(n_estimators=128, n_jobs=1,class_weight
=None)

print 'Fitting...'
rf.fit(andesTrain[:,0:-3], andesTrain[0:,-1])


#predicted_probs = [[index + 1, x[1]] for index, x in enumerate(rf.
predict_proba(testingSet))]

print 'Score of test data: ', rf.score(andesTest[:,0:-3], andesTest
[:,-1])
p=numpy.array(rf.predict_proba(andesTest[:,0:-3]))
#q=numpy.array(predicted_probs)

#Get a cross-fold validation score using all subsets of the data
scores = cross_val_score(rf, andesData[:,0:-3], andesData[:,-1], cv
=5)

print rf.feature_importances_
print scores
```

```
Running...
Fitting...
Score of test data:  0.9548872180451128
[0.13394091 0.28462403 0.42045076 0.16098429]
[0.61940299 0.69172932 0.83458647 0.70676692 0.60606061]
```

In [127]:

```
#Plot of feature importance
# paramLabels=["Seafloor Age","Distance to Trench Edge","Subducting
Plate Normal", "Subducting Plate Parallel",\
#               "Overriding Plate Normal", "Overriding Plate Paralle
l",\
#               "Convergence Rate","Convergence Parallel",\
#               "Subduction Polarity", "Subduction OBliquity"]

paramLabels=["Seafloor Age","Distance to Trench Edge","Convergence
Rate", "Subduction OBliquity"]

fig, ax = plt.subplots()

# rects=ax.bar([0,1,2,3,4,5,6,7,8,9,10],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6,7,8,9],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6,7,8],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6,7],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5,6],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4,5],rf.feature_importances_)
# rects=ax.bar([0,1,2,3,4],rf.feature_importances_)
rects=ax.bar([0,1,2,3],rf.feature_importances_)

#print len(rf.feature_importances_)

#Set the location of the tick marks
# ax.set_xticks([-0.8,-0.8,0.2,1.2,2.2,3.4,4.8,5.4,6.6,7.4])
ax.set_xticks([0.2,0.8,2.0,3.0])

# plt.ylim([0,0.15])

#ax.set_xticks([0,1,2,3,4,5,6,7,8,9,10])
ax.set_xticklabels(paramLabels,rotation=45)
ax.set_ylabel('Feature Importance')

font = {'family' : 'serif',
        'weight' : 'normal',
        'size'   : 14}
plt.rc('font', **font)

plt.show()

print "Feature Importance: ", rf.feature_importances_
```



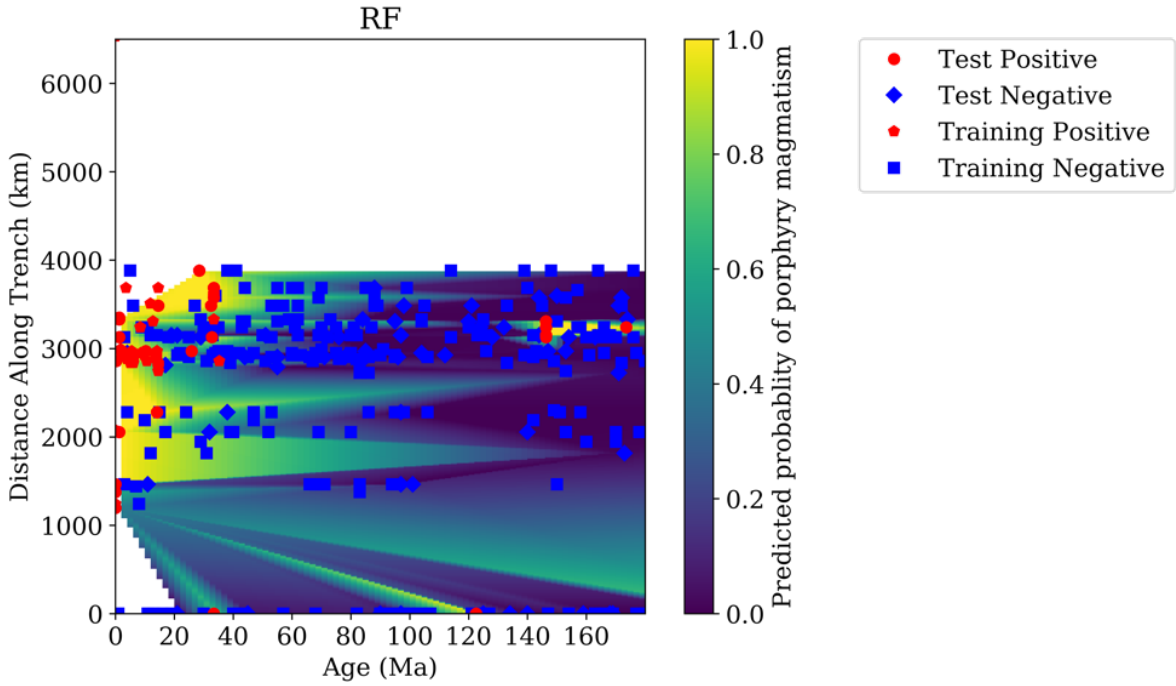

```
Feature Importance:  [0.13394091 0.28462403 0.42045076 0.16098429]
```

In [128]:

```
#Make some plots of the results

#Create vectors of the prediced and actual results
subset=andesTrain[andesTrain[:,-1]==1]
subsetpredict=andesTest[andesTest[:,-1]==1]
subsetNegative=andesTrain[andesTrain[:,-1]==0]
subsetpredictNegative=andesTest[andesTest[:,-1]==0]

#Create a time-space map showing when and where along the margin an
ore deposit may have formed

#Create a grid to map the ML results to
grid_x, grid_y = np.meshgrid(np.linspace(0,200,100),np.linspace(0,6
500,500))
#Retrieve the ML scores
values = p[:,1].flatten()
print "Number of points with an ML score: ", np.shape(values)
grid_z1 = ml.griddata(andesTest[:,-3].flatten(),\
                      andesTest[:,-2].flatten(),\
                      values, grid_x, grid_y,interp='linear')

print "Shape of grid:", np.shape(grid_z1)

fig = plt.figure(figsize=(8,6),dpi=600)
plt.imshow(grid_z1,origin='lower',\
           extent=[0,200,0,6500],aspect=0.03)

font = {'family' : 'serif',
        'weight' : 'normal',
        'size'   : 14}
```

```
plt.rc('font', **font)

cbar=plt.colorbar()
cbar.set_label('Predicted probablity of porphyry magmatism')

#Plot each of the result vectors
#negative testing
p2,=plt.plot(subsetpredictNegative[:,-3],subsetpredictNegative[:,-2
],'bD')

#negative training
p4,=plt.plot(subsetNegative[:,-3],subsetNegative[:,-2],'bs')

#positive training
p3,=plt.plot(subset[:,-3],subset[:,-2],'rp')

#positive testing
p1,=plt.plot(subsetpredict[:,-3],subsetpredict[:,-2],'ro')

plt.legend([p1,p2,p3,p4],\
           ["Test Positive","Test Negative","Training Positive","Tr
aining Negative"],
           bbox_to_anchor=(2, 1), loc=1, borderaxespad=0.,numpoints
=1)



#Adjust the plot
plt.clim([0,1])
plt.xlim([0,180])
plt.ylim([0,6500])
ax = plt.axes()
ax.set_xticks(np.arange(0,180,20))
ax.set_yticks(np.arange(0,6500,1000))

plt.ylabel('Distance Along Trench (km)')
plt.xlabel('Age (Ma)')
plt.title('RF')

plt.show()

print "Five-fold cross validation scores: ", scores
print 'SCORE Mean: %.2f' % np.mean(scores), 'STD: %.2f' % np.std(sc
ores)
```

```
Number of points with an ML score:  (133,)
Shape of grid: (500, 100)
```




```
Five-fold cross validation scores:  [0.61940299 0.69172932 0.83458
647 0.70676692 0.60606061]
SCORE Mean: 0.69 STD: 0.08
```

In [129]:

```
# Random Accuracy = (No. Positive Examples)^2 + (No. Negative Examp
les)^2

#points = 0.50 (0.63=0.13, SVM 0.55=0.05)
#part = 0.68 (0.77=0.09, SVM 0.70=0.02)
#part time restric = 0.51 (RF 0.59=0.08, SVM 0.60=0.09)
#points time restric = 0.54 (RF 0.59=0.05, SVM 0.57=0.03)

#Pick only positive or only negative
print 176./221 #part 45/176/221
print 154./301 #points 147/154/301
print 45./77 #part time rest 32/45/77
print 121./188 #points time rest 121/67/188
```

```
0.796380090498
0.511627906977
0.584415584416
0.643617021277
```

In [ ]: