A FOSSIL LOCALITY PREDICTIVE MODEL FOR THE EARLY CRETACEOUS CEDAR MOUNTAIN FORMATION, UTAH, USA

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FOSSIL LOCALITY PREDICTIVE MODEL

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Abstract

Hard work and chance are nearly always among the deciding factors in finding new, important, and productive paleontological localities. Fossil locality predictive models have the potential to reduce unproductive field time and maximize hard work thus increasing the chances researchers have to find important localities. This study uses remotely sensed data to design and test a fossil locality predictive model for the Early Cretaceous Cedar Mountain Formation. Landsat 8 OLI/TIRS data from known localities were summarized, reclassified and used in a weighted suitability analysis to categorize fossil locality potential of the study area. Field work was conducted to test model functionality. Field observations were used to refine the weighted suitability analysis. Landsat 8 OLI/TIRS data alone offers a less accurate prescription of fossil locality potential. Additional physical and environmental factors play a role in determining the chance of finding fossils. Slope degree and aspect data from known localities were summarized and analyzed to further refine the model. The usefulness of fossil locality predictive models is dependent upon the quality of input data and methods used to determine fossil locality potential. In order to fully determine the quality of a fossil locality predictive model, field work testing the model must be conducted.

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Chapter 1: Introduction

Statement of the Problem

This study assesses the effectiveness of using remotely sensed Landsat 8 Operational Land Imager / Thermal InfraRed Sensor (OLI/TIRS) spectral data for finding fossil localities in the Early Cretaceous Cedar Mountain Formation of Utah. The Cedar Mountain Formation is an important geological formation because it records a faunal shift in North America during global climate change at the end of the Early Cretaceous (Kirkland *et al*. 1999). New localities and new species are continually being found and described (McDonald *et al*. 2010; Senter *et al*. 2010; Senter *et al*. 2012a; Senter *et al*. 2012b; Taylor *et al*. 2011) which help to elucidate the effects of climate change on past life and ecosystems and add to our understanding of the possible effects of modern climate change. Reducing on-the-ground search time for new fossil localities by narrowing down potential search areas prior to field work can be a valuable time and money saving exercise.

Background and Need

Paleontology is the study of fossil life. Though it has earlier origins, paleontology became a recognizably discrete scientific discipline in the mid-19th century when many early researchers such as Gideon Mantell, William Buckland, and William Smith used the fossils they found to correlate rock strata across England, thus simultaneously advancing the scientific discipline geology (Smith 1816). Though the two disciplines have somewhat diverged since that time, the study and understanding of geology is still integral to paleontology and biostratigraphy. Recently, GIS has become a powerful new tool in solving problems and innovation in the study of paleontology.

As new technologies are developed, paleontologists have traditionally been fairly quick to adapt them for use in paleontology. Examples include photography (Hudson 1913), automobiles (Romer 1959), remote sensing (Stucky *et al*. 1989), Global Positioning Systems (GPS), and Geographic Information Systems (GIS). Use of GIS in paleontology to record positions of fossils, map localities, and manage geospatial fossil databases is now relatively widespread, but paleontological applications of remote sensing have lagged behind. Despite this, use of remote sensing in paleontology is just beginning to grow as the availability of data increases, as the quality of data improves, and as paleontologists learn more about the technology and its possible applications. Paleontologists are beginning to awaken to the statement issued over two decades ago; "remote sensing data provide geologic information of critical value to vertebrate paleontology" (Stucky and Krishtalka 1991, p. 75).

Beyond mapping and simple geospatial database storage, comparatively little work has been done in paleontology using GIS and remote sensing. Few fossil locality predictive models exist (Conroy et al. 2012; Egeland et al. 2010; Emerson and Anemone 2012; Malakhov et al. 2009; Oheim 2007), most of which have been conducted by paleoanthropologists, hybrids between archaeologists and paleontologists who specialize in the paleontology of near human relatives and other primates. GIS is a powerful tool for paleontologists and should be used in more robust ways beyond mapping or data storage.

The Cedar Mountain Formation is an important geologic formation evolutionarily and climatologically. Many important new fossil species representing faunal change are found in its rocks (Kirkland *et al*. 1997). The Cedar Mountain Formation also reveals information regarding the global climate change occurring at the end of the Early Cretaceous and how it affected faunal change (Kirkland *et al.* 1999). This study will potentially aid in finding new fossil localities with possibly important information on known and unknown species, thus finding answers to some of the many questions posed by this critical time period.

Justification/Rationale

Certain aspects of paleontological prospecting have stayed much the same for over a century. Finding fossils in the field largely consists of researchers wandering around in deserted and remote areas hoping to discover something using only topographic and geological maps, personal experience, and intuition, "many, perhaps most, new fossil localities are literally stumbled upon" (Anemone *et al*. 2011, p. 169). Much valuable field time is wasted with fruitless searching. Recently, paleontological research institutions have been faced with budget cuts (Rea 2002; Ruiz Mantilla 2013; Shen 2012; Switek 2009) and often have difficulty obtaining funding for research (Farley 2008; Plotnik 2007; Prothero 2009; Savazzi 2009). Since funding is a critical issue, paleontologists must be wise with expenditures in order to further research (Maples 1997).

GIS and remote sensing technologies have advanced rapidly in the past few decades (Klinkenberg 1997). Availability of geospatial data is increasing and governmental institutions such as the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) are offering their data at no cost to the user. Landsat 8 OLI/TIRS data has not yet been tested for its fossil locality modeling and prediction capabilities.

Several studies regarding remotely sensed data and its predictive modeling capabilities have reported success in identifying areas of potentially higher paleontological productivity (Conroy *et al*. 2012; Egeland *et al*. 2010; Malakhov *et al*. 2009; Oheim 2007). No reported prior fossil locality predictive models have been created for the Cedar Mountain Formation. The Cedar Mountain Formation is important for understanding past climate change and its effects on life (Kirkland *et al*. 1999).

The evidence of faunal change over time in North America is clear but there are several unconformities in the Cedar Mountain Formation (Kirkland *et al*. 1997). Unconformities are gaps in the geological record which represent times of erosion or non-deposition where there are simply no rocks from those times. Additionally, there are Members within the Cedar Mountain Formation which have few or no fossils within them (Kirkland *et al*. 1999).

Finding more fossils in the Cedar Mountain Formation would give researchers more information about its biota and the paleoenvironmental conditions surrounding that period of climate change. Since tools and data such as GIS software and Landsat imagery are readily available and relatively inexpensive, this study has the potential to help maximize funds and time spent in the field finding new fossil localities with more fossils and new species. In turn, this new data can teach researchers more about climate change and its effects on life.

Research Objectives

The purpose of this study is to create a fossil locality predictive model for the Early Cretaceous Cedar Mountain Formation near Moab, UT. The model compares Landsat 8 OLI/TIRS spectral reflectance data from known fossil localities to all mapped surface exposure of the Cedar Mountain Formation. Areas within the Cedar Mountain Formation which have physical and spectral attributes similar to the known fossil localities are identified as potential fossil localities. Sampled sites falling within the potential fossil locality area are field checked for new fossil localities. Using data gathered from the field, the model is refined further.

Study Area

The Early Cretaceous Cedar Mountain Formation of Utah is a fossil rich geological formation of critical importance for understanding the terrestrial fauna change from the Late Jurassic to the Late Cretaceous in North America. Stratigraphically it unconformably overlays the Late Jurassic Brushy Basin Member of the Morrison Formation and is in turn unconformably overlain by the Late Cretaceous Dakota Sandstone. Figure 1 shows the surface extent of the Cedar Mountain Formation within the study area. The Cedar Mountain Formation records a climatic shift from arid and semi-arid conditions to progressively more humid conditions (Garrison *et al*. 2007). Rocks in the Cedar Mountain Formation were deposited in fluvial, lacustrine, and littoral environments about 127-98 million years ago (Kirkland *et al.* 1999). Rock types in the Cedar Mountain Formation include conglomerate, mudstone, sandstone, limestone, paleosols, local lignite coal deposits, and a few ash beds. Early Cretaceous terrestrial sediments are relatively rare in North America so the Cedar Mountain Formation is exceptional in its potential to reveal the details of climate and faunal change (Kirkland *et al.* 1999).

The Cedar Mountain Formation is divided into five members. From oldest to youngest they are: the Buckhorn Conglomerate, the Yellow Cat Member, the Poison Strip Sandstone, the Ruby Ranch Member, and the Mussentuchit Member. The Yellow Cat, Ruby Ranch, and Mussentuchit Members have produced the majority of vertebrate fossils from the formation. Very few fossils have been found from the Poison Strip Sandstone while the Buckhorn Conglomerate has failed to produce fossils (Kirkland *et al.* 1999). Overall, numerous fossil localities have been studied, but the extensive outcroppings of the Cedar Mountain Formation have yet to be fully prospected.

Since the outcrops of the Cedar Mountain Formation are exposed over a wide area covering several counties of northeastern and southeastern Utah, the study area will be limited to those exposures in the Moab 30' x 60' (1:100,000 scale) quadrangle which covers portions of Grand and Emery Counties. This area has an arid to semi-arid environment and a low population. The city of Moab is the largest population center with very small towns in nearby areas. Arches National Park is also located within this quadrangle.

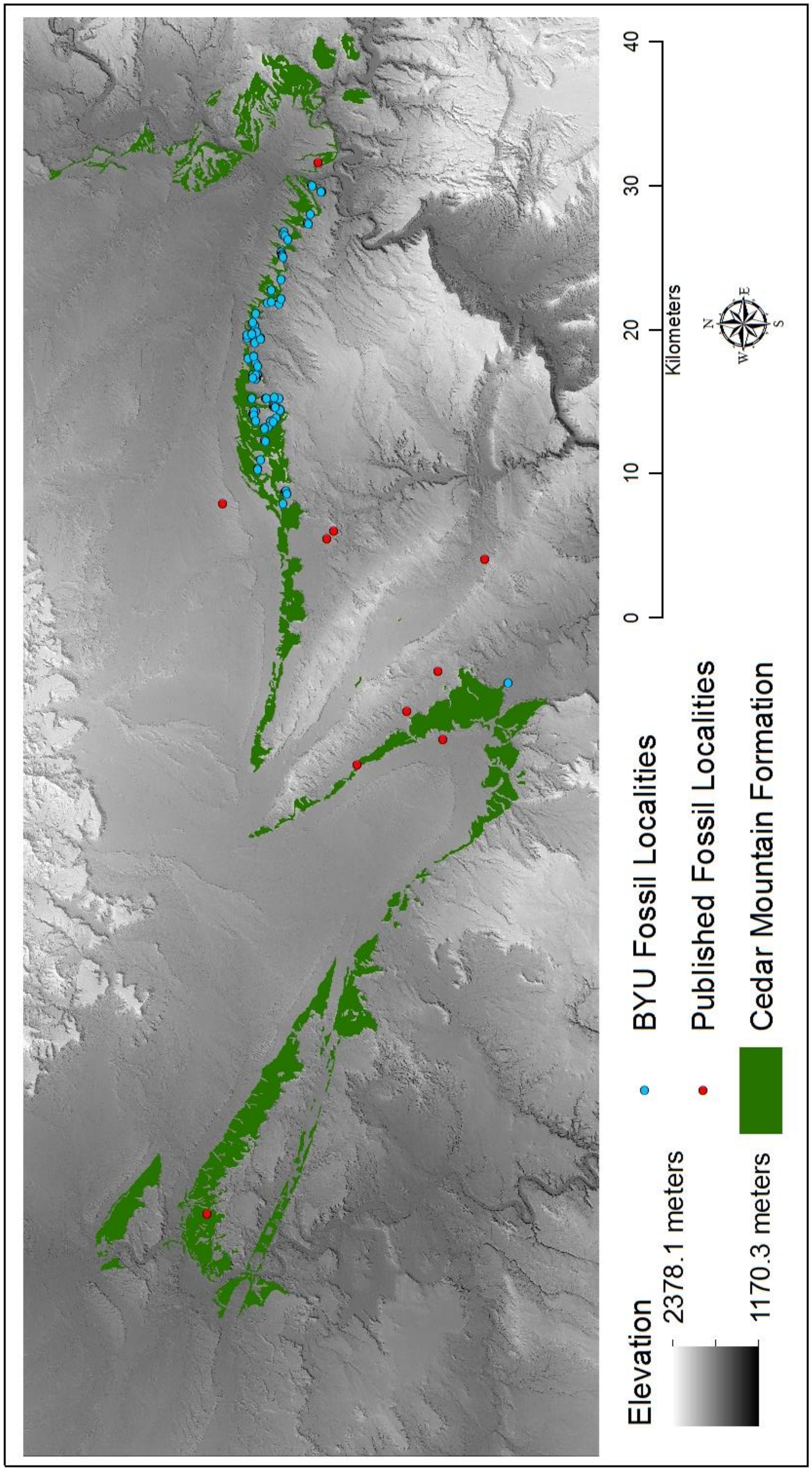

Figure 1: Early Cretaceous Cedar Mountain Formation surface exposure, elevation, and fossil localities.

CHAPTER 2: LITERATURE REVIEW

Geologists have long identified the tools provided by remote sensing as important to geological mapping in remote areas (Stucky and Krishtalka 1991). Likewise, archaeologists and paleoanthropologists have utilized remote sensing as a tool for narrowing down potential prospecting sites (WoldeGabriel *et al*. 1992). In contrast, very few vertebrate paleontologists have embraced the combination of technologies found in remote sensing and GIS to create predictive models. However, several important studies have been conducted recently in various parts of the world demonstrating the utility of GIS predictive models in remote prospecting for fossils.

In the most recently published study, Conroy *et al.* (2012) used a spectral signature model and the spatial analysis and image classification functions of ArcGIS 10 to create interactive land cover maps of their study area. Their targets were the Eocene sedimentary rock formations of the Uinta Basin, Utah. The model used Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery and "trained" algorithms using the spectral signatures of known fossil localities found prior to 2005. Six land cover classifications relevant to the study area were determined and included in the analysis. They consisted of: fossil localities, oil/gas field infrastructure, water, agriculture, scrub/tree cover, and steep slopes. The algorithms were then used to find other areas with a >98% probability of having the same spectral signatures as their "fossil localities" land cover class as well as being mapped as Eocene sediment on geologic maps. The model identified several "hot spots" with high potential where fossils had not been found prior to 2005. "Post-hoc" validation of hot spots found fossils in all regions predicted by the model.

Egeland *et al.* (2010) used a cost raster analysis in their predictive model to discover 25 new paleoanthropological sites in Armenia. Relevant data sources for input in the model included vegetation, distance to water, and topographic setting. To narrow down search areas, they found the least cost route from the nearest paleoanthropological locality in the Levant to known localities in Dmanisi. They also found that the Debed River valley of northeastern Armenia was the closest area within "the high potential dispersal region (as determined by the cost path analysis)" (Egeland *et al.* 2010, p. 92) which preserves alluvial, lacustrine, and datable volcanic deposits which are considered necessary for paleoanthropological sites. They considered the Debed River Valley as attractive because there were no known paleoanthropological sites within it nor had prior paleoanthropological studies been conducted there. Criteria for creating three suitability categories were slope, aspect, elevation, land cover, and proximity to rivers. Lastly, they affirmed that "remote GIS predictive modeling, while providing a useful guide for site identification, is no substitute for (and can be modified by) on-the-ground experience" (Egeland *et al.* 2010, p. 96) because, through their ground truthing reconnaissance, one of the sites they found was within their lowest potential category.

In another very recent study, Emerson and Anemone (2012) used a neural network classifier which successfully identified Eocene mammalian fossil sites in the Great Divide Basin, Wyoming. It used spectral signatures of known fossil localities to identify potentially productive sites. Landsat 7 ETM+ images were used to find the spectral characters of existing sites. National Land Cover Data was included in order to exclude wetlands and include barren ground and scrubland, land cover types ideally suited for finding fossils due to the lack of obscuring vegetation. DEM data were included in the analysis because 80% of existing localities were located on areas of slope 5% or greater. Through the analysis, two potential areas were scheduled for study in the summer of 2012. Currently, no report yet exists documenting the success of the field work. Future refinements of the model will include slope, ground curvature, surface geology, and accessibility.

Malakhov *et al.* (2009) showed how remotely prospecting a large field area can be done efficiently and at low cost with Landsat 7 ETM+ data. They cataloged the spectral characteristics of the sedimentary rocks in their field area which aided them to easily identify the locations of potentially fossiliferous strata for future on the ground prospecting. In contrast to previous studies, they did not have a complete database of environmental factors for their study area; however, they successfully searched for fossils using their remote approach in the Lower Syrdarya Uplift in southern Kazakhstan.

Oheim (2007) described a suitability analysis conducted to find new paleontological localities in the Cretaceous Two Medicine Formation of Montana, USA. The Two Medicine Formation is a relatively flat-lying geological formation without extensive folding or faults, has low human population, and the land encompassed is primarily used for grazing. All of these factors contribute to the satisfactory use of the formation for predictive modeling. Four variables were used in the analysis: geology, elevation, vegetation cover, and distance to roads. All data was rasterized, reclassified, weighted, and summed. By field testing the model and performing further analysis, Oheim (2007) was able to accurately predict areas with high, medium, and low fossil potential. Thirty-one new fossil localities were found as a result of this analysis. Using the new data gathered in the field, the model was refined, but as of publication no further field reconnaissance was conducted.

No predictive models have been conducted in the Cedar Mountain Formation to date. The success of previous studies is promising for future studies, provided that the input parameters are properly selected. Predictive models are not assumed to be perfect representations, nor will they accurately predict potential fossil localities all of the time. The experience of Egeland *et al*. (2010) testifies to this end. However, they are valuable tools for more effective allocation of resources especially in remote field areas.

CHAPTER 3: CONCEPTUAL FRAMEWORK AND METHODOLOGY

Data Sources

Landsat 8 OLI/TIRS Imagery

Landsat 8 OLI/TIRS imagery covering the study area (Figure 2) was obtained from the USGS EarthExplorer website (earthexplorer.usgs.gov). The selected scene is LC80360332013162LGN00, Path 36, Row 33 taken June 11, 2013. This scene was chosen because it covers the entire field area, was the most recent daytime scene available at the time of download (July 20, 2013), has no snow cover, and has only 0.02% cloud cover none of which was over the Cedar Mountain Formation.

Landsat 8 OLI/TIRS imagery consists of nine Operational Land Imager (OLI) bands and two Thermal Infrared Sensor (TIRS) bands. Table 1 describes the eleven Landsat 8 OLI/TIRS bands, the wavelengths each detects, and its spatial resolution.

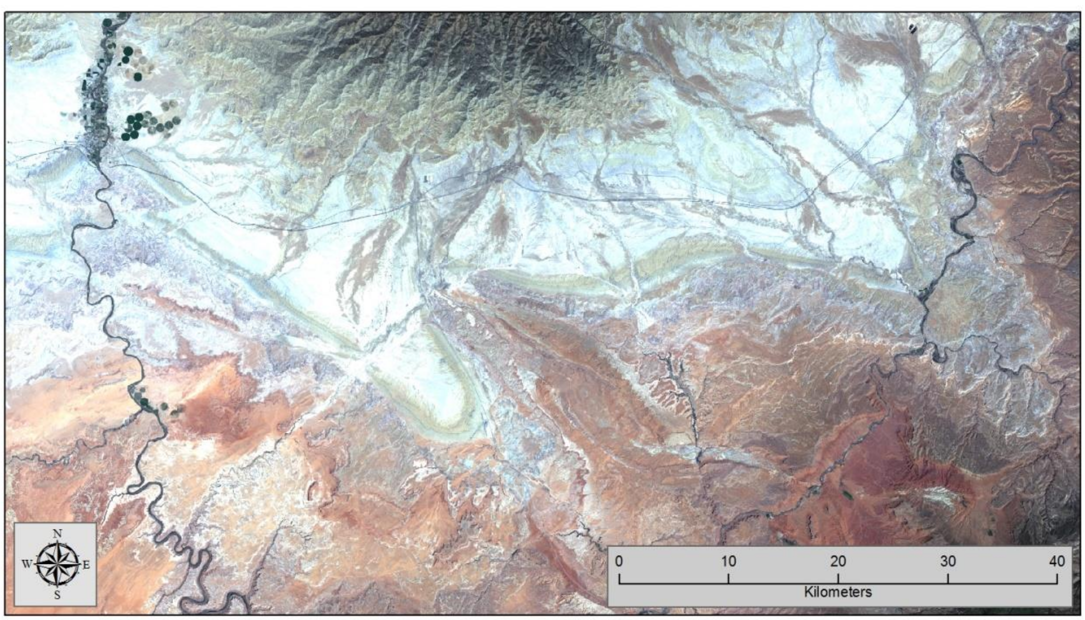

Figure 2: Landsat 8 natural color composite image centered on the Cedar Mountain Formation.

Table 1: Summary of Landsat 8 OLI/TIRS bands (adapted from Irons *et al*. 2012)

Spectral Band	Wavelength	Resolution
Band 1 - Coastal / Aerosol	0.433 - 0.453 µm	30 m
Band 2 - Blue	0.450 - 0.515 µm	30 m
Band 3 - Green	0.525 - 0.600 µm	30 m
Band 4 - Red	0.630 - 0.680 µm	30 m
Band 5 - Near Infrared	0.845 - 0.885 µm	30 m
Band 6 - Short Wavelength Infrared	1.560 - 1.660 µm	30 m
Band 7 - Short Wavelength Infrared	2.100 - 2.300 µm	30 m
Band 8 - Panchromatic	0.500 - 0.680 µm	15 m
Band 9 - Cirrus	1.360 - 1.390 µm	30 m
Band 10 - Long Wavelength Infrared	10.30 - 11.30 µm	100 m
Band 11 - Long Wavelength Infrared	11.50 - 12.50 µm	100 m

Geologic Maps

Geologic data on Cedar Mountain Formation surface exposure comes from the associated vector GIS data for Doelling (2002) which was downloaded from the Utah Geological Survey (UGS) Geologic Map Portal website (geology.utah.gov/maps/geomap/interactive/index.htm). The 1:100,000 scale map covers the Moab 30'x60' quadrangle and the eastern portion of the San Rafael Desert 30'x60' quadrangle. Data for the map was compiled from a variety of previously published sources, interpreted through aerial photography, and gathered from surface reconnaissance mapping surveys.

Two suites of larger scale (1:24,000) geologic maps which cover about two thirds of the study area were used for comparative purposes. Figure 3 shows the surface extent of these maps compared to the Cedar Mountain Formation. The older suite of 1:24,000 scale geologic maps was published during the years 1955-1956. They consist of maps for the Green River (Sable 1956), Horse Bench East (Sable 1955a), Daly (Sable 1955b), Green River SE (Sable 1955c), Dee Pass (Detterman 1955), Jug Rock (Bates 1955a), and

Merrimac Butte (Bates 1955b) quadrangles. The newer suite of maps was published during the years 1994-2009. They consist of the Hatch Mesa (Chitwood 1994), Valley City (Doelling 1997), Merrimac Butte (Doelling and Morgan 2000), Thompson Springs (Doelling and Kuehne 2009a), Sagers Flat (Doelling and Kuehne 2009b), White House (Doelling and Kuehne 2009c), and Dewey (Doelling 1996) quadrangles. GIS data for these 14 maps are all georeferenced raster files with no accompanying vector data. They were obtained from the UGS Geologic Map Portal website and the USGS National Geologic Map Database (http://ngmdb.usgs.gov). Data for the maps was compiled from previously published sources, interpreted through aerial photography, and gathered from surface reconnaissance mapping surveys. Table 2 shows a summary of all geological maps used in this study.

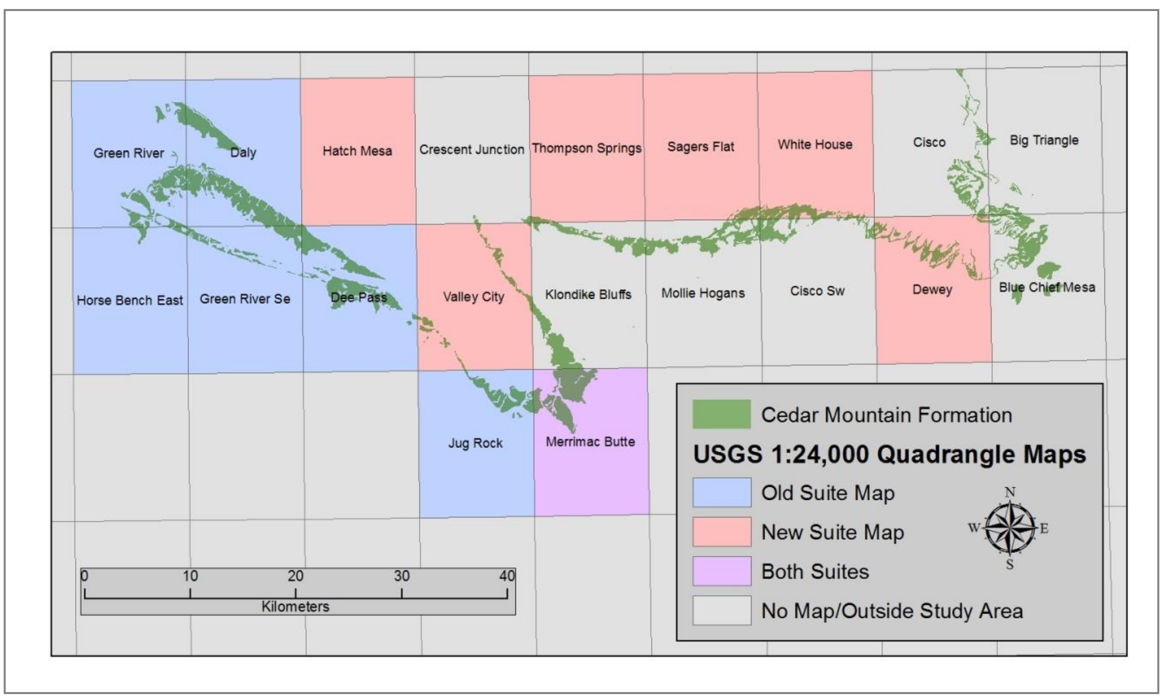

Figure 3: Surface coverage of 1:24,000 scale geological maps.

Table 2: Summary of Geologic Maps used in this study.

Author(s)	Year	Quadrangle Name	Scale
Bates	1955a	Jug Rock	1:24,000
Bates	1955b	Merrimac Butte	1:24,000
Chitwood	1994	Hatch Mesa	1:24,000
Detterman	1955	Dee Pass	1:24,000
Doelling	1996	Dewey	1:24,000
Doelling	1997	Valley City	1:24,000
Doelling	2002	Moab & San Rafael Desert	1:100,000
Doelling & Kuehne	2009a	Thompson Springs	1:24,000
Doelling & Kuehne	2009b	Sagers Flat	1:24,000
Doelling & Kuehne	2009c	White House	1:24,000
Doelling & Morgan	2000	Merrimac Butte	1:24,000
Sable	1955a	Horse Bench East	1:24,000
Sable	1955b	Daly	1:24,000
Sable	1955c	Green River SE	1:24,000
Sable	1956	Green River	1:24,000

BYU Fossil Localities

Information regarding Cedar Mountain Formation fossil localities was provided by the Brigham Young University (BYU) Museum of Paleontology. A dataset of 134 fossil localities was trimmed down to include only vertebrate fossil localities within the Cedar Mountain Formation, with reliable geospatial locations, and containing identifiable bone. The resulting dataset contains 98 fossil localities (see Figure 1). Fossil localities were found via ground reconnaissance surveys. GPS data was recorded for each locality using a handheld Garmin Montana 650t GPS receiver set to the WGS84 geographic datum. Horizontal coordinate accuracy was between two and three meters. Data was provided in a digital spreadsheet which was converted into a point shapefile.

Digital Elevation Model (DEM)

Auto-correlated 5 meter resolution DEM data were obtained for the field area from the Utah Automated Geographic Reference Center (gis.utah.gov/data). The data was created from aerial photography collected during the 2006 National Agriculture Imagery Program. It is of a finer resolution but contains anomalies not seen in datasets developed by other methods such as LiDAR, photogrammetry, or radar (Kelson 2007). The DEM data is available in 20,000 by 20,000 meter blocks across the entire state of Utah as ASCII files. Ten individual adjacent ASCII files were needed to cover the entire field area. The ASCII datasets were converted to Esri GRIDs, then combined into a single raster mosaic in a file geodatabase (see Figure 1). Slope and aspect data for the Cedar Mountain Formation were extracted from the DEM (see Figure 4).

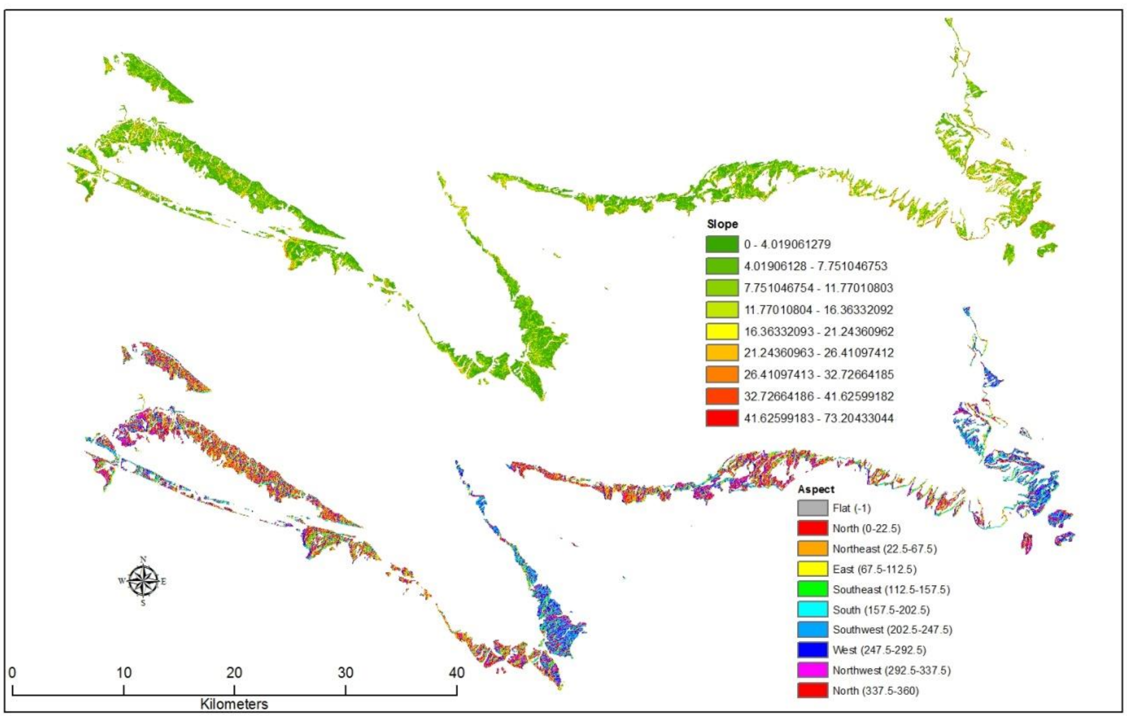

Figure 4: Slope and Aspect data for the Cedar Mountain Formation.

Published Fossil Localities

Spatial data regarding fossil localities described in published literature was obtained from the Paleobiology Database (paleobiodb.org). The Paleobiology Database is a non-governmental, non-profit online resource containing paleobiological taxonomic, geospatial, and reference data aggregated by numerous member researchers working from a variety of institutions (Alroy and Uhen 2013). Geospatial data was available for ten published Cedar Mountain Formation localities (see Figure 1). References describing fossil localities include Bodily (1969), Carpenter *et al*. (1999), Galton and Jensen (1978), Gilpin *et al*. (2007), Kirkland *et al*. (1998), Kirkland and Madsen (2007), McDonald *et al*. (2010), Santucci and Kirkland (2010), Senter *et al*. (2012b), and Taylor *et al*. (2011). Geospatial data does not necessarily come directly from the publications, but can be submitted to Paleobiology Database by member researchers.

Research Methodology

Overview

Statistics regarding spectral reflectance for the BYU fossil localities and the Cedar Mountain Formation were summarized and differences of means were compared. A weighted suitability analysis using differences of means was conducted to determine fossil locality potential for the Cedar Mountain Formation. The model was field tested and data and observations were gathered regarding model functionality. Field observations were used to revise the model. Model results were compared to published fossil localities. Slope and aspect data were combined with additional observations to further refine the model. Figure 5 illustrates a simplified flowchart of the methodology.

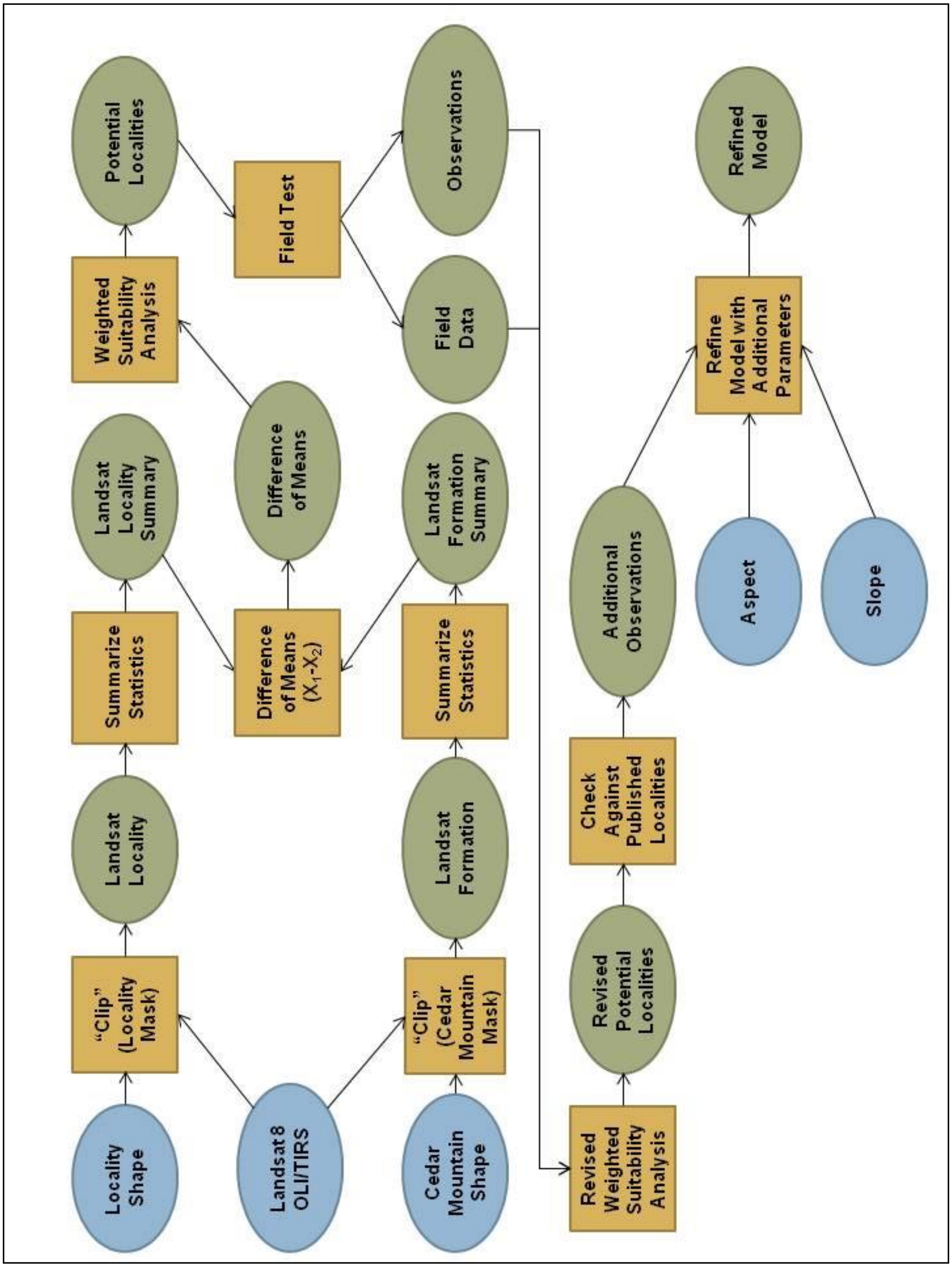

Figure 5: Simplified flowchart showing methodology.

Summary of Fossil Locality Spectral Reflectance

The spectral reflectances of the BYU fossil localities were summarized to establish the physical profile of fossil localities (see Table 3). The spectral reflectances of the entire Cedar Mountain Formation as mapped by Doelling (2002) were also summarized for comparison to the fossil localities (see Table 4). All eleven Landsat 8 OLI/TIRS bands were summarized for the entire formation and the fossil localities, but special attention was initially paid to bands 7, 10 and 11 which are roughly equivalent to Landsat 7 ETM+ bands 6 and 7 (Irons *et al*. 2012) which are most useful in geological applications (American Museum of Natural History - Center for Biodiversity and Conservation 2003). ETM+ band 6 (10.40 - 12.50 µm, thermal infrared) is useful in differentiating rock types because they vary in heat absorption and retention. The wavelength ranges of OLI/TIRS bands 10 and 11 (10.30 - 11.30 µm and 11.50 - 12.50 µm, respectively) overlap ETM+ band 6 and can be used similarly. ETM+ band 7 (2.08 - 2.35 µm, mid-infrared) is useful for differentiating mineral and rock types because of their varying moisture content. OLI/TIRS band 7 (2.100 - 2.300 µm) overlaps ETM+ band 7 and can be used for the same purpose.

These summaries were used to identify which OLI/TIRS bands have more restricted ranges in fossil localities when compared to the entire Cedar Mountain Formation. Figure 6 shows the difference of means from values in Tables 3 and 4. The difference of means for each band is calculated by subtracting the mean of the localities (X_1) from the mean of the entire Cedar Mountain Formation (X_2). A low difference of means indicates that there is little difference between the two datasets whereas a high difference of means indicates a greater difference between the datasets.

Table 3: Summary of Landsat 8 OLI/TIRS spectral reflectance values for BYU fossil localities.

Localities (X_1)	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10	Band 11
Min	12046	11723	11885	13149	15913	16656	14894	12103	5053	33617	31272
Max	15424	15792	17097	19598	23183	27431	23548	17202	5121	37427	34134
Mean	13284	13280	13970	15795	19045	21682	19464	14571	5087	35632	32796
St. Dev	625	776	1101	1349	1675	2687	2156	1237	16	819	598
# Obsv.	84	84	84	84	84	84	84	88	84	84	84
Range	3378	4069	5212	6449	7270	10775	8654	5099	68	3810	2862

Table 4: Summary of Landsat 8 OLI/TIRS spectral reflectance values for the Cedar Mountain Fm.

CMF (X_2)	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10	Band 11
Min	10547	9982	9854	9006	7579	5619	5814	8707	5032	29753	28386
Max	20503	21474	22904	25674	30303	33324	30605	25317	5155	39072	35259
Mean	14201	14332	15125	16692	20006	23083	20529	15867	5095	35717	32925
St. Dev	1799	2110	2431	2808	3380	4196	3793	3186	32	1680	1373
# Obsv	191110	191110	191110	191110	191110	191110	191110	764537	191110	191110	191110
Range	9956	11492	13050	16668	22724	27705	24791	16610	123	9319	6873

Bands 8 and 9 were removed from subsequent analysis. Band 8 is the panchromatic band which detects wavelengths that span bands 2-4, the visible light bands. It is usually reserved for pansharpening, a process which increases visual resolution in these bands for production of higher quality images. Band 9 is primarily used for detection of cloud cover. This study is not concerned with cloud cover and the OLI/TIRS imagery was specifically chosen for its lack thereof.

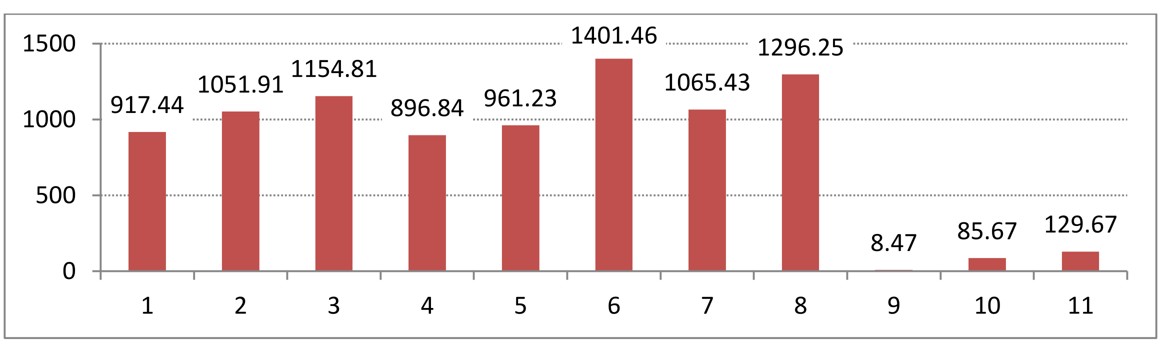

Figure 6: Differences of means between fossil localities and Cedar Mountain Formation (X_1-X_2).

Weighted Suitability Analysis

The nine remaining OLI/TIRS bands were reclassified for the weighted suitability analysis. The analysis mask was set to the extent of the Cedar Mountain Formation to exclude areas outside its mapped extent. Values outside the range present in the localities were given a reclassified value of "1" and values inside the range present in the localities were given a reclassified value of "5". Table 5 shows the reclassified values for each band.

Weights were assigned by comparing the difference of means of each band to the sum of the differences of means of the nine remaining bands. A percentage of how much influence each band had on the sum of the differences of means was used to determine its weight in the suitability analysis. Table 6 contains the weights given to each band. Figure 7 contains the results of the weighted suitability analysis. The reclassified cell values of each band were multiplied by the corresponding weight, then summed to produce the suitability analysis results.

Table 5: Reclassified values for OLI/TIRS bands used in weighted suitability analysis.

Reclassed Value	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 10	Band 11
1	10547-12045	9982-11722	9854 - 11884	9006 - 13148	7579 - 15912	5619 - 16655	5814 - 14893	29753 - 33616	28386 - 31271
5	12045 - 15424	11722-15792	11884 - 17097	13148 - 19598	15912 - 23183	16655 - 27431	14893 - 23548	33616 - 37427	31271 - 34134
1	15424-20503	15792-21474	17097 - 22904	19598 - 25674	23183 - 30303	27431 - 33324	23548 - 30605	37427 - 39072	34134 - 35259

Table 6: Suitability analysis weights for model.

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 10	Band 11
% Weight	12%	14%	15%	12%	12%	18%	14%	1%	2%

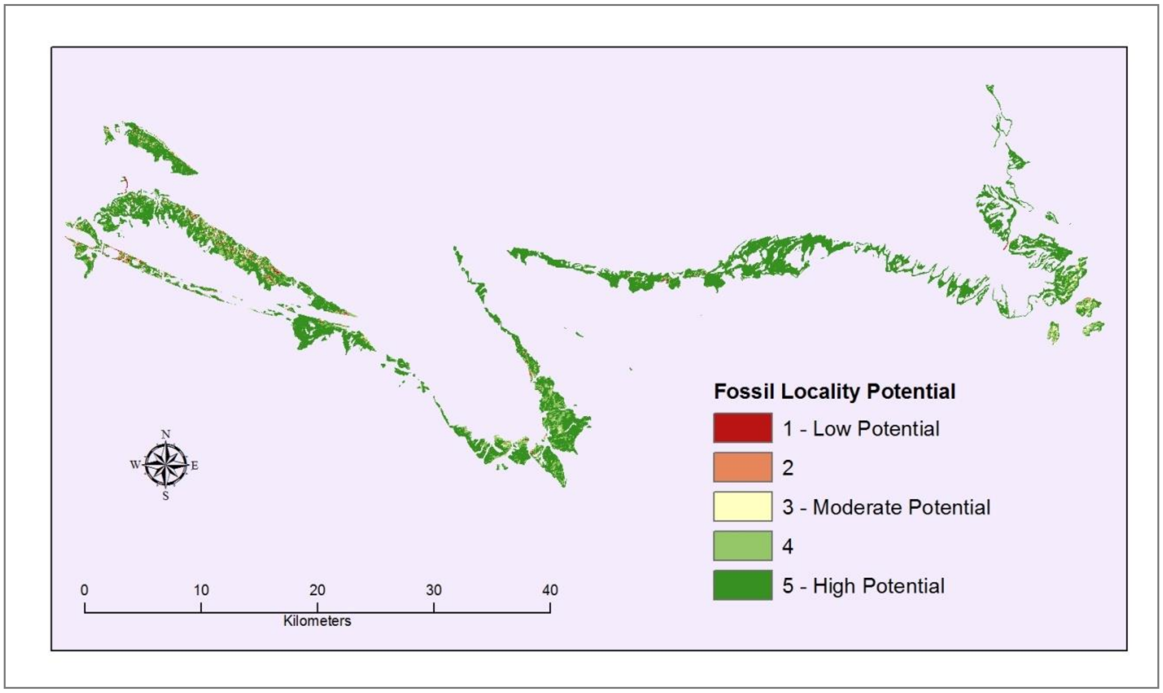

Figure 7: Weighted suitability analysis results.

Field Test of Model

Ten sample high potential sites were chosen to field test the predictive value of the model. Sites were chosen to be within a short distance from roads for good driving access in areas where there were no known BYU localities. Each site was 30m x 30m corresponding to a single pixel from the model. Ground surveys of the sites were conducted by walking the entire surface area of each site and visually inspecting it for signs of fossils. Geological and paleontological data were gathered from each site (see Table 7) including descriptions of rock types present, descriptions of fossils found (if any), the member of the Cedar Mountain Formation on which the site occurs, and other pertinent notes. Photographs were taken of each site (see Figure 8). Observations regarding model functionality were recorded.

Table 7: Summary of field test results.

Site	Geological Description	Paleontological Description	Member	Notes
1	Light brown, medium-coarse grained, planar bedded sandstone with gravel conglomerate stringers; green white, and rusty red mudstone; and white and orange sandy limestone.	No vertebrate fossils found.	Yellow Cat	
2	Surface is covered mostly by colluvium with some outcrop of brown, medium grained, planar bedded, sandstone to conglomerate with spheroidal iron concretions; red, fine-grained sandstone; brown mudstone; and whitish limestone.	No vertebrate fossils found.	Yellow Cat	
3	Surface is covered mostly by colluvium with some boulders of light brown, medium - coarse grained, planar bedded, sandstone with irregular ripples; green, white and red mudstone; and greenish-white very coarse grained sandstone to gravel conglomerate.	No vertebrate fossils found.	Yellow Cat	Slope too steep to survey safely.
4	Surface is covered mostly by colluvium with some boulders of light brown, medium - coarse grained, planar bedded, sandstone with irregular ripples; green, white and red mudstone; and greenish-white very coarse grained sandstone to gravel conglomerate.	No vertebrate fossils found.	Yellow Cat	Slope too steep to survey safely.
5	Surface is covered mostly by colluvium with some outcrop of light brown, medium grained, planar sandstone; and green, light brown, and purple mudstone.	No vertebrate fossils found.	Yellow Cat	Inverte-brate trace fossils found.
6	Surface is covered mostly by colluvium with some outcrop of light brown, medium grained, planar sandstone; and green, purple, and white mudstone.	No vertebrate fossils found.	Ruby Ranch	
7	Light brown, medium grained, planar sandstone with minor light brown sandy topsoil.	No vertebrate fossils found.	Ruby Ranch	
8	Light brown and whitish orange coarse grained sandstone with pebble conglomerate lenses.	10-20 large bone fragments found.	Ruby Ranch	Possibly Poison Strip
9	Surface is covered mostly by light grayish brown, muddy colluvium with minor outcrop of light brown, medium grained sandstone and pebble conglomerate.	No vertebrate fossils found.	Ruby Ranch	Slope very flat, little outcrop.
10	Surface is covered mostly by light grayish brown, muddy colluvium with minor outcrop of light brown, medium grained sandstone and pebble conglomerate.	No vertebrate fossils found.	Ruby Ranch	Slope very flat, little outcrop.

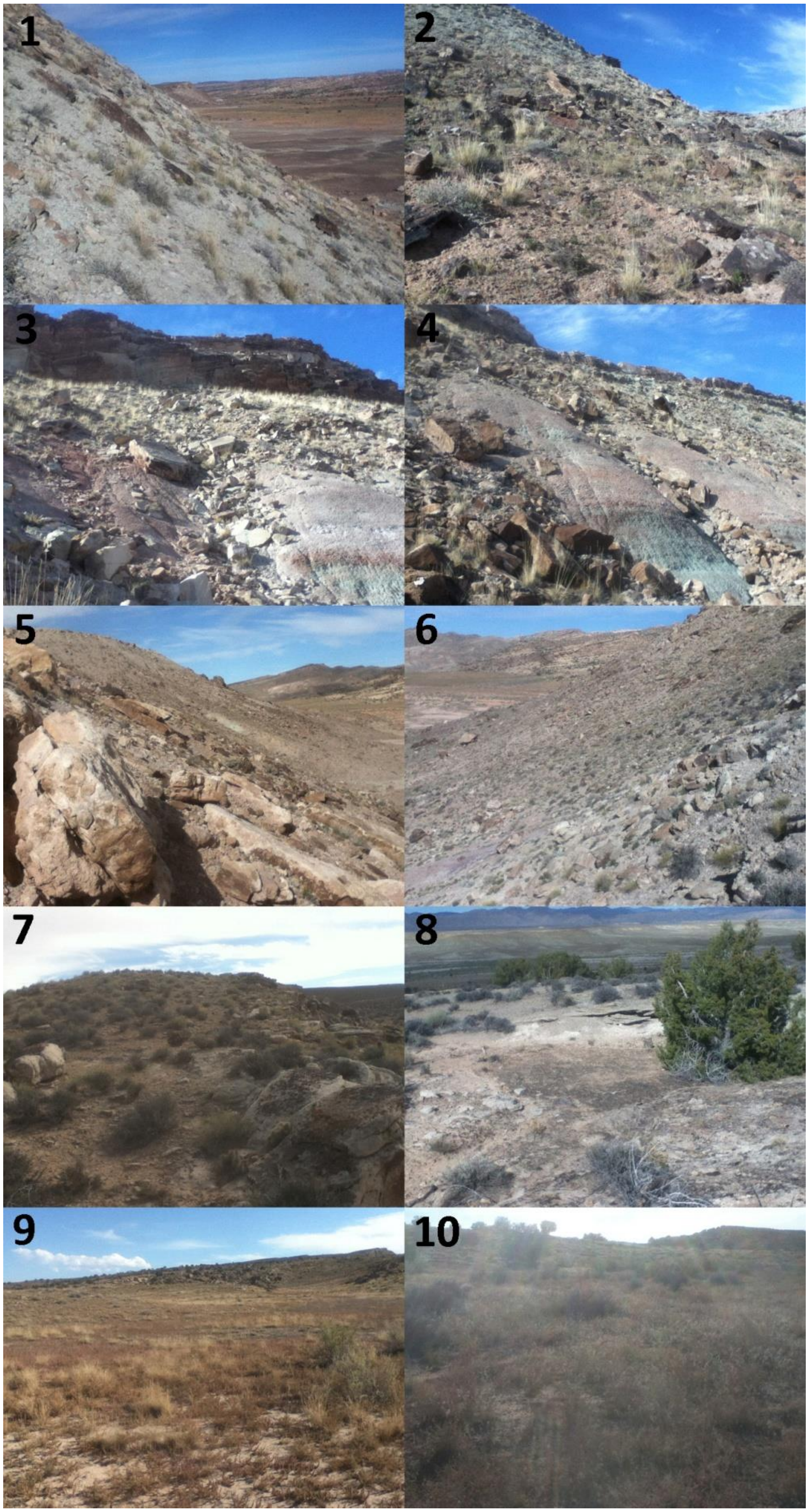

Figure 8: Photos of the ten test sites. Numbers correspond to those in Table 6.

CHAPTER 4: ANALYSIS RESULTS AND DISCUSSION

Problems with Model

Initially Observed Problems

In Figure 6, it becomes immediately apparent that bands 10 and 11 have relatively low difference of means compared to the first seven bands. Consequently, they were given equally low weights in the suitability analysis (see Table 6). Because their overall influence on the model is insignificant, they were removed from subsequent analysis. It was initially assumed that bands 10 and 11 would play a greater role in the analysis because of their common role in distinguishing rock types due to differential heat retention. This proved false likely due to the prevalence of similar rock types within the Cedar Mountain Formation which is primarily composed of mudstones, sandstones, and conglomerates with similar lithologic compositions.

It can be seen in Figure 7 that most of the Cedar Mountain Formation is given high fossil locality potential with only minor numbers of cells in any of the other categories. Figure 9 is a histogram presenting the numbers of cells in each fossil potential category. There is a heavy negative skew with nearly 81% of cells receiving a high fossil potential value. The parameters of the model are too inclusive and not robust enough to distinguish finer differences between fossil localities and the Cedar Mountain Formation as a whole. To ameliorate this problem, further revisions to the model would require a more exclusive reclassification scheme for the OLI/TIRS bands.

Problems Observed Through Field Work

During field work, several additional observations were made regarding model functionality. The scale of the geologic map was too small for sufficiently accurate mapping of formational boundaries. Surface exposure of outcrop on north facing slopes was poor when compared to slopes facing different directions. Slopes which were too steep were difficult and dangerous to prospect for fossils. Two of the chosen test sites (3 and 4) proved to fall into this category and were left unprospected. Three more test sites (1, 2, and 5) also proved difficult to navigate and were also nearly left unprospected. Slopes that were too flat proved to have little outcrop and consisted mostly of Quaternary colluvium and alluvium. Two of the test sites (9 and 10) fell into this category. The model does not take into account the different members of the Cedar Mountain Formation and necessarily lumps them together due to the quality of the geological data.

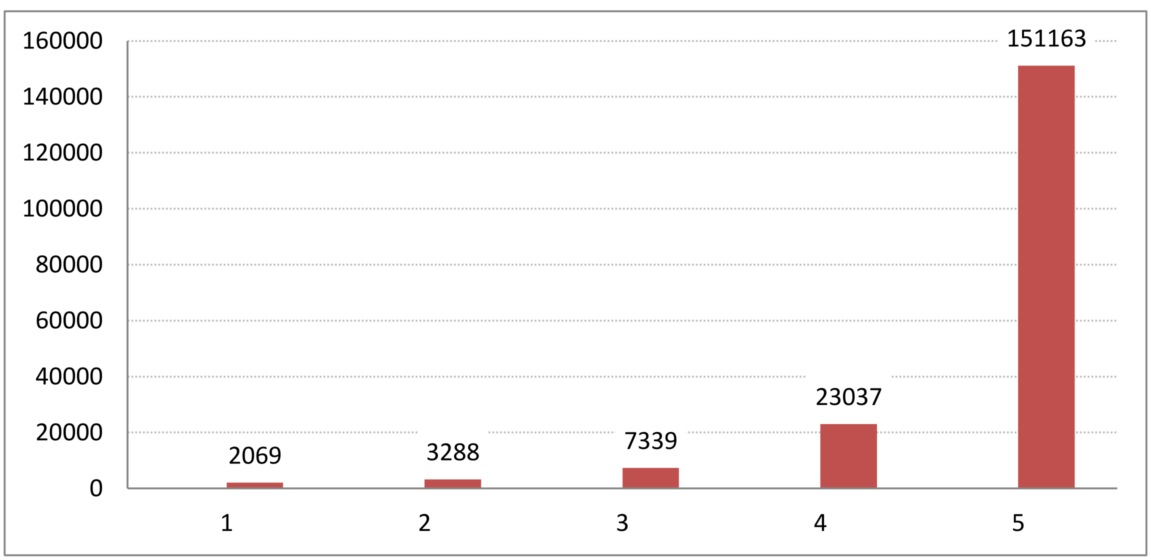

Figure 9: Number of cells assigned to each fossil potential value for the model.

Revised Weighted Suitability Analysis

Revised Reclassification

Due to the limitations of the model, a second weighted suitability analysis was conducted with new reclassification and weights. Bands 10 and 11 were excluded from subsequent analysis. The seven remaining bands were reclassified for a revised weighted suitability analysis. Once again, analysis mask was set to the extent of the Cedar Mountain Formation to exclude areas outside its mapped extent. Values within one standard deviation of the fossil locality mean were given a reclassified value of "9", values between one and two standard deviations from the fossil locality mean were given reclassified values of "5", and values outside of two standard deviations from the fossil locality mean were given reclassified values of "1". Table 8 shows the reclassified values for each band.

Revised Weights

Revised weights were again assigned by comparing the difference of means of each band to the sum of the differences of means of the nine remaining bands. A percentage of how much influence each band had on the sum of the differences of means was used to determine its weight in the suitability analysis. Table 9 contains the weights given to each band. Figure 10 contains the results of the revised weighted suitability analysis.

When Figures 7 and 10 are compared visually, it becomes apparent that the balance of cells in each class is much more stratified in the revised model, greatly narrowing down potential search areas. Figure 11 is a histogram presenting the numbers of cells in each fossil potential category. Though there is still a distinct negative skew it

Table 8: Reclassified values for OLI/TIRS bands for revised model.

Reclassed Value	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7
1	10547 - 12033	9982 - 11729	9854 - 11769	9006 - 13097	7579 - 15695	5619 - 16308	5814 - 15152
5	12033 - 12658	11729 - 12504	11769 - 12870	13097 - 14446	15695 - 17370	16308 - 18995	15152 - 17308
9	12658 - 13909	12504 - 14056	12871 - 15071	14446 - 17145	17371 - 20720	18995 - 24369	17308 - 21620
5	13909 - 14534	14056 - 14831	15071 - 16172	17154 - 18494	20720 - 22395	24369 - 20720	21620 - 23776
1	14534 - 20503	14831 - 21474	16172 - 22904	18494 - 25674	22395 - 30303	20720 - 22395	23776 - 30605

Table 9: Suitability analysis weights for revised model.

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7
% Weight	12%	14%	16%	12%	13%	19%	14%

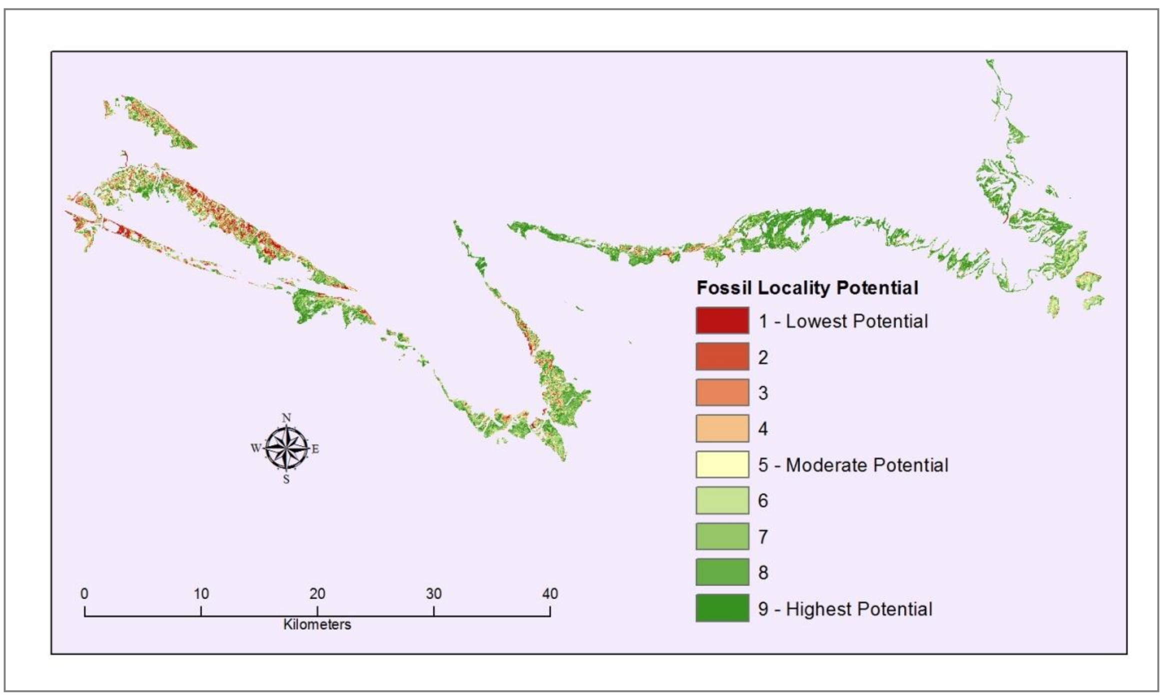

Figure 10: Revised weighted suitability analysis results.

is much reduced compared to the original model with only 23% receiving the highest fossil potential value.

Using this revised model, the ten test sites were examined to determine if their fossil potential classes changed (see Table 10). In the original model the highest possible fossil potential value is "5" whereas, in the revised model the highest possible fossil potential value is "9". Therefore, values of "5" in the original model can be assumed to have a value equivalent to "9" in the new model. Using this assumption, fossil potential for six of the test sites decreased. None received a "low" potential value (between "1" and "4"), but two (sites 3 and 4, not surveyed for steepness) went down to a moderate value of "5". Four remained at the highest potential one of which (site 8) was the only site which contained vertebrate fossils. It is interesting to point out that site 5 which contained invertebrate trace fossils also maintained the highest fossil potential value.

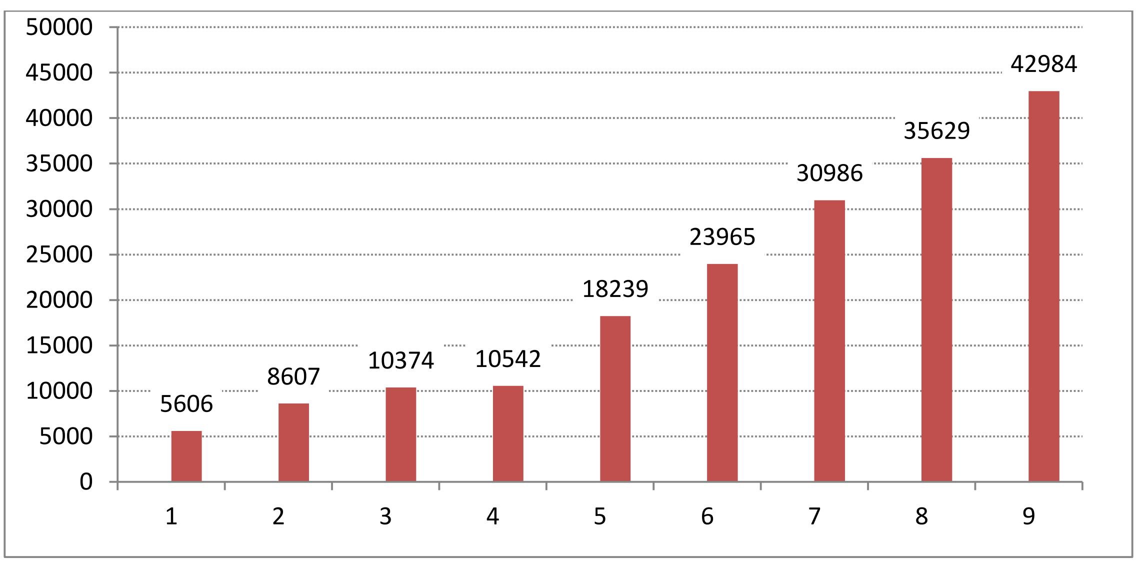

Figure 11: Number of cells assigned to each fossil potential value for the revised model.

Table 10: Test site change in fossil potential between models.

Potential	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
Original	5	5	5	5	5	5	5	5	5	5
Revised	6	8	5	5	9	9	9	9	7	7

Testing the Revised Model

After the original field work and model revisions, the author moved states due to a change in employment and was unable to conduct additional field work due to difficulty travelling to the study area. Furthermore, the study area was largely snow-covered making field work a less effective endeavor. Rather than leaving the revised model completely untested, data was obtained for previously published fossil localities in the Cedar Mountain Formation. These localities were mapped and compared to the model with inconclusive results. Published data was available for only ten fossil localities (see Figure 1).

Only two of the ten published localities fall within the mapped extent of the Cedar Mountain Formation. One of these localities falls onto a cell with a fossil potential value of "8", while the other occurs in a cell of value "5". Taking into account a 50.8 meter margin of error for a 1:100,000 scale map (United States Bureau of the Budget, 1947), a buffer was added to the mapped extent of the Cedar Mountain Formation, however the number of localities falling into its boundaries only increases to three. Distances of the remaining published localities to the buffered Cedar Mountain Formation range from about 10-1800 meters. Spatial data from five of the localities were gathered prior to the descrambling of the GPS signal in 2000 (Clinton 2000), but two of those older localities fall within the mapped boundaries of the Cedar Mountain Formation. Since it is unknown how the coordinates for these localities were obtained, this data set is unreliable at best for analytical purposes. Additional field work or more reliable locality data from another source are needed for more rigorous testing.

Refined Model: Additional Parameters

Thus far this model has only tested the utility of Landsat 8 OLI/TIRS data for its predictive modeling capabilities. No other existing published model relies solely on remotely sensed data of this kind, but includes other available datasets. Though Landsat 8 OLI/TIRS data can still be tested providing time and resources, it was decided to add slope and aspect data to this model in order to refine it further.

Surface Aspect

Burk (2012) hypothesized that fossils are less likely to be found on surfaces with northern aspects. This is likely due to a number of reasons including but not limited to a more active freeze-thaw cycle, greater abundance of vegetation, decreased insolation, greater presence of water, and more developed regolith when compared to surfaces with southern aspects. Figure 12 shows a graphic comparison to the percentages of cells which fall into each of eight cardinal direction aspect classes. Northern (combined NW, N, and NE) aspects consist of 46% of all the cells of the Cedar Mountain Formation. Among BYU localities, northern aspects consist of 29% of all cells. Assuming that aspect has no effect on the presence of fossil localities, 46% of all localities would fall on aspects with northern aspects because 46% of Cedar Mountain Formation cells have northern aspects. If Cedar Mountain Formation aspects were equally distributed in all cardinal directions, only 37.5% of cells would have northern aspects. It appears that there is a bias in the Cedar Mountain Formation to favor northern aspects, whereas the localities show a reduced tendency to appear on northern aspects. So there may be a bias against fossils being found on northern aspects as Burk (2012) suggested.

This bias may be a result of the underlying geologic structure of the region. In this area, the Cedar Mountain Formation has an overall regional dip to the north. This means that the stratigraphic rock beds are not flat, but are tilted downward to the north. As a result, the northern aspects are composed of large exposures of the upper surfaces of rock beds which are more resistant to erosion whereas the southern aspects are comprised of surfaces which cut across multiple rock beds. If a resistant rock bed on a northern aspect has few fossils, there will be few fossils exposed. If a southern aspect cuts across multiple rock beds, there is a greater chance for beds containing fossils to be exposed. Additionally, a more stable surface underlain by a bed of erosion resistant rock is more likely to collect colluvium and debris and be obscured by vegetation than a surface where active erosion is taking place.

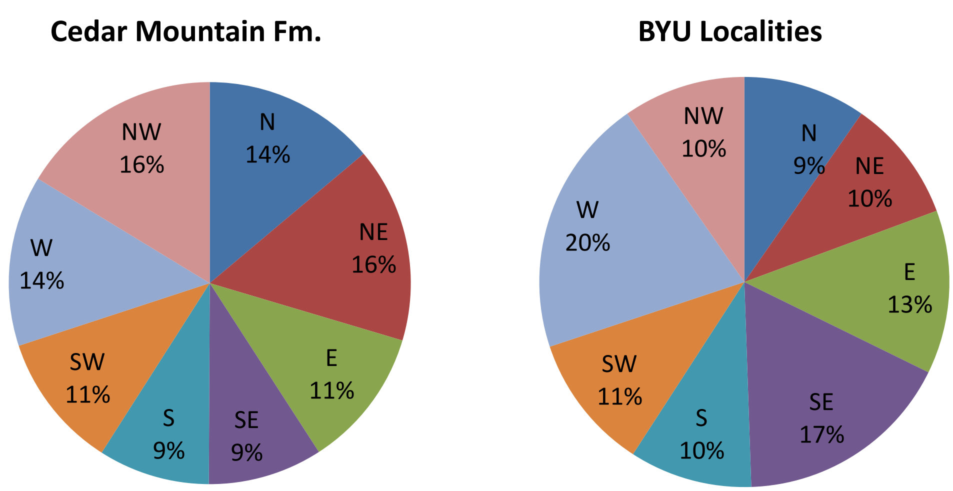

Figure 12: Comparison of aspects between the entire Cedar Mountain Formation and BYU fossil localities.

Surface Slope

Burk (2012) also hypothesized that fossils are less likely to be found on surfaces with higher angle slopes because they have less available surface area with which to expose fossils. He found that fossils were more likely to be exposed on surfaces with a slope less than 10°. Though his exact hypothesis doesn't correspond to data from this study, the general principal holds true; slopes that are too steep tend to have fewer fossil localities. This could be due to limited amount of formational surface rock exposed or could be due to a sampling bias because slopes that are too steep are difficult and dangerous to navigate. Figure 13 shows a visual comparison of the distribution of cells in five degree incremental classes for both the entire Cedar Mountain Formation and BYU fossil localities.

The slopes of the Cedar Mountain Formation follow a strong trend with most cells having a low angle slope with nearly exponentially decreasing numbers of cells in higher angle slope classes. This manifests itself in a distinctly strong positive skew on the histogram. However, the slopes of fossil localities have a recognizably normal distribution with 75% occurring on slopes between 15° and 38° (±1 standard deviation). The Cedar Mountain formation only has 17% of its exposures in that range. There are only two outlying localities on slopes steeper than 45° further indicating a strong bias for fossil localities clustering on lower angle slopes. Field observations indicated that very flat lying slopes (<5°) such as those from test sites 9 and 10 were mainly alluvium and colluvium with little visible outcrop. However eight fossil localities were located on these flat lying slopes. Table 11 contains the detailed data used to construct Figure 13.

Table 11: Distribution of slopes for the entire Cedar Mountain Formation compared to BYU fossil localities.

Slope	BYU Localities	% Total	Cedar Mountain Fm.	% Total
0°-5°	8	8.60%	2,641,591	38.47%
5°-10°	7	7.53%	2,039,087	29.70%
10°-15°	5	5.38%	940,622	13.70%
15°-20°	4	4.30%	508,347	7.40%
20°-25°	13	13.98%	339,526	4.95%
25°-30°	22	23.66%	201,090	2.93%
30°-35°	15	16.13%	112,555	1.64%
35°-40°	12	12.90%	51,371	0.75%
40°-45°	5	5.38%	18,215	0.27%
45°-50°	1	1.08%	7,913	0.12%
50°-55°	0	0.00%	3,391	0.05%
55°-60°	0	0.00%	1,500	0.02%
60°-65°	1	1.08%	468	0.01%
65°-70°	0	0.00%	126	0.00%
70°-75°	0	0.00%	10	0.00%
Total	93	100.00%	6,865,812	100.00%
Minimum	1.7179		0	
Maximum	56.2603		73.2043	
Mean	26.7111		9.2717	
Standard Dev.	10.7417		7.9199	

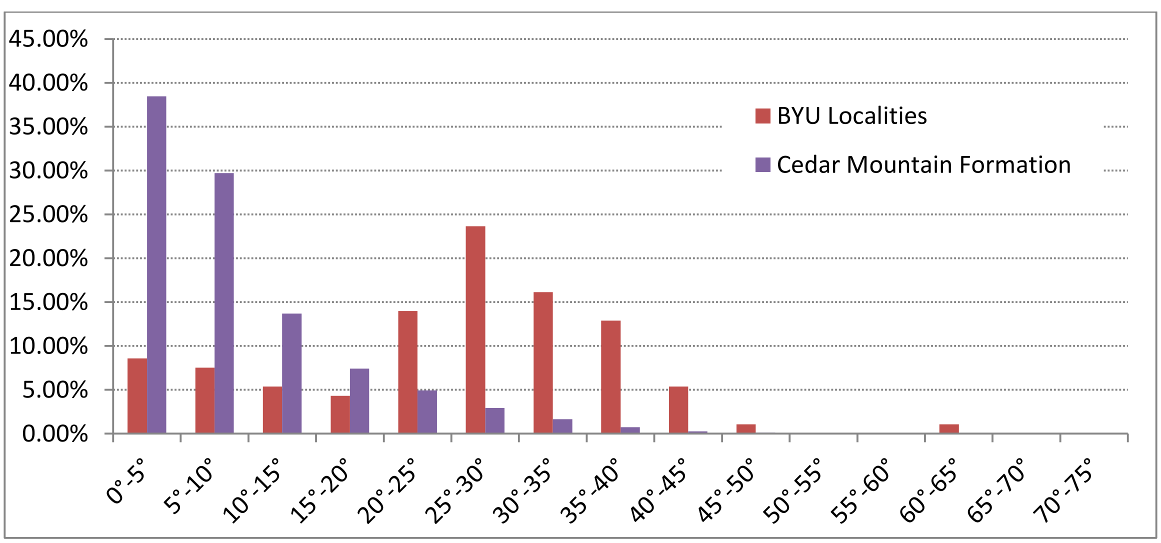

Figure 13: Comparison of slopes between the entire Cedar Mountain Formation and BYU fossil localities.

Refined Model Results

Since there seems to be a bias against fossil localities on northern aspects, raster operations were used to exclude northern aspects (aspects ≤ 22.5° and ≥ 337.5°) from the predictive model. Since there is also a bias against fossil localities occurring on high angle slopes, those greater than 45° were also excluded from the predictive model using raster operations. Though there may still be a bias against fossil localities being found on flat lying surfaces due to the low number of localities compared to the high percentage of flat lying Cedar Mountain Formation, low angle slopes were not excluded from the analysis. Figure 14 presents the results of the refined model. Figure 15 is a side-by-side detail comparison of the original, revised, and refined models.

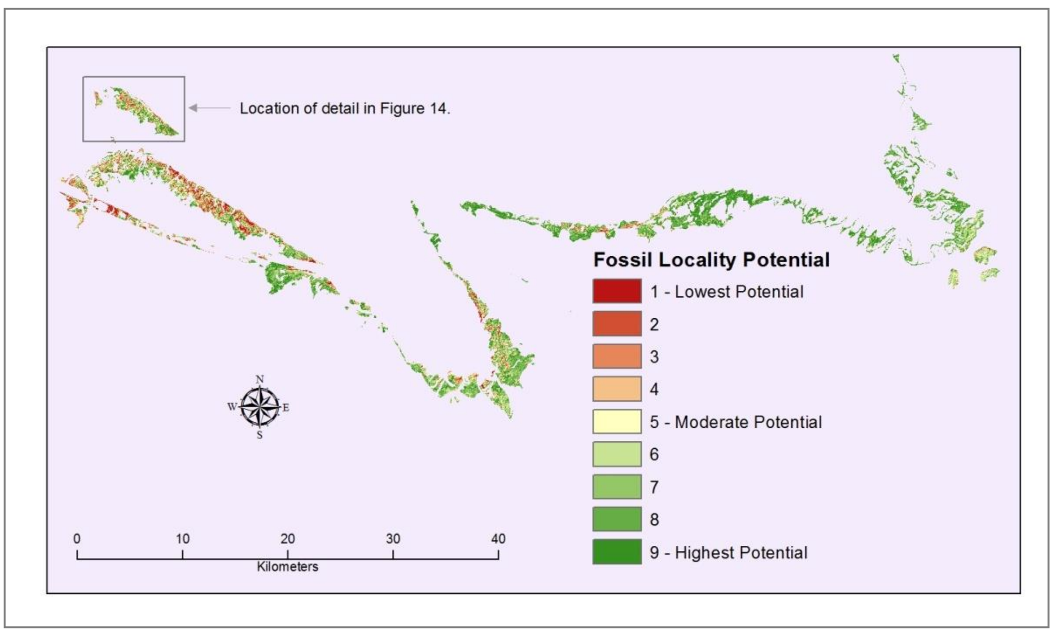

Figure 14: Refined model results.

Additional Issues

Geologic Map Accuracy

The geologic map (Doelling 2002) which was used in the model is small scale (1:100,000) so details about its contacts with adjacent units may be inaccurate. As a result, the model likely excludes areas of actual Cedar Mountain Formation from its parameters as well as including areas that actually belong to adjacent formations. Only 43 of the 98 BYU localities (43.88%) fall within the Cedar Mountain Formation as mapped by Doelling (2002). Taking into account a 50.8 meter margin of error, the number increases to 73 of 98 (74.49%). Adding a 5 meter buffer to fossil localities to account for GPS signal accuracy error does not move any of them into the buffered Cedar Mountain Formation.

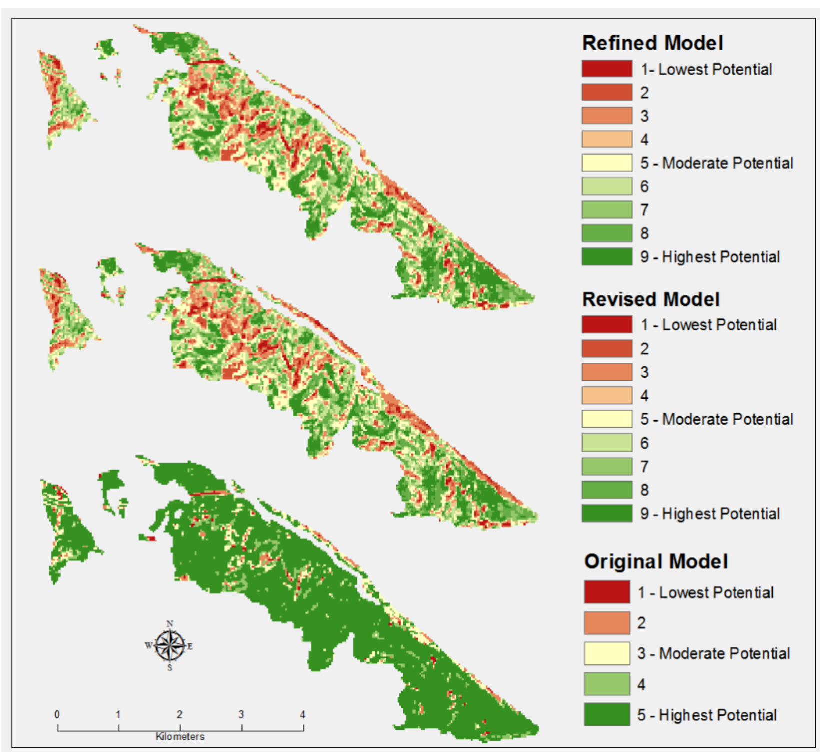

Figure 15: Detailed comparison of model versions.

At this point, larger scale geologic maps were obtained for comparison to the small scale map used in the model and to the fossil localities. The large scale (1:24,000) maps can be divided into two suites; an older suite published from 1955 to 1956 and a newer suite published from 1994 to 2009 (see Table 12; also see Figure 3 and detailed description of maps in Chapter 3). These maps only cover a portion of the study area, but are illustrative of the issues regarding this type of data as a whole.

The older suite of large scale maps were published prior to the modern understanding of the extent and nature of the Cedar Mountain Formation in this area. Of the seven maps, five show what is now recognized as the Cedar Mountain Formation as "probable equivalent of the Burro Canyon Formation" divided into upper and lower units (Detterman 1955; Sable 1955a; Sable 1955b; Sable 1955c; Sable 1956). The other two maps simply call it the Burro Canyon Formation (Bates 1955a; Bates 1955b). The Burro Canyon Formation is currently recognized as the time equivalent formation to the Cedar Mountain Formation east of the Colorado River (Stokes 1952). In places, Bates (1955b) showed the Cedar Mountain Formation as an undifferentiated unit combined with the overlying Dakota Sandstone further confusing the issue. It is common practice to combine adjacent units when their individual surface exposures are too thin to be displayed accurately at the map scale or where it is too difficult to separate them accurately. In places, Doelling (2002) also combined both the Burro Canyon Formation and the Cedar Mountain Formation with the Dakota Sandstone. In some areas the larger scale maps are more detailed with less generalization and position inaccuracy and in other areas the smaller scale map is more detailed (see Figure 16). This is perhaps due to changes in mapping methods and understanding of the geologic units over time.

With regards to BYU's localities, only one (the well known Dalton Wells Dinosaur Quarry) exists within the mapped extent of the older suite of large-scale map boundaries of the Burro Canyon Formation whereas it falls outside the boundaries of the Cedar Mountain Formation in Doelling (2002). Additionally, only one published locality (Don's Ridge) falls within the mapped extent of the large-scale maps (Sable 1955b) where it falls within the boundaries of the mapped Burro Canyon Formation (see Figure 16). The Don's Ridge fossil locality also falls within the mapped Cedar Mountain Formation in Doelling (2002).

The newer suite of large scale maps are also more detailed regarding geologic unit boundaries than Doelling (2002). Chitwood (1994) showed no Cedar Mountain Formation within its boundaries even though Doelling (2002) showed a small portion of it in the SW corner. Without additional field work to resolve this discrepancy, it remains unknown which of the two maps is correct in this case. Three of the remaining maps (Doelling 1996, 1997, Doelling & Morgan 2000) represent the Cedar Mountain

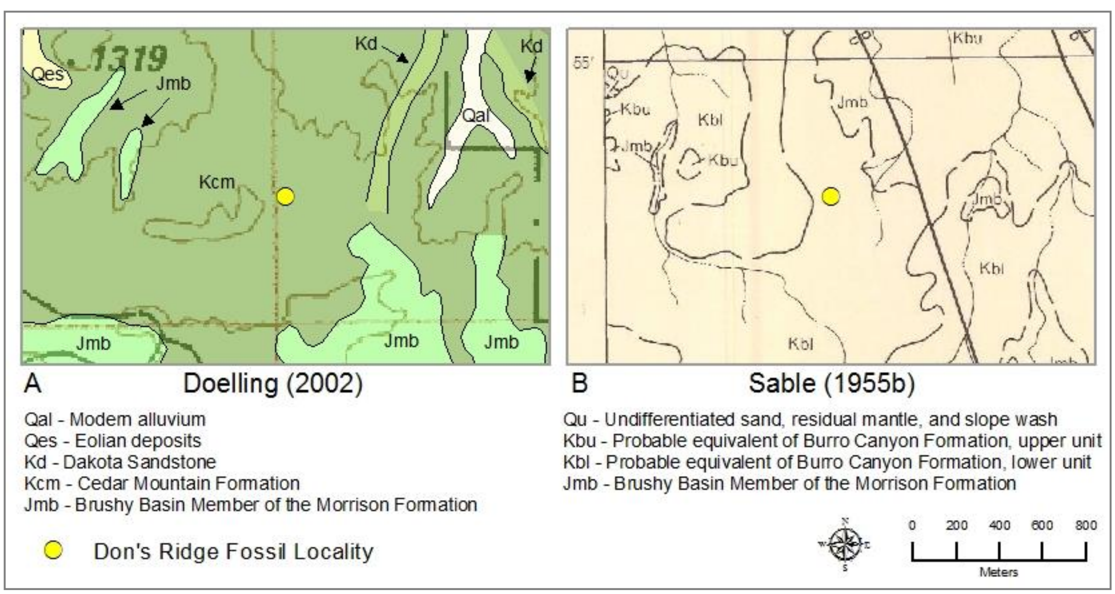

Figure 16: Detailed comparison of small (A) and large scale (B) maps.

Formation as an undivided unit. The other three maps (Doelling & Kuehne 2009a, 2009b, 2009c) display the Yellow Cat, Poison Strip, and Ruby Ranch Members as separate units. The map descriptions for the Poison Strip and Ruby Ranch Members in these maps mention the presence of fish, reptile, and dinosaur fossils as well as petrified wood. The Buckhorn Conglomerate and Mussentuchit Members are not present in this area.

Thirty-two BYU localities fall within the boundaries of the newer maps. Allowing for 12.2 meters of error in 1:24,000 scale maps (United States Bureau of the Budget 1947), only one of these localities falls outside the mapped extent of the Cedar Mountain Formation. When compared to Doelling (2002) 26 of these localities are inside the 50.8 meter buffered extent of the Cedar Mountain Formation and six are outside. Three published localities fall within the boundaries of the newer maps. All three fall outside the mapped extent of the Cedar Mountain Formation. When compared to Doelling (2002), two fall outside the buffered Cedar Mountain Formation while one falls inside further emphasizing the suspect nature of this dataset.

The Merrimac Butte 7.5' quadrangle is the only portion of the entire study area for which there is overlap between the older series of 1:24,000 scale maps (Bates 1955b), the newer series of 1:24,000 scale maps (Doelling and Morgan 2000) and the 1:100,000 scale map (Doelling 2002). No published localities and only one BYU locality occur within the quadrangle. Doelling & Morgan (2000) showed the Dalton Wells Dinosaur Quarry roughly 60 meters outside the mapped extent of the Cedar Mountain Formation in an area mapped as the Brushy Basin Member of the Morrison Formation. As discussed previously, the Dalton Wells Dinosaur Quarry falls within the boundaries of the mapped

Burro Canyon Formation (Cedar Mountain Formation equivalent) in Bates (1955a) whereas it falls outside the boundaries of the Cedar Mountain Formation in Doelling (2002). Figure 17 offers a detailed comparison of the three maps centered around it.

Table 12 lists by map how many fossil localities of each type fall inside and outside of the boundaries of the Cedar Mountain (or Burro Canyon) Formation taking into account buffers for allowable errors at their respective map scales. Sixty-six of the BYU localities are within the boundaries of two USGS 7.5' quadrangles (Cisco SW and Mollie Hogans) for which there are no accompanying 1:24,000 scale geologic maps (see Figure 3 for quadrangle names and locations). Six published localities are within the boundaries of three USGS 7.5' quadrangles (Mollie Hogans, Klondike Bluffs, and The Windows Section) for which there are no accompanying 1:24,000 scale geologic maps. Since these represent the majority of the fossil localities, more accurate geologic data for their areas would be valuable.

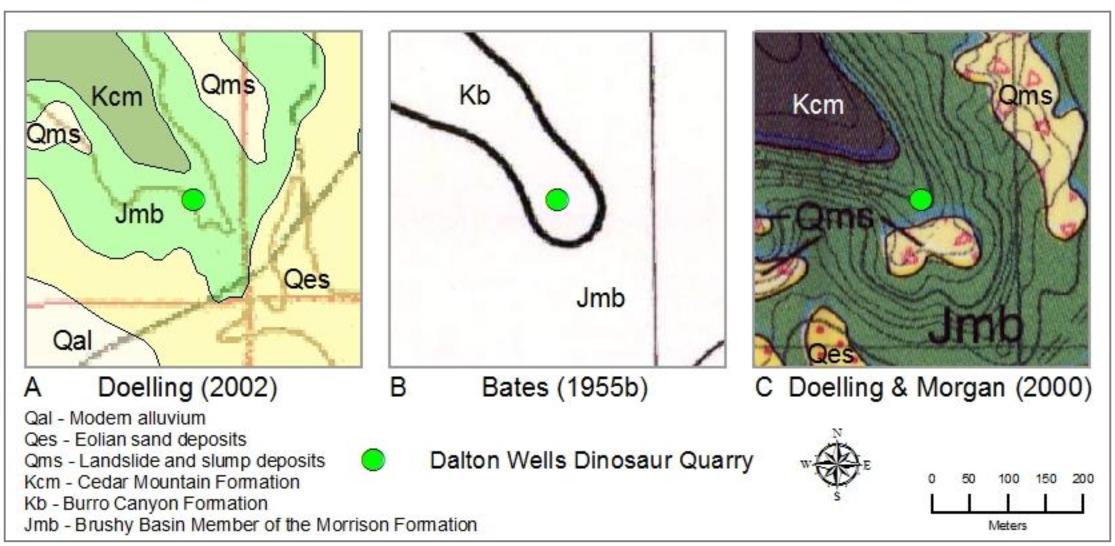

Figure 17: Detailed comparison of geologic maps in the area surrounding the Dalton Wells Dinosaur Quarry.

Table 12: Summary of fossil localities relative to Cedar Mountain Formation per geologic map.

		BYU Localities		Published Localities	
	Quadrangle and Map	Inside	Outside	Inside	Outside
Old Suite 1:24,000	Green River (Sable 1956)				
	Horse Bench East (Sable 1955a)				
	Daly (Sable 1955b)			1	
	Green River SE (Sable 1955c)				
	Dee Pass (Detterman 1955)				
	Jug Rock (Bates 1955a)				
	Merrimac Butte (Bates 1955b)	1			
New Suite 1:24,000	Hatch Mesa (Chitwood 1994)				
	Valley City (Doelling 1997)				1
	Merrimac Butte (Doelling & Morgan 2000)		1		
	Thompson Springs (Doelling & Kuehne 2009a)				
	Sagers Flat (Doelling & Kuehne 2009b)				1
	White House (Doelling & Kuehne 2009c)	13			
	Dewey (Doelling 1996)	18			1
	Old Suite Totals	1	0	1	0
	New Suite Totals	32	1	0	3
	Moab 30'x60' (Doelling 2002)	73	25	3	7

Errors in geologic data could adversely affect model effectiveness. These errors may result from a poor understanding of the geologic units, less effective mapping methods, and distortion or inaccuracies introduced through georeferencing. Knowing the limitations of the data is important because most researchers cannot produce it firsthand but must rely on previous work.

Unresolved Problems with the Model

While usually not distinguishable to the naked eye in the field, microfossils play an important role in paleontological investigations. Though well known from the Cedar Mountain Formation (Cifelli 1999, Cifelli and Madsen 1998, Eaton and Cifelli 2001, Gardner 1999, Nydam 2000, Nydam and Cifelli 2002), microfossils were not tested for in this model. None of the localities used in the analysis were microfossil localities nor were they sampled for during field work. Fossil plants (Dayvault and Hatch 2007, Thayn and Tidwell 1984, Thayn *et al*. 1983, Thayn *et al*. 1985) and invertebrates (Sames *et al*. 2010), though known from the Cedar Mountain Formation, were similarly ignored by the model.

The BYU fossil locality data consists of all localities containing identifiable vertebrate bone. Some of these localities consisted solely of fragments of bone only identifiable as vertebrate but not of insufficient quality or quantity to determine which group of vertebrates it came from. Some of the localities are quarries which have produced articulated and associated skeletons or even mass mortality assemblages. In this study relative importance of localities was not distinguished.

Accurate locality data with reasonably large population sizes are difficult to come by. Exact physical locations of fossil localities are often closely and jealously guarded to avoid fossil poaching by amateurs, accidental damage by the curious public, and even collection by rival research groups. Geospatial data on only ten published vertebrate fossil localities was able to be obtained and most of these proved unreliable.

Though the NAD1983 UTM Zone 12 N projected coordinate system was used for the analysis, source data was created using several different projected coordinate systems. The conversion from one coordinate system into another likely caused minor spatial errors. Table 13 lists the data sets and their respective coordinate systems.

Table 13: Coordinate systems of datasets used in analysis.

Dataset	Coordinate System
Landsat 8 OLI/TIRS	WGS 84 UTM Zone 12N
Doelling (2002)	NAD 1927 UTM Zone 12N
1:24,000 scale maps	NAD 1927 UTM Zone 12N
DEM	NAD 1983 UTM Zone 12N
BYU localities	WGS 84 UTM Zone 12N
Published Localities	NAD 1983 UTM Zone 12N

CHAPTER 5: CONCLUSION

The purpose of this study was to create a fossil locality predictive model for the Early Cretaceous Cedar Mountain Formation near Moab, UT which was successfully completed. The model used Landsat 8 OLI/TIRS spectral reflectance data, slope degree and aspect data, and known fossil localities to identify areas within the Cedar Mountain Formation which have similar physical and spectral attributes. The model was field tested and refined. Areas of high fossil locality potential were identified.

Successful field testing of the model after final refinements was unable to be completed due to distance from the field area. Known fossil localities were compared to the fossil potential values in the final predictive model to check for internal model consistency. Though most localities ended up being outside the boundaries of the final model due to datum conflicts and quality of geologic boundary data, all localities falling within the final predictive model boundaries were located on cells of fossil potential value "5" (moderate fossil potential) to "9" (highest fossil potential) with more in the highest fossil potential class than any other (see Table 14).

In general, fossil locality predictive models have various common problems. They are not intended as substitutes for field work and do not have the capability to determine exact locations of fossil sites. Rather they are intended as a tool to aid researchers in narrowing down potential search areas and to allocate time and resources more wisely. The quality of fossil locality predictive models is dependent on the quality of the input data and the methods of determining suitability. There is no one predictive model solution for all types of field areas and those creating them must already have a strong understanding of environmental conditions surrounding them. Additionally, they

Table 14: Comparison of Fossil Potential to BYU and Published Localities.

Fossil Potential Value	1	2	3	4	5	6	7	8	9	Outside	Total
BYU Localities					5	4	4	5	12	68	98
Published Localities									1	9	10

are of very limited use in populated areas where the surface of the earth has been obscured or heavily modified due to human habitation.

This study represents the first fossil locality predictive model for the Cedar Mountain Formation. Using the results of this predictive model, Cedar Mountain Formation researchers could potentially find new fossil localities containing valuable information answering some of the questions regarding faunal overturn and climate change posed by these rocks and the fossils found within them. This study demonstrates the ease and usefulness of using remotely sensed data and GIS to further paleontological investigations. With tools such as this, many more paleontologists could reduce unproductive prospecting time, save money, and maximize effort in the field.

Perhaps the largest problem remaining with this study is that the final predictive model has not been field tested for accuracy. This task would be the next logical step in the research. Additionally, the inaccuracies with the geologic map data could possibly be ameliorated by using the 50.8 meter buffered Cedar Mountain Formation as the analysis mask. Alternately, the entire Landsat 8 OLI/TIRS dataset could be used in the analysis and personal knowledge of Cedar Mountain Formation extent could be used in the field to limit search areas.

Other fossil locality predictive models used differing datasets such as land use/land cover classifications (Conroy *et al.* 2012, Emerson and Anemone 2012, Oheim

2007) and differing methods such as cost raster analysis (Egeland *et* al. 2010) neural network classification (Emerson and Anemone 2012). Further study could compare the use of those datasets and methods to those in this study to see if some offer better results than others. New methods such as object based image analysis could also be applied and tested in fossil locality predictive models.

Lastly, no fossil locality predictive model study has ever compared a set of random sites selected without using a predictive model to a set of sites identified by a predictive model. Nor have many low potential areas been intentionally investigated to test model accuracy. Further study in this area could strengthen the claims of researchers pioneering this field.

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