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Lithium extraction from oilfield brine

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Lithium extraction from oilfield brine

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Abstract

Lithium extraction from oilfield brine

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Lithium production through atmospheric evaporation of saline brine is generally the most economically efficient method of extraction. As global demand for lithium increases, production technology has evolved to reduce processing time of lithium from brine. The resulting technology invites the opportunity to consider lithium production from lower concentration petroleum brines, a long-overlooked lithium-rich resource. Capitalizing on advanced filtration technology and petroleum well infrastructure, the petroleum-producing geologic formations in the U.S. were evaluated for their lithium production potential.

The U.S. Geological Survey National Produced Waters Geochemical Database was utilized to identify lithium-rich brine from wells across the U.S. The volume and concentration potential of the most promising lithium-enriched geologic formation were calculated. Historical and current well production data were compiled and used to estimate the expected lithium production for the geologic formation. This data was then applied to a financial model to determine the method of brine production under which extracting lithium from oilfield brine would be profitable.

Advanced technology offers the advantage of recovering Li from concentrations as low as 70 mg/L. Of the produced water samples, only 344 samples had Li concentrations greater than or equal to 70 mg/L. The majority of the high Li concentration samples were identified in the Smackover Formation. The Smackover was selected to analyze for lithium extraction and production. Lithium-enriched brine can be gathered from the Smackover by collecting produced water from active wells in the formation or by drilling a purpose-designed well to access brine.

Despite the ability to recover low-concentration lithium in brines, Results from the financial analysis indicate that the profitability of lithium extraction from Smackover oilfield brine is dependent on the lithium concentration of brine that is processed by the facility. Profit can be further enhanced by using economies of scale to increase the brine processing capacity of the facility. In this analysis, drilling a purpose-designed well resulted in the only profitable endeavor. When utilizing existing infrastructure to collect brine, the profitability is highly dependent on the number of active wells that produce from the Smackover Formation. This analysis indicates that a standalone lithium extraction company is best positioned to capitalize on lithium extraction from oilfield brine.

Table of Contents

List of Tables x

List of Figures xii

Chapter 1: Introduction 1

1.1 Statement of purpose..1

1.2 Hypothesis...1

Chapter 2: The Lithium Market 2

2.1 Market overview 2

2.2 Market forecast 5

2.2.1 Demand 5

2.2.2 Supply 6

2.2.3 Price 8

2.3 Lithium as a strategic mineral..13

Chapter 3: Lithium Resources and Production 14

3.1 Introduction...14

3.2 Hard rock mining 14

3.2.1 Geology..14

3.2.2 Mineral resources...16

3.3 Brine..17

3.3.1 Geology..17

3.3.2 Brine resources...21

3.4 Additional resources 23

3.4.1 Clays 23

3.4.2 Zeolite 23

3.4.3 Geothermal brines..24

3.5 Oilfield brines 24

3.5.1 Resources 24

3.5.2 Smackover geology..26

Chapter 4: Data Analysis 36
4.1 Overview 36
4.2 Data set 36
4.3 Lithium distribution analysis 38
4.4 Smackover lithium distribution analysis 42
4.5 Smackover resource prediction maps 52
Chapter 5: Financial Model Assumptions 64
5.1 Scenario overview 64
5.2 Reserve estimates 65
5.3 Well production capacity 66
5.4 Associated costs 71
5.4.1 Rights to brine and oil 71
5.4.2 Well costs 72
5.4.3 Transportation of brine 73
5.4.4 Facility and extraction technology 74
5.4.5 Disposal of residuum 76
5.5 Commodity prices 77
5.5.1 Lithium prices 77
5.5.2 Oil prices 78
Chapter 6: Commercial Analysis 81
6.1 Scenario 1: Produced water acquired from operators 81
6.2 Scenario 2: Oil company sells producing wells to lithium company 87
6.3 Scenario 3: Lithium producer drills well 96
Chapter 7: Conclusion 101
7.1 Hypothesis 101
7.2 Discussion 101
7.2.1 Break-even analysis 101
7.2.2 Production challenges 103
7.2.2.1 Existing infrastructure 103

7.2.2.2 Supply interruption 104
7.2.3 Commercial competition and strategy 104
7.3 Recommendations...107
7.3.1 Analysis...107
7.3.2 Implementation 108
Appendix A...110
Appendix B 118
Glossary 119
References...121

List of Tables

Table 2.1: New lithium production projects from brine and mineral resources with 2020 start date or earlier. Data modified from Verma et al., 2016. 8

Table 2.2: Predicted price of LCE per metric ton from 2015 - 2017 regression. ..10

Table 3.1: Enriched and depleted ions in the Smackover brine relative to brine originating from seawater. 28

Table 4.1: Statistics for the Smackover Formation, Subsets 1 and 2, and their adjusted subsets. 45

Table 4.2: Nearby wells associated with outlier well in Subset 1. 47

Table 4.3: Nearby wells associated with outlier value Li = 1430 ppm in Subset 2.50

Table 4.4: Nearby wells associated with outlier value Li = 1700 ppm in Subset 2.51

Table 4.5: Comparison of average concentrations in Smackover formation to seawater..61

Table 4.6: Comparison of concentration ratios measured in the Smackover to that observed in seawater. The ratio is written as Smackover: Seawater.61

Table 4.7: Averages of selected ions from USGS Smackover data (in ppm) and respective regression statistics. 62

Table 4.8: Averages of selected ions from Subset 1 of USGS Smackover data (in ppm) and respective regression statistics. 62

Table 4.9: Averages of selected ions from Subset 2 of USGS Smackover data (in ppm) and respective regression statistics. 62

Table 5.1: Lithium reserve calculation for Subsets 1 and 2 of the Smackover Formation. 66

Table 5.2: Compiled averages of Smackover characteristics from surveyed research. 70
Table 5.3: Ideal specific flow rate of a newly drilled well in the Smackover Formation. 70
Table 5.4: Model of financial compensation for rights to access brine. 71
Table 5.5: Prices per metric ton of LCE used in analysis. 77
Table 5.6: Prices per barrel of oil used in analysis. 80
Table 7.1: Break-even analysis of the conditions required for each scenario to have an NPV greater than zero. 102
Table 7.2: Production capacity and utilization of lithium facilities from major lithium producing countries. From Verma et al., 2016. 105
Table 7.3: Potential processing facility expansion and corresponding lithium carbonate production under Scenario 3 parameters. 107
Table A-1: Selected data from Subset 1 (in ppm) 111
Table A-2: Selected data from Subset 2 (in ppm) 113
Table B-1: Production data from a producing well in the Smackover Formation from Subset 1. 118

List of Figures

Figure 2.1: Global lithium production by country. Data from Swain, 2017............3

Figure 2.2: Global end-use market of lithium in 2017. Data from Jaskula, 2018. ..4

Figure 2.3: Average price of LCE per metric ton and year over year growth. Data from Benchmark Minerals, 2017 and "Lithium Price," 2018............9

Figure 3.1: Cross section of the concentric arrangement of pegmatites enriched in rare minerals. From Bradley et al., 2017...15

Figure 3.2: World map of lithium brines, clays, and zeolites. From Bradley et al., 2017..18

Figure 3.3: Diagram of depositional model for lithium brine. From Bradley et al., 2013..20

Figure 3.4: Paleoposition and wind direction during the Late Jurassic. The area of the Smackover Sea is highlighted in yellow. Prevailing winds (red) and winter winds (blue) show the direction of sediment transport to the area of the Smackover. Modified from Hunt, 2013................................25

Figure 3.5: Stratigraphic setting of Jurassic sediments. From Stueber et al., 1984.27

Figure 3.6: Igneous intrusions proximal to wrench faulting in the Late Cretaceous. Modified from Zimmerman, 1992. 31

Figure 3.7: Model for lithium enrichment of Smackover brines from Alleghenian volcaniclastics and air fall tuff. From Chuchla, 2018. 32

Figure 3.8: Seismic imaging of the Norphlet Formation in Mobile Bay, AL showing east-west trending normal faults and northwest trending dunes. From Ajdukiewicz et al., 2010. 34

Figure 4.1: Geographic distribution of lithium-bearing well samples in the United States. 37
Figure 4.2: Cumulative frequency distribution of lithium concentration in well samples. 39
Figure 4.3: Notable intervals of the cumulative frequency distribution of lithium samples. 40
Figure 4.4: Anomalously high lithium concentrations displayed by formation. ...41
Figure 4.5: The geographical distribution of lithium-bearing samples from the Smackover Formation are identified in two distinct regions. 43
Figure 4.6: Histogram of lithium samples from the Smackover Formation. 44
Figure 4.7: Histogram of lithium Samples from Subset 1 of the Smackover Formation, located in Alabama, Florida, and Mississippi. 46
Figure 4.8: Histogram of lithium samples from Subset 2 of the Smackover Formation, located in Arkansas, Louisiana, and Texas. 49
Figure 4.9: Approximate geographic extent of the Smackover Fairway, as illustrated by Collins, 1976. 53
Figure 4.10: Prediction maps of lithium concentrations in the Smackover Subset 1 using different methods of computing: A) Inverse Distance Weighting; B) Ordinary kriging with a second-order trend removal and a logarithmic transformation..54
Figure 4.11: Regional faulting in the Gulf of Mexico. From MacRae and Watkins, 1996...55

Figure 4.12: Prediction maps of lithium concentrations in the Smackover Subset 2 using different methods of computing: A) Inverse Distance Weighting; B) Ordinary kriging with and third-order trend removal and no transformation. 57

Figure 4.13: Fault zones influencing potential control on the predicted lithium pathways in Subset 2 area. Modified from Hammes and Frebourg, 2012. 58

Figure 4.14: Predictive map of lithium concentration in the Smackover Formation Subsets. The Smackover Fairway connects both of the modeled areas but has not been modeled here due to lack of available data. 59

Figure 5.1: Tornado diagram of factors that impact reserve estimates. 67

Figure 5.2: Oil price decks constructed for assessing future oil price. 79

Figure 6.1: Sources of revenue in Scenario 1. 82

Figure 6.2: Breakdown of costs for Scenario 1....................83

Figure 6.3: Overview of free cash flow in Scenario 1 with respect to oil and brine rights royalty payments. 85

Figure 6.4: Scenario 1 production cost per metric ton of lithium carbonate compared to market price of LCE. 86

Figure 6.5: Expected revenues and costs for OilCo from Smackover producing wells. 89

Figure 6.6: Sources of revenue for LithiumCo in Scenario 2. 90

Figure 6.7: Breakdown of costs in Scenario 2. 92

Figure 6.8: Scenario 2 production cost per metric ton of lithium carbonate compared to market price of LCE. 93

Figure 6.9: Overview of free cash flow in Scenario 2 with respect to oil and brine rights royalty payments. 95
Figure 6.10: Revenue and costs in Scenario 3. 98
Figure 6.11: Overview of free cash flow in Scenario 3 with respect to brine rights royalty payments. 99

Chapter 1: Introduction

1.1 Statement of purpose

Lithium is considered a strategic mineral for its application in batteries. Lithium production through atmospheric evaporation of saline brine is generally the most economically efficient method of extraction. As global demand for lithium increases, production technology has evolved to reduce the processing time of lithium from brine. The resulting technology invites the opportunity to consider lithium production from lower concentration petroleum brines, a long-overlooked lithium-rich resource. Evaluating the production potential of lithium from oilfield brines in the U.S. is a potentially worthwhile resource to enhance energy independence and combat inflated lithium prices.

1.2 Hypothesis

The untapped lithium resource in the Smackover Formation can be profitably extracted by combining advanced filtration technology with a purpose-drilled well to gather brine. The profitability of the operation can be further enhanced by the sale of processed brine from the Smackover to downstream markets. This will be possible due to thorough decontamination of the brine that must take place before lithium extraction, resulting in a byproduct of "clean" water for resale or reuse.

Chapter 2: The Lithium Market

2.1 Market overview

Production of lithium is dominated by hard rock mineral mining in Australia and brine extraction in Chile, as shown in Figure 2.1. These countries have a significant portion of the world's lithium reserves. A lithium reserve refers to the portion of the total resource that is economically recoverable at the time of determination (USBM and USGS, 1980). In 2017, global production of lithium was estimated to be 43,000 metric tons and global reserves were determined to be 16 million metric tons (Jaskula, 2018).

Lithium is traded in three forms: as lithium minerals from hard rock, as lithium compounds from brine, or as lithium metal from electrolysis of lithium compounds (Bradley et al., 2017). Since its discovery in 1817 by Johan Arfvedson, a Swedish chemist, lithium has been useful in a breadth of applications. Lithium has the highest specific heat capacity and redox potential value of any solid element (Swain, 2017). Lithium is used in air treatment, lubricants, polymers, pharmaceuticals, ceramics, glass, batteries, and much more (Kesler et al., 2012). The breakdown of the end-use market is exhibited in Figure 2.2. Batteries represent a sizeable portion of the end-use market of lithium. From 2015-2017, the end-use market for lithium in batteries increased from 35 percent to 46 percent (Jaskula, 2018). Glass and ceramics have made a significant use of lithium as well, comprising more than 25 percent of the end-use market.

Many substitutes exist that can replace lithium in its application. Sodic or potassic fluxes can be applied for glass and ceramics manufacturing, and the lithium in batteries can be substituted for calcium, magnesium, mercury, or zinc (Bradley et al., 2017). The high-power density of lithium and its historically low cost has made lithium the ideal battery

Figure 2.1: Global lithium production by country. Data from Swain, 2017.

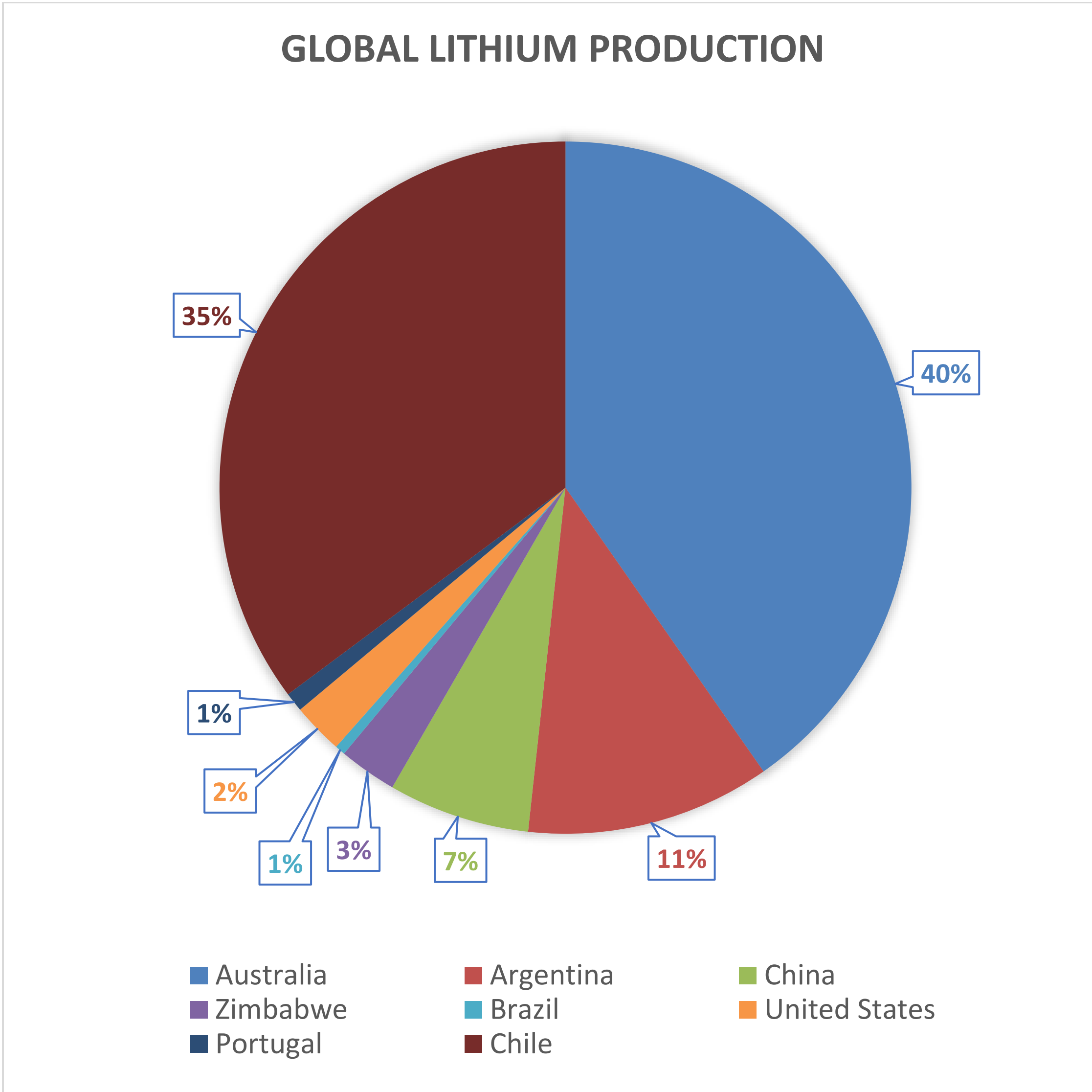
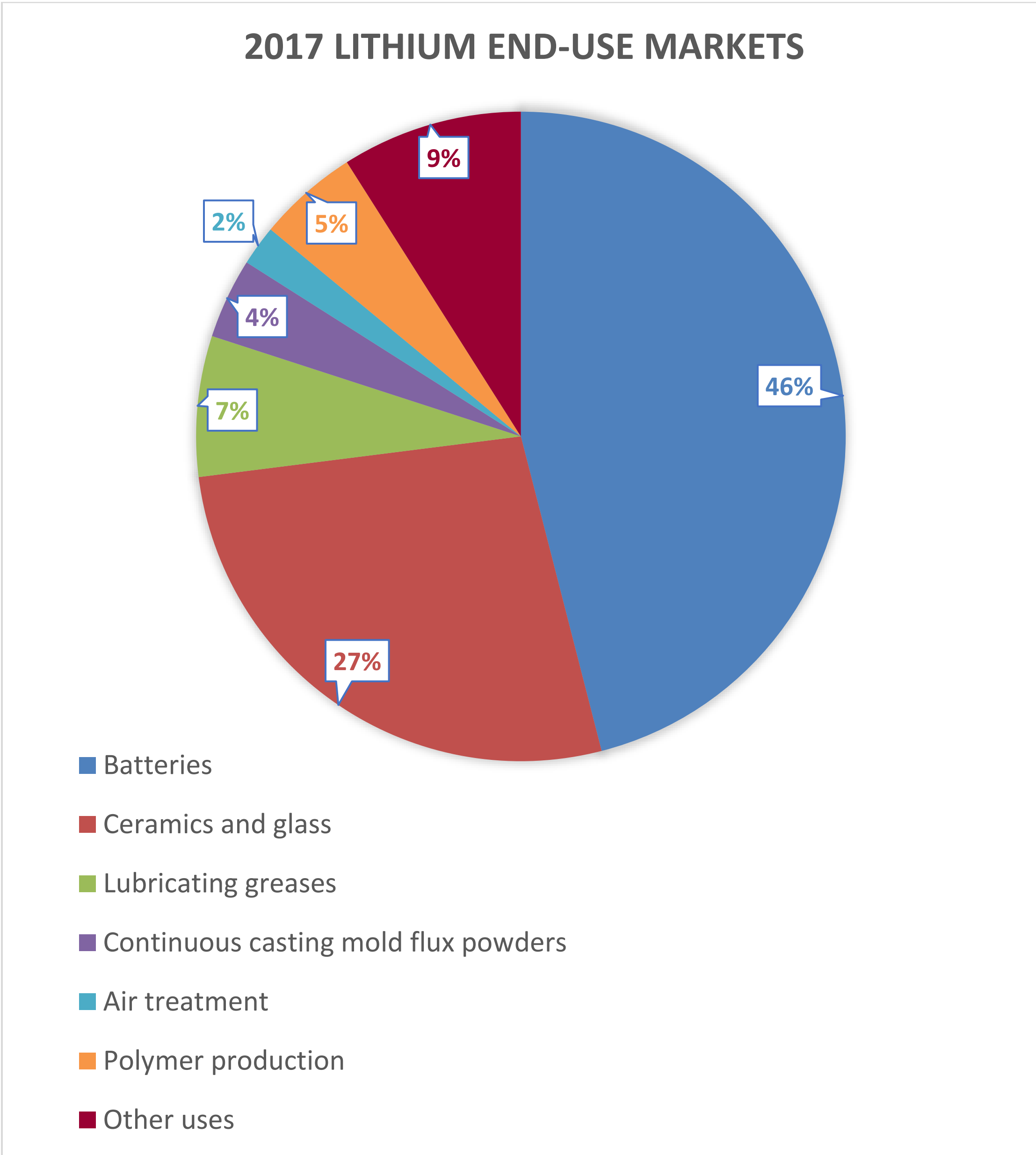


Figure 2.2: Global end-use market of lithium in 2017. Data from Jaskula, 2018.



component for energy storage needs, particularly in the production of hybrid and electric vehicles (Benson et al., 2017). However, in 2017, John Goodenough, the co-inventor of the lithium-ion battery, and Maria Braga developed a solid-state sodium glass battery that has more than three times the energy density of lithium-ion batteries, as well as a faster charging rate ("Lithium-Ion Battery," 2017). The use of sodium as an alternate material for energy storage threatens the application of lithium in batteries because of the global abundance of sodium. The commercial application of this alternative battery is being explored.

2.2 Market forecast

2.2.1 Demand

The highest potential growth sector for lithium is in batteries. Since the year 2000, the use of lithium in batteries has increased by 20 percent each year (Martin et al., 2017). Lithium-ion batteries (LIB) can be either single-use or rechargeable, and are classified as primary batteries or secondary batteries, respectively. Secondary lithium batteries have seen increased demand in personal electronics over their non-lithium battery counterpart equivalents (Bradley et al., 2017).

The 2016 Paris Agreement incentivized a geopolitical effort to reduce greenhouse gas emissions which has translated to increased lithium demand. The countries participating established measurable objectives for reducing emissions, which include transitioning their economies away from fossil fuels towards alternative and less emissive energy resources, such as renewable energy. Under the assumption that LIBs remain the preferred battery for energy storage, secondary LIBs will be instrumental in transitioning vehicles away from fossil fuels and to address issues of intermittency from wind and solar power. Increased use of batteries will translate to an anticipated lithium demand increase between eight and eleven percent annually (Martin et al., 2017). Kesler et al. (2012) estimate that lithium demand to satisfy all markets through 2100 will reach 20 million metric tons.

2.2.2 Supply

In the 2017 USGS Mineral Commodities Summary the worldwide lithium resources were estimated to be 40 million tons. In its 2018 summary, the worldwide lithium resources increased to an estimated 53 million tons (Jaskula, 2018). The identification of new resources is the result of exploration teams eager to capitalize on the growing demand of and increasing price for lithium. Although the estimate of lithium resources currently exceeds that of lithium demand, not all lithium resources are equally favorable for lithium extraction. The most economically attractive lithium resources are exploited first, leaving the more difficult lithium resources to be extracted later, once technological developments decrease the cost of extraction. In the meantime, bridging the gap between demand and supply will depend on recycling, new resource development, and material substitution (Verma et al., 2016).

In 2009, the U.S. Department of Energy awarded $9.5 million to a U.S. lithium metal and lithium-ion battery recycling company to facilitate construction for a lithium-ion vehicle battery recycling operation in the U.S. By 2050, lithium recycling is expected to substitute 25 percent of the world's lithium supply (Martin et al., 2017). Lithium is believed to be recyclable indefinitely, yet less than one percent of lithium is recycled today (Bradley et al., 2017; Martin et al., 2017). The reason behind a poor lithium recycling market can be attributed to an ever-evolving and complex LIB chemistry that impedes development of a profitable pathway (qtd. in Vikstrom et al., 2013). Additionally, due to the small amount of lithium used in LIBs relative to other valuable metals, such as cobalt, the other metals become the focus of recovery and recycling. The process of recovering other valuable minerals from LIBs can result in a loss of lithium from the LIBs, further diminishing the recovery potential and often yielding inefficient recovery rates of lithium (Vikstrom et al., 2013).

The manufacturing of large automotive batteries may be able to surmount the obstacles facing lithium battery recycling by creating a standard application of lithium in batteries. Large vehicle battery recycling programs would be established and modeled after existing lead-acid battery recycling systems. Unlike traditional lead-acid batteries used in fueled vehicles, the lifetime of large automotive batteries can be up to 15 years from date of purchase (Peiro et al., 2013). The long lifespan of battery replacement in EVs would dampen the recycling rates of automobile batteries.

Despite advancements in lithium recycling, new resource development is required to meet growing demand. A compilation of 15 new hard-rock and brine lithium production projects can be found in Table 2.1. The projects have a target start date of 2020 or earlier and have a combined production capacity of approximately 320,000 metric tons per year (tpy) of LCE (lithium carbonate equivalent) (Verma et al., 2016). Using a conversion rate of 5.31 metric tons of LCE to one metric ton of lithium, global annual output of lithium after 2020 could reach 103,000 metric tons (or 548,000 metric tons LCE) when new lithium project production is added to 2017 lithium production. It is noted that one of the projects listed in Table 2.1 involves lithium extraction from Smackover petroleum brine.

Table 2.1: New lithium production projects from brine and mineral resources with 2020 start date or earlier. Data modified from Verma et al., 2016.

Country	Company	Project	Source Type	Production Capacity (LCE tpy)
Argentina	Galaxy Resources Ltd.	Sal de Vide	Continental brine	25,000
Argentina	Lithium Americas	Cauchari-Olaroz	Continental brine	20,000
Argentina	Orocobre	Olaroz lithium plant	Continental brine	17,500
Argentina	Rodonia	Salar de Diablillos	Continental brine	15,000
Australia	Reed Resources	Mount Marlon	Pegmatite	25,000
Australia	Altura	Pilgangoora	Pegmatite	19,000
Bolivia	Comibol	Salar de Uyuni	Continental brine	30,000
Canada	Nemanska Lithium Inc.	James Bay	Pegmatite	47,000
Chile	Albermarle	La Negra	Continental brine	20,000
Finland	Kliber Oy	Ostrobothnia	Pegmatite	4,000
Mexico	Bacanora Minerals Ltd.	Sonora	Hectorite clay	35,000
USA	Western Lithium	Kings Valley	Hectorite clay	26,000
USA	*Standard Lithium*	*Arkansas*	*Oilfield brine*	*20,000*
USA	Simbol	Salton Sea	Geothermal brine	16,000
Total				**319,500**

2.2.3 Price

Historical lithium prices have exhibited modest price increase. Since 2015, the spot market for lithium has been subject to high volatility, as shown in Figure 2.3. The annual price per metric ton of LCE in the U.S. first exceeded $6,000 in 2015. In 2016, the average price per metric ton of LCE exceeded $10,000, a 61 percent price increase from 2015. Prices in 2017 averaged almost $14,000 per metric ton of LCE, a 33 percent price increase from the previous year, and the beginning of 2018 has averaged $16,500 ("Lithium Price," 2018). Martin et al., (2017) believe that LCE prices of $25,500 per metric ton will be feasible by 2020. This forecast was nearly realized in February 2016 when the lithium spot price in China reached $22,900 per metric ton of lithium carbonate.

Figure 2.3: Average price of LCE per metric ton and year over year growth. Data from Benchmark Minerals, 2017 and "Lithium Price," 2018.

Table 2.2 displays the predicted lithium price over the next 20 years by regressing the monthly lithium price from 2015 to 2017. The monthly lithium prices were selected from this period to capture the growth of prices in response to an unprecedented increase in lithium demand. For comparison, the actual lithium price averages for years 2015 to 2017 are shown. According to this method of analysis, the price of lithium will exceed

Table 2.2: Predicted price of LCE per metric ton from 2015 - 2017 regression.

	Predicted Price	***Actual Price***
2015	$ 5,961	*$ 5,899*
2016	$ 10,368	*$ 10,470*
2017	$ 14,441	*$ 13,969*
2018	$ 20,509	
2019	$ 28,225	
2020	$ 37,999	
2021	$ 50,124	
2022	$ 64,869	
2023	$ 82,477	
2024	$ 103,146	
2025	$ 127,025	
2026	$ 154,208	
2027	$ 184,727	
2028	$ 218,553	
2029	$ 255,599	
2030	$ 295,720	
2031	$ 338,724	
2032	$ 384,372	
2033	$ 432,393	
2034	$ 482,489	
2035	$ 534,341	
2036	$ 587,621	
2037	$ 619,194	

$100,000 per metric ton of LCE by 2024 if the observed rate of price increase persists. However, at prices like this, lithium will quickly be substituted for other materials. In the future, certain price-diminishing factors exist that will weaken the recently observed drastic increase in lithium price.

The threat of substitution will be instrumental in tempering the price of lithium over the coming years even as demand continues to increase. High lithium prices will incentivize the use of alternative and more economical materials. Similarly, inevitable improvement in the chemical composition of batteries could alleviate a battery manufacturer's dependency on lithium. This factor, along with cost optimization from mass-manufacturing of large batteries, will contribute to future price erosion (Berckmans et al., 2017). Additionally, the upcoming lithium production capacity improvements (from Table 2.1) will increase the supply of lithium in the market and enable market competition.

While the effect of the above-mentioned factors will most likely work to decrease the price of lithium, demand and available supply are actively responsible for the increase in prices recently witnessed. Looking forward, Martin et al., (2017) pegs forecasted lithium price to three factors:

1. Decreased lithium liquidity in the Chinese spot market
2. A monopolized lithium market
3. Geopolitical conflict and ecological repercussions in South America

First, the Chinese government is strongly supportive of consumers purchasing electric vehicles and offers many incentives to both consumers and manufacturers. This has translated to an increase in domestic lithium demand from producers and manufacturers and, in turn, a scarcity of available resources. Until a larger lithium production capacity exists, the lithium spot market in China will continue to experience elevated prices (Filice, 2017).

Secondly, the lithium market is dominated by four companies: SQM, FMC, Talison, and Albemarle. These major players have held a competitive cost advantage over smaller companies by employing economies of scale to sustain a low cost of production. They have the power to underprice smaller operations while maintaining high profit margins. However, smaller lithium operations that hold patented lithium processing technology could threaten the market share held by the four major lithium producers.

Lastly, expansion of lithium production volume in South America raises environmental concerns. South American operations, and Chile in particular, concentrate lithium using evaporation processes that can potentially result in local groundwater pollution. If the annual output of lithium from Chile is increased, the current methods of operation will be critically assessed by ecological stakeholders. Furthermore, environmental regulations have restricted total capacity from Chile to not exceed 200,000 metric tons LCE before 2030 (Martin et al., 2017). These regulations will need to be revisited before further production expansion is established.

Predicting the future price of lithium is challenging due to the unknown effect of materials science improvement in batteries and the various restraints on supply growth. The price of lithium is most likely to continue increasing until the additional lithium projects come online in 2020. Subsequently, prices are not likely to fall below $10,000 per metric ton of LCE (Graves, 2017). This is the price that will enable the marginal producers (high-cost hard-rock operations) to supplement the additional lithium capacity required to meet increasing demand that low-cost brine operations simply cannot achieve.

2.3 LITHIUM AS A STRATEGIC MINERAL

A metal is determined to be critical when it is subject to supply risk, is vulnerable to supply restriction, and has environmental implications in its absence. Graedel et al. (2015) assigned lithium a score of medium criticality. Bradley et al. (2017) considers lithium to be a near-critical element because of its role in renewable resource technologies. While debate about the criticality of lithium ensues, lithium can more accurately be considered a strategic mineral. For the United States, a strategic mineral is considered to be one that could contribute to U.S. energy independence and align with future needs of economic development. If lithium supply is dependent on foreign producers, the U.S. will potentially be subject to supply chain bottlenecks and unnecessary price inflation. The U.S. has a significant lithium resource from which it can derive its supply. Estimates of the resource vary between 6.8-10.2 million tons (Jaskula, 2018; Bradley et al., 2017). Since the year 2000, the U.S. is estimated to have produced about 2000 metric tons of lithium annually (Vikstrom et al., 2013).

American lithium operations do not benefit from the economies of scale that are achieved by larger lithium operations in foreign countries. Furthermore, many of the U.S. resources are found in nontraditional forms, such as geothermal brines, clays, and oilfield brines. Oilfield brines in particular are an underexplored resource. Lithium that is found in oilfield brines can realize economies of scope if the lithium-bearing brines are coproduced during hydrocarbon production. Alternatively, economies of scale could also be achieved if a lithium producer in the U.S. vertically integrates with a lithium processing company. Presently there are two companies in the U.S. that process lithium compounds for downstream lithium use (Jaskula, 2016). The existing footprint of lithium processing capabilities in the U.S., although small, reinforces the potential to increase the domestic lithium economy.

Chapter 3: Lithium Resources and Production

3.1 Introduction

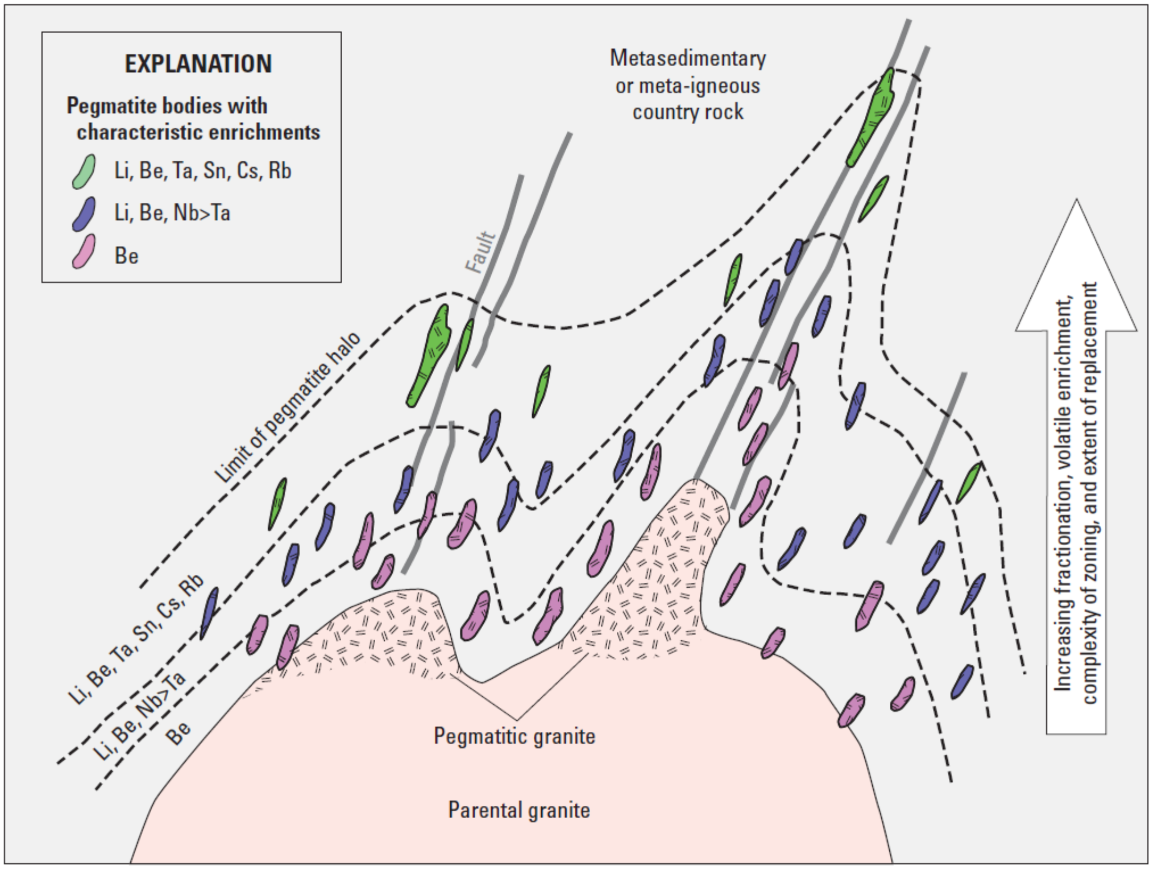
Lithium resources are primarily found in pegmatites and brines. Pegmatites are hard-rock mineral resources that contain crystallized lithium commonly in the form of spodumene. Brines are saline, mineral-enriched solutions that can occur both at the surface and subsurface. Lithium can be concentrated in brines through a variety processes that mobilize lithium from its original source and deposit it in a closed basin. Additional lithium resources can be found in clays. Lithium-bearing clays such as hectorite result from the leaching and alteration of rhyolitic volcanics upon interaction with meteoric waters or hydrothermal fluids (Benson et al., 2017).

3.2 Hard rock mining

3.2.1 Geology

Lithium deposits are typically associated with felsic rocks. Lithium is incompatible in the crystal structure of most all minerals that crystallize from cooling magmas. Thus, lithium tends to be concentrated in the residual fluids of felsic, rhyolitic melts. Benson et al. (2017) show that lithium is present in elevated levels in rhyolites which have intruded felsic continental crust compared to those which have intruded more mafic continental crust. Additionally, felsic rocks which have formed through the melting of crustal sedimentary rocks, such as S-type granites or peraluminous rhyolites, can have extreme lithium enrichment. Lithium minerals are commonly found in zoned granitic pegmatites (Kesler et al., 2012). The zoning occurs during late stage crystallization of water-rich rhyolitic magmas and is attributed to either sequential crystallization of a single magma or

Figure 3.1: Cross section of the concentric arrangement of pegmatites enriched in rare minerals. From Bradley et al., 2017.



multiple fluid injections of different compositions from crystallizing melts (Benson et al., 2017; Kesler et al., 2012). As exhibited in Figure 3.1, many pegmatites are found above large granitic intrusions, and lithium pegmatites are commonly identified as the most distal pegmatite from the intrusion.

Lithium minerals most commonly manifest as spodumene, and less often can take the form of petalite, lepidolite, and eucryptite. Eucryptite has the highest lithium concentration of these minerals and forms from only extremely lithium-rich melts, which are rare. In addition to the lithium concentration of the magma, the type of lithium-bearing mineral that forms is also controlled by the pressure at which the melt crystallizes. For example, petalite will form under low pressure while spodumene, the second highest lithium-bearing mineral, will form under high pressure.

3.2.2 Mineral resources

Pegmatite lithium deposits are found globally and account for half of the lithium produced today (Benson et al., 2017). Mining lithium minerals can be done through open-pit or underground mining. Traditionally an economically viable hard rock resource will have 0.28 percent lithium (Kesler et al., 2012). However, other incompatible rare earth elements are often present in lithium-bearing pegmatites. If other rare earth elements can be extracted from the lithium pegmatite, the grade of lithium for recovery could be lower and still economical. A significant challenge facing these mining operations are the multiple lenses of zoning that form. Often the lithium-pegmatites are present as multiple ore bodies. The distance between the ore bodies and their relative position to the surface may not warrant production if the interstitial country rock dilutes the total production volume of lithium.

The highest-grade lithium mineral resource in the world is the Greenbushes pegmatite in Western Australia. This site was originally mined for tantalum, a transition metal used as a minor component in alloys and as a substitute for platinum. However, the market for tantalum declined in the early 2000's while the lithium market consistently increased over time. For this reason, lithium became the main source of income for the operation (Greenbushes, 2018). The spodumene present in this highly zoned pegmatite has average lithium content of 1.9 percent (Vikstrom et al., 2013). The total resource of lithium is 450,000 metric tons (Kesler et al., 2012). The company stopped producing lithium carbonate (Li_2CO_3) in 1998 when SQM entered the market with brine production from the Salar de Atacama. The Greenbushes operation now focuses its production on lithium oxide (Li_2O) and produces an annual output of about 38,000 tpy lithium carbonate (Meridian, 2008; Greenbushes, 2018).

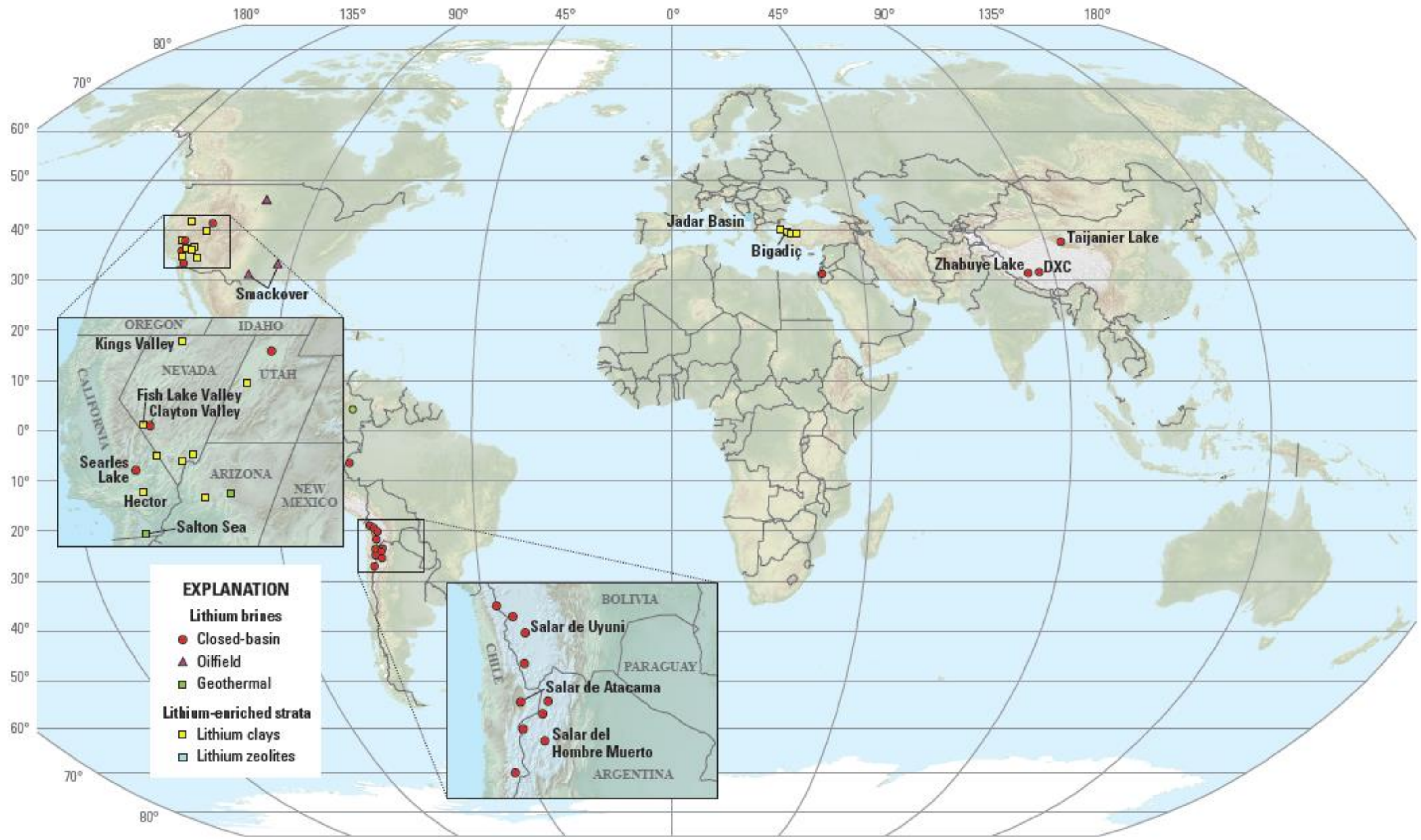
In the United States, lithium pegmatite deposits are found in Bessemer City, North Carolina and at Kings Mountain, North Carolina. The average lithium content of these deposits is about 0.68 percent (Vikstrom et al., 2013). The operations from both deposits produced a total of 23,000 tpy lithium carbonate (Meridian, 2008). However, these mines ceased being economically competitive as lithium carbonate producers in the 1980s, and subsequently were closed down.

3.3 BRINE

3.3.1 Geology

A lithium-enriched brine deposit is an accumulation of saline groundwater with high concentrations of dissolved lithium. According to Garrett (2004), brines are enriched

Figure 3.2: World map of lithium brines, clays, and zeolites. From Bradley et al., 2017.



Base from U.S. Geological Survey Global 30 arc-second elevation data (1996) and from Natural Earth (2014); Robinson projection; World Geodetic System 1984 datum in lithium from geothermal waters, clays, volcanic ash, or potentially other rocks. Lithium is present in ocean water but cannot be concentrated to economic levels without enrichment from the aforementioned sources. Figure 3.2 provides a global perspective of identified brine resources.

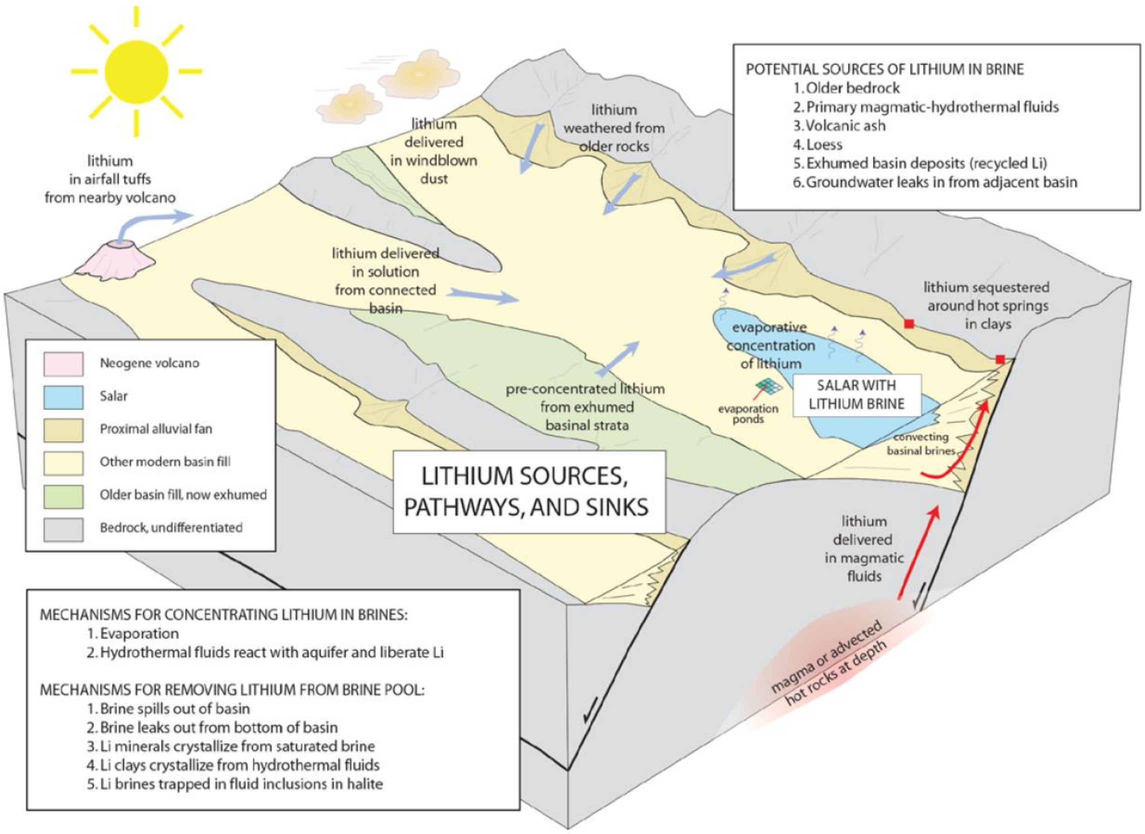
All producing lithium brine deposits share many first-order characteristics that are responsible for the containment and concentration of lithium. The interaction of these features is illustrated in Figure 3.3, and are as follows:

- Tectonically driven subsidence
- Associated igneous or geothermal activity
- Suitable lithium source rocks
- Closed basin containing a playa or salar
- Arid climates
- Sufficient time to concentrate a brine
- One or more adequate aquifers

Soluble lithium is either mobilized from rock sources through weathering or derived from hydrothermal fluid interaction with source rocks in a closed basin. A closed basin is one that allows the entry of meteoric waters or continental drainage to collect in a playa, or salar, with no drainage opportunity. Water in the salars cannot flow out of the basin. Closed basins are formed in tectonically active basins and are commonly associated with active faulting. The basin activity results in tectonically driven subsidence and accommodation space (Bradley et al., 2013).

Over time, a closed basin can only be sustained if the water level of the basin does not exceed the basin's capacity, in which case there would be spillover from the basin and

Figure 3.3: Diagram of depositional model for lithium brine. From Bradley et al., 2013.



a loss of fluid and minerals. Arid climates facilitate more evaporation than precipitation and therefore can sustain the closed basin environments. The rapid evaporation in arid climates concentrate the mineral resource. Lithium tends to remain suspended in the brine and not precipitate. With sufficient time to concentrate the brine, the closed basin will eventually become a lithium-enriched aquifer or dry lake.

3.3.2 Brine resources

Lithium production from brine is often less expensive and less energy intensive than extraction from hard-rock mining. Seventy percent of the world's economic lithium deposits are located in brines found in South America, in an area known as the Lithium Triangle (Meridian, 2008). The Lithium Triangle extends across northern Chile, Bolivia, and Argentina.

Chile hosts the highest quality lithium brine in the Salar de Atacama, with an average concentration of 1,400 ppm (Bradley et al., 2017). Before production began, the Salar de Atacama was estimated to hold 450,000 metric tons of lithium (Meridian, 2008). The brine deposits in Chile have been concentrated with lithium that was leached from surficial rhyolitic rocks in the surrounding mountain ranges by meteoric water, which was then trapped in a closed basin (Benson et al., 2017). The operations in the Salar de Atacama concentrate the lithium-enriched brine in solar evaporation ponds. This method of concentration has a 50 percent recovery factor and capitalizes on the Atacama Desert's arid climate and high elevation. This process takes eight to twelve months on average to complete, but due to the large volume of lithium has proven to be a highly productive yield (Verma et al., 2016).

The Salar de Uyuni is located in Bolivia and is estimated to contain nine million metric tons of lithium reserves, or 15 percent of the world's lithium resources (Bradley et al., 2017). The Salar de Uyuni extends across a 10,000 km^2 salt flat and has highly variable concentrations ranging from 500 to 4,700 ppm. It also has an extremely high magnesium concentration, which is three times greater than that of brine from the Atacama (Meridian, 2008). Magnesium in brine affects the lithium recovery process in late stage evaporation (Kesler et al., 2012). Due to the vast expanse of the total area, the variable concentrations, high magnesium content, and a less arid climate than that of Atacama, producers have struggled to create commercial production from the Salar de Uyuni. Production is currently estimated to be 120 metric tons per year (Alper, 2017). Pretreatment of brine to remove magnesium appears to offer promise in improving lithium recovery from magnesium-rich brines.

Argentina is home to the Salar de Hombre Muerto. Hombre Muerto is smaller than the Salar de Atacama in surface area but has a greater depth from which lithium can be recovered. Its concentration hovers at an average of 650 ppm, and it is expected to have 375,000 metric tons of extractable lithium reserves (Meridian, 2008). Lithium is extracted using an alumina adsorption system which yields a 47 percent rate of recovery (Meridian, 2008). Annual production from Hombre Muerto is about 12,000 tpy lithium carbonate (Meridian, 2008). Other brine source extraction processes in Argentina are from the Salar del Rincon and the Salar del Olaroz. The reserves in these locations are estimated to contain 250,000 and 325,000 metric tons, respectively (Meridian, 2008).

Outside of the Lithium Triangle, additional brine reserves are in China and the U.S. China hosts three notable lithium reserves: the Zhabuye Salt Lake, the DXC Salt Lake, and the Qaidan basin. The Zhabuye Salt Lake is the only recorded instance where lithium carbonate has naturally precipitated and crystallized on its lakeshores. The DXC Salt Lake is a small resource with concentrations averaging 400 ppm and a lithium reserve of 160,000 tons, while the Qaidan basin is home to the largest lithium carbonate plant in the world. In the U.S., lithium brine extraction started in Clayton Valley, Nevada in 1966 and uses solar evaporation to concentrate the brine. Lithium reserves were estimated to be 118,000 tons before the operation commenced. The concentration of lithium has declined from an initial 360 ppm in 1966 to 230 ppm in 2008 (Meridian, 2008).

3.4 Additional resources

3.4.1 Clays

Lithium-bearing clay deposits have been estimated to hold up to seven percent of global lithium resources (Bradley et al., 2017). Lithium-rich clays are developed in ash-rich basins, where lithium is leached from the rhyolitic volcanic ash sediments of a nearby source by meteoric fluids (Benson et al., 2017). Lithium becomes structurally bound in clay. Known lithium-bearing clays are found in the U.S. in Arizona, California, and Nevada. Previously these clays were not mined for lithium but were used for their physical properties, such as water absorption (Bradley et al., 2017). However, the largest lithium resource in the U.S. is found in clays at the McDermitt/Kings Valley deposit in Nevada. This deposit holds an estimated two million metric tons, and the lithium can be recovered through leaching using sulfuric acid (Benson et al., 2017).

3.4.2 Zeolite

There is one documented instance of a lithium zeolite deposit of jadarite, located in the Jadar basin in Serbia. Jadarite has replaced and is interbedded within the existing strata of oil shale, carbonate rocks, evaporites, and tuff. Three percent of the world's lithium resource is estimated to be contained in this single jadarite deposit (Evans, 2008).

3.4.3 Geothermal brines

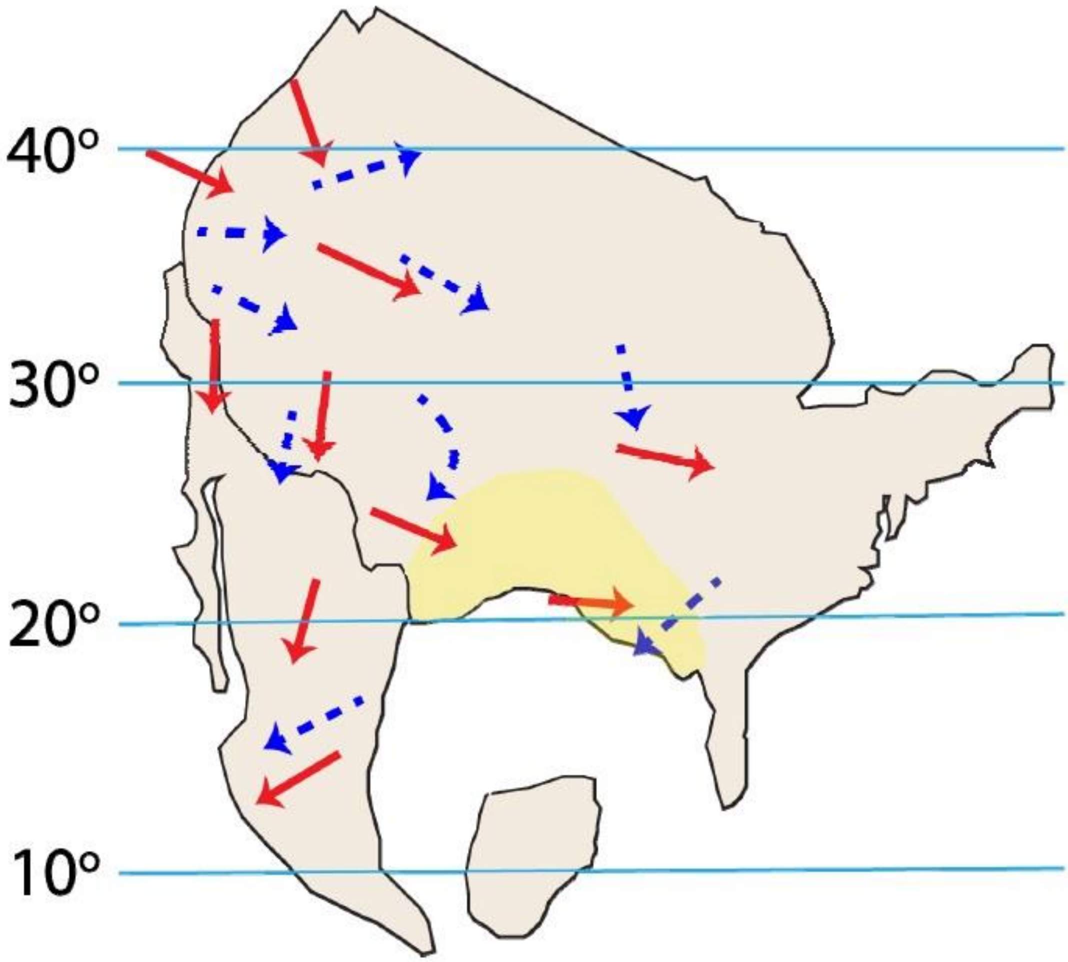
Another potential lithium source is found in geothermal brines. The primary value of geothermal brines is the contained heat which can be converted into mechanical energy (Bradley et al., 2017). It is common for geothermal energy producers to experience mineral scaling on the production facilities. Scaling refers to the precipitation of minerals from suspension and their deposition on a surface. Geothermal producers proactively remove minerals from the brine they process to address this problem. As of 2010, Simbol, Inc. has been producing lithium from geothermal brine in California's Salton Sea as an intentional byproduct, along with manganese and zinc minerals (*Simbol Materials*, 2011).

3.5 Oilfield brines

3.5.1 Resources

Lithium-enriched oilfield brines have been documented by Collins (1976) and Bradley et al., (2017). In the U.S., lithium bearing brines have been identified in Texas, Arkansas, North Dakota, Wyoming, and Oklahoma (Collins, 1976). The highest concentrations have been identified in the Smackover Formation, but further assessment of the lithium resource has been limited.

Figure 3.4: Paleoposition and wind direction during the Late Jurassic. The area of the Smackover Sea is highlighted in yellow. Prevailing winds (red) and winter winds (blue) show the direction of sediment transport to the area of the Smackover. Modified from Hunt, 2013.

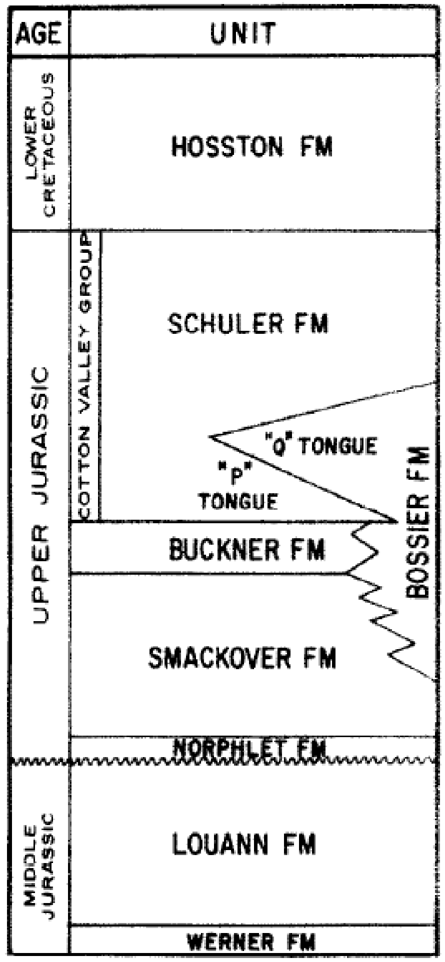


3.5.2 Smackover geology

Starting in the Triassic, extension related to the break-up of Pangea led to the formation of the Gulf of Mexico. The Smackover Formation was deposited in the Late Jurassic between 160-156 million years ago. The area of the Smackover Sea is highlighted in yellow in Figure 3.4. Figure 3.5 depicts the stratigraphy of the Smackover and its adjacent units. The Smackover was deposited on top of the Norphlet Formation. The Norphlet is comprised of conglomerates, sandy siltstone, shale, and sandstone from aeolian- and alluvial-deposits (Vestal, 1950; Zimmerman, 1992). The Norphlet Formation varies in thickness. In southern Arkansas and northern Louisiana, it is 15 m (50 ft) thick, while in Alabama and Mississippi it has been measured between 244 to 305 m (800 to1000 ft) (Zimmerman, 1992; Hunt, 2013). The Norphlet Formation has a significant volume of volcaniclastics. It was deposited on top of the Louann salt, a salt layer measured to be over 3,050 m (10,000 ft) thick in some area (Zimmerman, 1992).

The Smackover can be divided into two members based on the paleodepositional environment of the system (Vestal, 1950): a lower member deposited in a low energy marine environment, and an upper member deposited in a shallow, higher energy marine environment. Knowing the depositional environment provides an explanation for the petrophysical features of the formation seen today. The calmer marine environment in which the lower Smackover formed created dense limestone with argillaceous bands (Vestal 1950). During this time, sea level was rising. The upper Smackover member is composed of ooids and nonskeletal carbonates that created an oolitic, chalky limestone (Vestal, 1950). This stratigraphy was deposited during a highstand systems tract that occurred in response to a decrease in relative sea level (Tonietto and Pope, 2013). The Smackover's petrophysical characteristics have been measured in core samples and

Figure 3.5: Stratigraphic setting of Jurassic sediments. From Stueber et al., 1984.



extrapolated from well logs. The formation is estimated to be between 213-366 m (700-1200 ft) in thickness and is found at depths of 1800-4800 m (Vestal, 1950; Collins, 1976; and Garrett, 2004).

The source of lithium in the Smackover has yet to be verified. The brine in the Smackover is assumed by some to have originated from seawater that was deposited simultaneously with the sediments. However, Collins (1976) has noted that many ions were either enriched or depleted in the Smackover as would be typical of seawater's natural precipitation and evolution. Thus, considerable alteration in the brine must have occurred. The enriched and depleted ions observed by Collins are listed in Table 3.1. Of particular note was the deficiency in magnesium in the water relative to most evaporative-formed brines.

Table 3.1: Enriched and depleted ions in the Smackover brine relative to brine originating from seawater.

Depletion	**Enrichment**
Sodium	Lithium
Potassium	Calcium
Magnesium	Strontium
Boron	Barium
Chloride	Copper
Sulfate	Iron
Total equivalent Magnesium	Manganese
	Iodide

Collins (1976) proposes that the lithium presence could be a result of the continental drainage of lithium-enriched solutions into the sea. Collins (1976) proposes that the source of lithium stems from Triassic age volcanic rocks in the Gulf coast: continental water from springs or other hydrothermal fluids along the Mexia-Talco fault system could have leached lithium from Triassic age volcanic rocks. These lithium-enriched fluids then drained into the Smackover Sea and the water was then concentrated by evaporation. This hypothesis is in agreement with the relative decrease in sea level occurring along the Gulf Coast in the late Jurassic period. Collins (1976) also offers that bitterns from the Louann Salt probably mixed with the Smackover brines to create some of the deviations from characteristic seawater.

The Triassic age volcanic rocks that may be the lithium source rocks have yet to be verified, but igneous-volcanics in the Gulf Coast region have been identified. Vestal (1950) notes that most Smackover wells drilled in Arkansas encounter an igneous base rock that is considered to be intrusive in nature and related to the Ouachita mountains. Kidwell (1951) studied igneous rocks in core samples from Arkansas, Louisiana and Mississippi and concluded that two distinct igneous intrusive rocks exist in the area. One type is a mafic diabase and basalt intrusion that intermittently rose from the upper mantle in the Mesozoic and Cenozoic. Mafic rocks are typically depleted in lithium. The second type is comprised of various alkaline rocks of Late Cretaceous age (Kidwell, 1951; Zimmerman, 1992). Saunders and Harrelson (1992) characterize the igneous-volcanic complex of Jackson Dome, Mississippi, which has a similar time of formation. The main igneous rocks of the Jackson Dome are phonolites and mafic alkalic rocks, and they are believed to be part of a carbonatite complex (Saunders and Harrelson, 1991).

In the Smackover brine, the ratios of Sr^{87}/Sr^{86} are significantly more radiogenic than strontium ratios identified in Late Jurassic seawater, but the extent of enrichment appears to be random (Stueber et al., 1984). This suggests significant strontium contributions are from detrital sources, or were acquired during brine migration (Stueber et al., 1984). Stueber et al., (1984) propose the enriched source of strontium comes from the Bossier Formation. The Bossier Formation is the most radiogenic unit in the stratigraphic vicinity. In the North Louisiana salt basin, the Bossier Formation interfingers with the Smackover Formation (Moore and Druckman, 1981). Fluids expelled from the underlying Louann Salt in the Louisiana salt basin are proposed to have migrated through the Bossier Formation updip into the Smackover (Stueber et al., 1984).

The migration of brines into the Smackover Formation is plausible due to extensive regional faulting of the area. Extensive normal and wrench faulting since Oxfordian time has subjected the Smackover Formation to tectonic fracturing (Zimmerman, 1992). The fracturing is evident in east-west and north-south trends in northern Louisiana and southern Arkansas. Zimmerman (1992) identifies a higher intensity of faulting in northern Louisiana relative to other areas of the Smackover Formation. This specific region of faulting in the Smackover would overlap with the region of interfingering with the Bossier Formation. The fault systems of the region would act as conduits and migratory pathways for fluids, as well as hydrocarbons, to migrate into the Smackover Formation from underlying units.

The fault systems in the Gulf Coast not only offer migration pathways for fluid migration, but also act as zones of weakness along which igneous intrusions could enter (Kidwell, 1951). In Figure 3.6, Zimmerman (1992) identifies that alkaline rock intrusions of Late Cretaceous age are spatially clustered around wrench zones in southeast Arkansas and northeast Louisiana. If the alkaline intrusive rock is lithium-rich, the overlap of fluid migration through regions of alkaline intrusive rock could be the source of lithium to the Smackover Formation. However, the data set used for this analysis identifies high lithium

Figure 3.6: Igneous intrusions proximal to wrench faulting in the Late Cretaceous. Modified from Zimmerman, 1992.

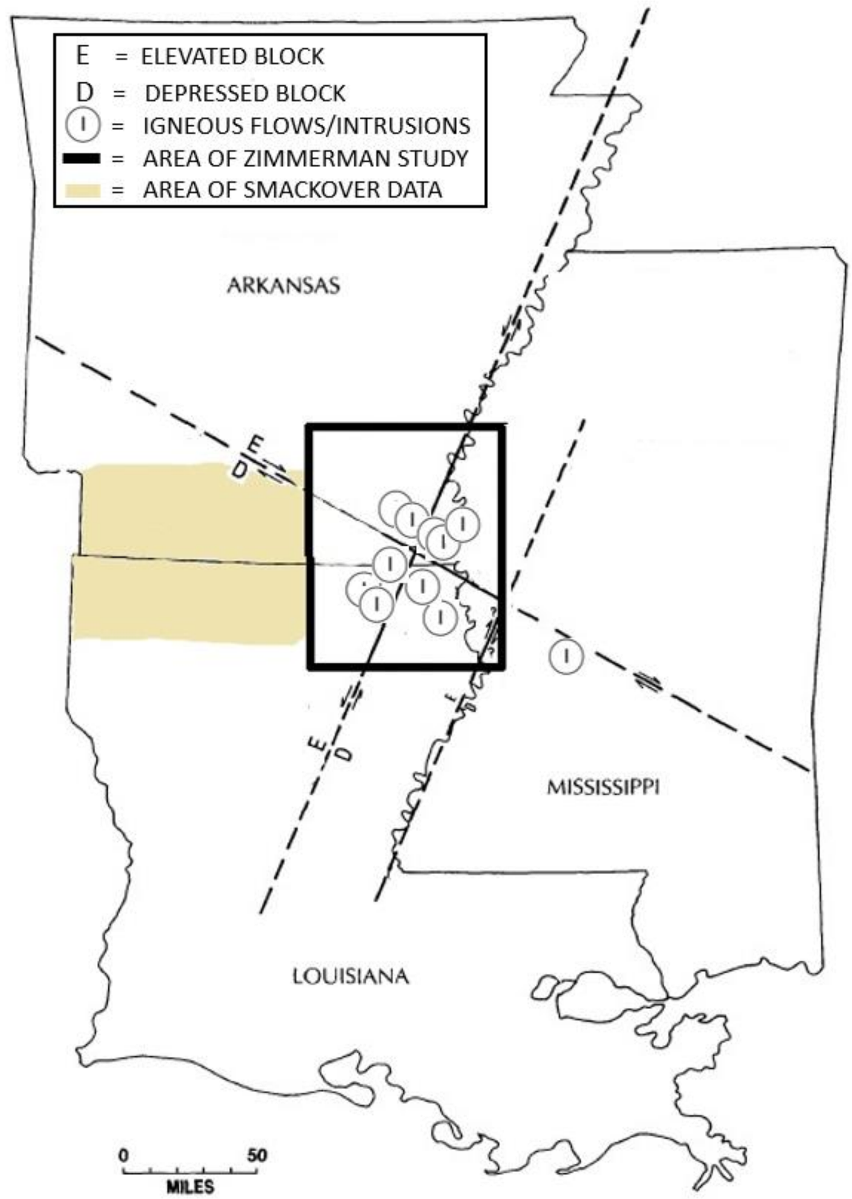
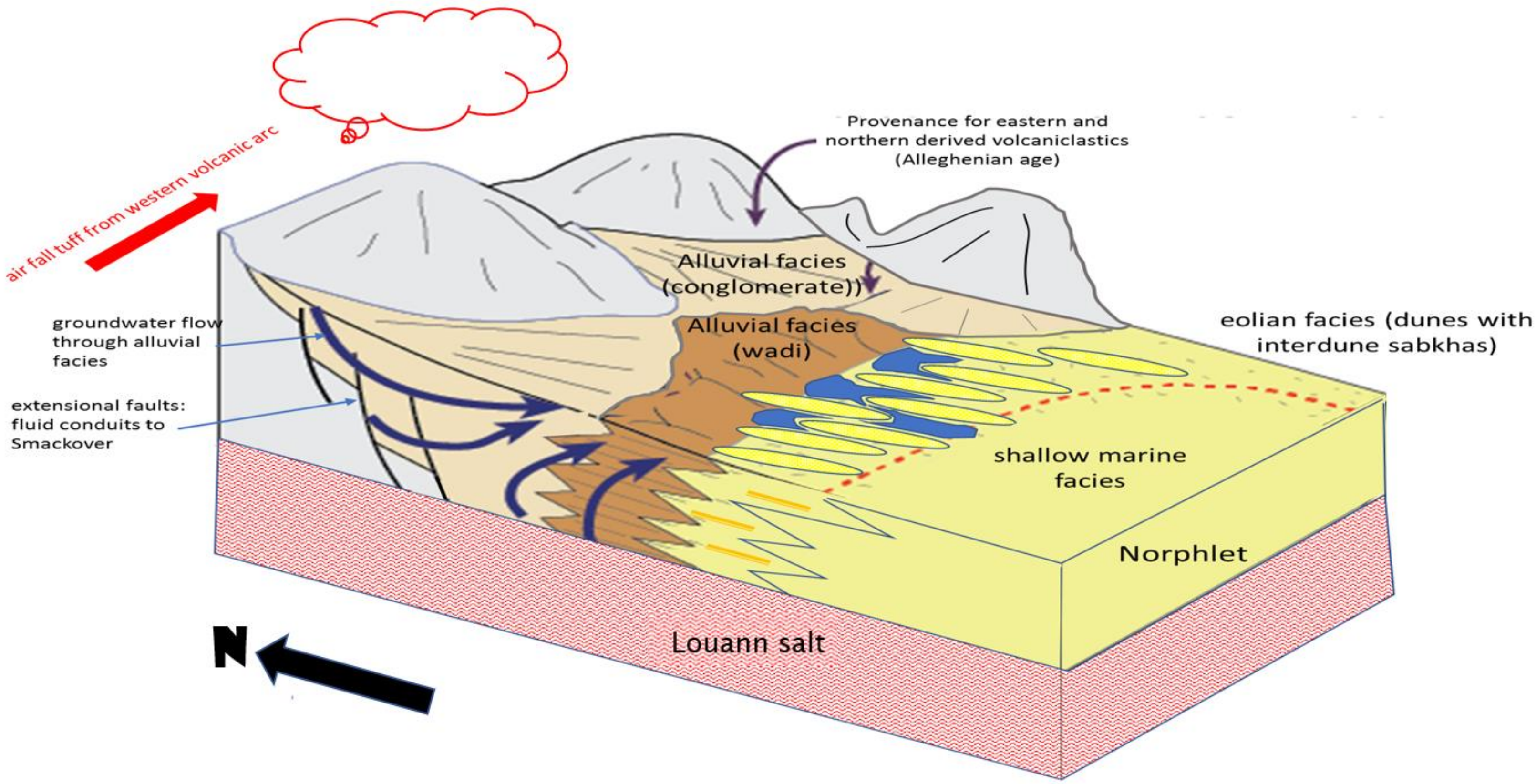


Figure 3.7: Model for lithium enrichment of Smackover brines from Alleghenian volcaniclastics and air fall tuff. From Chuchla, 2018.

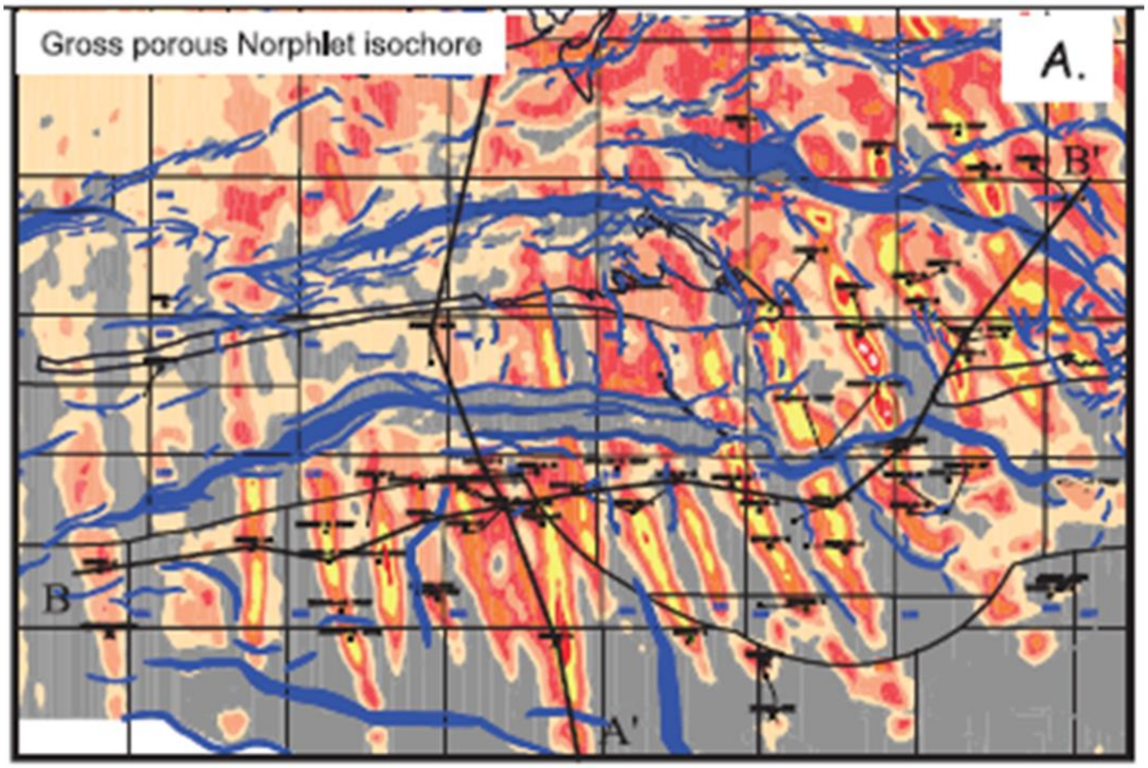


concentrations in the Smackover in southwest Arkansas and northwest Louisiana, as shown in yellow in Figure 3.6. The nearby South Arkansas fault zone and North Louisiana fault zone extend into the western areas of Arkansas and Louisiana. These fault zones could have acted as conduits for fluid migration, or as potential weak zones for igneous intrusions in the area which would allow lithium to be leached during fluid migration into the Smackover.

The lithium source rock is still yet to be associated with any definite source. Chuchla (2018) has proposed an alternative model for lithium enrichment in the Smackover brines, as shown in Figure 3.7. The Norphlet formation underlying the Smackover is notable for igneous lithics which are sourced from the Appalachians. The Appalachians contain plutonic rocks, including typically highly lithium-enriched S-type granites of Alleghenian age (Hatcher, 1987). Zircons from the Norphlet formation were dated using U-Pb and confirm that Norphlet sediments have an Alleghenian provenance (Lisi and Weislogel, 2013; Hunt, 2013). Chuchla (2018) proposes that lithium was mobilized from the Alleghenian-sourced volcaniclastics and then concentrated in the Norphlet. These fluids could have originated in the Louann salt and migrated upwards through faults or from shallower circulation through the alluvial and wadi facies of the Norphlet. The hydrothermal fluids would have spilled into wadis and interdune sabhkas where fluid chemistry was altered by rock fluid interactions. Lithium would ultimately be precipitated during evaporation in this arid environment.

Figure 3.8 portrays 3-D seismic data from the Norphlet Formation in southwest Alabama. Lithium-rich petroleum brines are found in the overlying Smackover Formation of this area. Visible in the figure are the east-west trending normal faults created during the early rifting leading to the formation of the Gulf of Mexico. Also imaged are the northwest trending dunes of the Norphlet Formation. Lithium may have been enriched in the

Figure 3.8: Seismic imaging of the Norphlet Formation in Mobile Bay, AL showing east-west trending normal faults and northwest trending dunes. From Ajdukiewicz et al., 2010.



interdune sabhkas and then remobilized along the normal faults into the above Smackover Formation. Palmer and Gabitov (2017) note that these brines appear to be of the chloride-calcium type, suggesting that their chemistry was driven more by rock/fluid interactions in the playa rather than by interaction with the Louann Salt.

In addition, Chuchla (2018) proposes that lithium may have been introduced from air fall tuff from the upper Jurassic volcanic arc along the western margin of North America. Studies have shown that 45 percent of volcanic/magmatic lithium is lost to the atmosphere during eruption and degassing (Benson et al., 2017). The air fall tuff would be carried by prevailing westerlies active during this time period, illustrated in Figure 3.4. The model proposed by Chuchla (2018) is consistent with the criteria for lithium brine deposition posed by Bradley et al. (2013) in Figure 3.3.

Chapter 4: Data Analysis

4.1 OVERVIEW

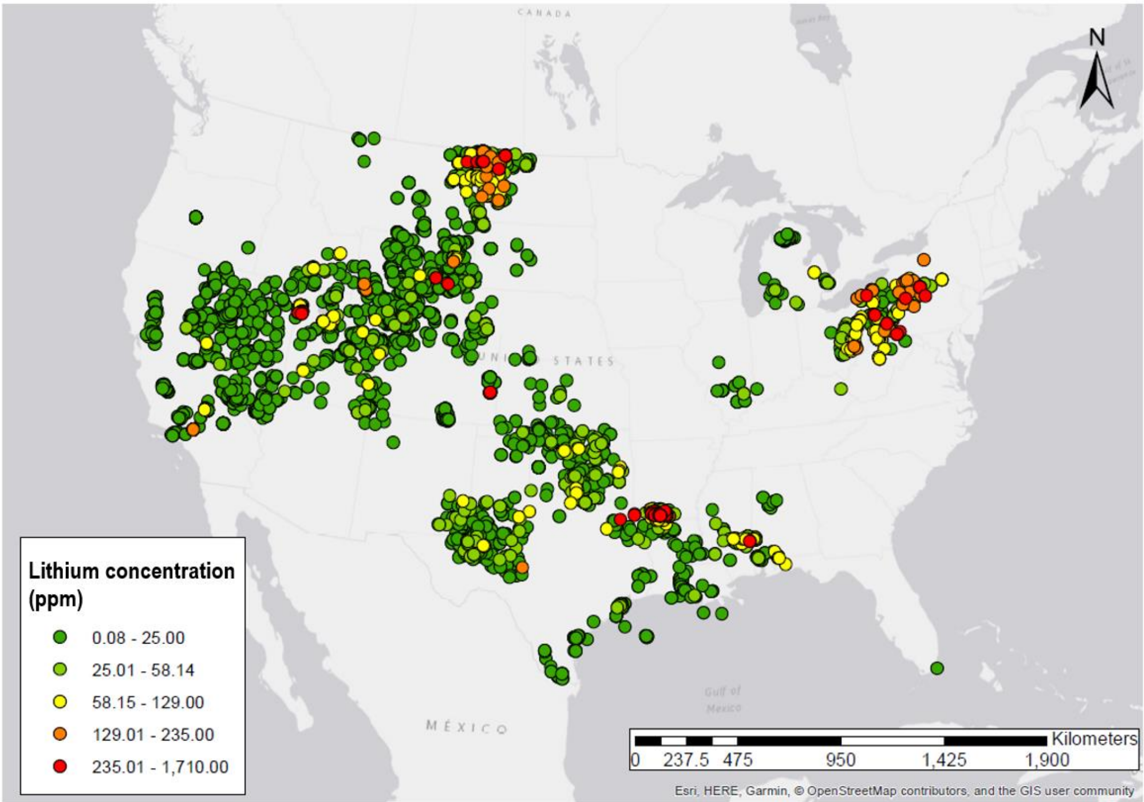
The purpose of this analysis is to identify under what economic scenarios and financial arrangements lithium can be profitably extracted from produced water. The data set for analysis was obtained from the USGS and used to identify lithium-rich petroleum brine formations. Of the identified lithium-bearing formation brines, the Smackover Formation was selected to evaluate lithium production from its produced water.

4.2 DATA SET

The dataset used for this analysis was compiled by the United States Geological Survey (USGS). This dataset, the USGS National Produced Waters Geochemical Database v2.2, contains geochemical information from wellheads across the U.S. and was used to identify wells with recorded lithium in the sample. The supplementary documentation to the database explains that it is a compilation of 40 individual databases, publications, or reports that contain geochemical information for 165,960 produced water samples (Blondes et al., 2016). Samples contained in the USGS Database do not reflect a comprehensive nor spatially representative distribution of water compositions across the U.S. because formations were not universally required to have been tested for geochemical produced water data.

Sample collection dates range between 1886- 2013. The recording of geochemical information was not regulated and is subject to variation. The measurement threshold of the data is also unknown due to the variety of collection dates and implied discrepancy in processing technique (Blondes et al., 2016). In an effort to verify the validity of lithium

Figure 4.1: Geographic distribution of lithium-bearing well samples in the United States.



samples spanning over a century, a lithium brine testing company was consulted to discuss the evolution of lithium testing. It was determined that older data with lithium concentrations less than 1 ppm (mg/L) should be viewed with caution (Weikel, 2018).

Of the produced water samples contained in the USGS Database, 5.7 percent of the samples had reported lithium concentrations. The population of lithium samples was further filtered by requiring associated latitudinal and longitudinal coordinates. The data was also parsed for duplicate wells. When a well was sampled on multiple dates and had multiple lithium values reported for the same formation, only one reported lithium value was maintained in the lithium population set to be used for analysis. The sample to be maintained was either the most recent sample taken from the well or, if more than one sample was taken on the same date, the sample that spanned over the greatest range of depth. The application of the above criteria resulted in a lithium data population of 8,649 samples used for the remaining analysis. The geographical distribution of well samples is illustrated in Figure 4.1.

4.3 Lithium distribution analysis

A lithium brine is considered to be economically viable when the lithium concentration exceeds 200 ppm (Bradley et al., 2013). However, it is still possible to yield economic recovery when lithium concentration hovers between 65-70 ppm (McEachern, 2017; Meridian, 2008). Figure 4.2 shows the cumulative frequency distribution of the lithium population from the USGS Database. The distribution of lithium concentrations within the population are positively-skewed, with the majority of the samples having lower lithium concentrations. Figure 4.3 illustrates notable percentage intervals of the entire population. A total of 344 samples meet or exceed the concentrations necessary to be

Figure 4.2: Cumulative frequency distribution of lithium concentration in well samples.

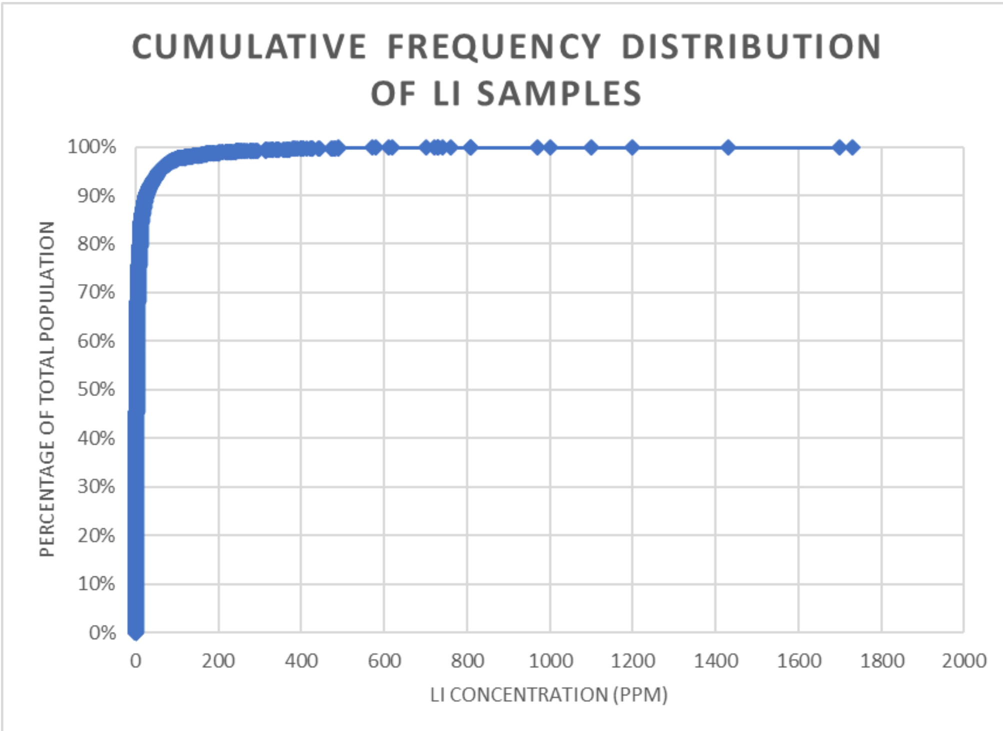


Figure 4.3: Notable intervals of the cumulative frequency distribution of lithium samples.

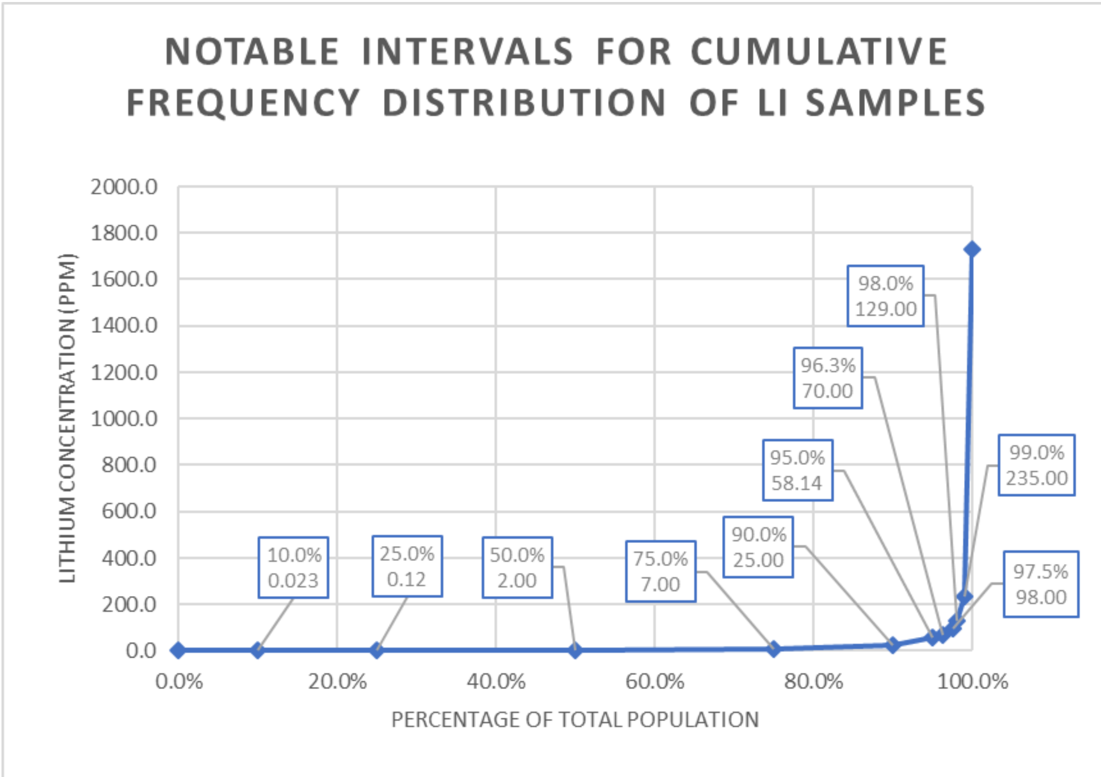
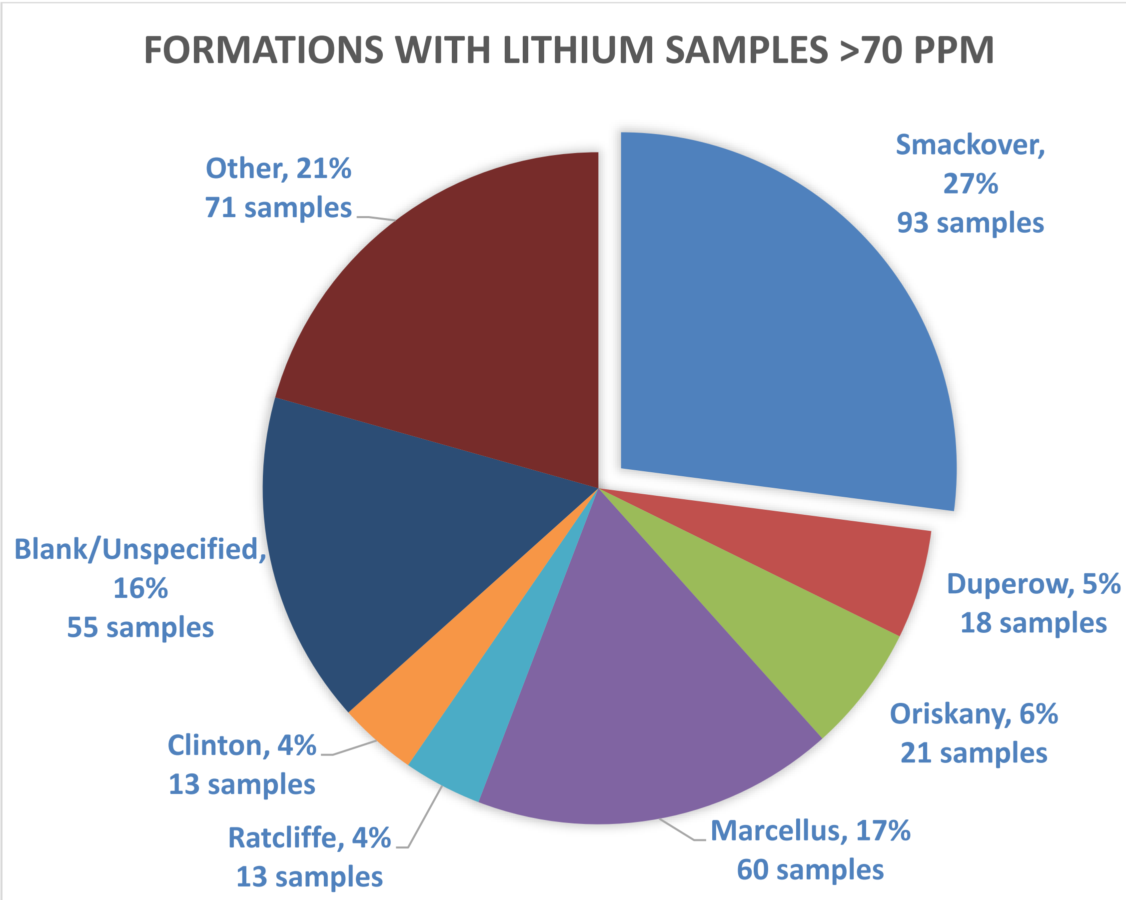


Figure 4.4: Anomalously high lithium concentrations displayed by formation.



considered economically feasible for production. Of these samples, 63 percent were from six units: the Smackover Formation, the Duperow Formation, the Marcellus shale, the Oriskany sandstone, the Ratcliffe Member of the Charles Formation, and the Clinton sandstone. Twenty-one percent of the samples are spread across 39 formations and 16 percent were attributed to Unspecified formations. See Figure 4.4 for further clarification.

4.4 Smackover lithium distribution analysis

The largest amount of lithium concentrations greater than 70 ppm are found in the Jurassic Smackover Formation (93 samples). Smackover samples were collected in tightly clustered areas, which is conducive for more accurately predicting lithium concentrations across a specified area. Less fracking has occurred in the Smackover than in the formation with the next largest amount of lithium samples, the Marcellus shale. The Smackover Formation was selected to perform a complete analysis of economic lithium production from produced water. Including samples with lithium concentrations less than 70 ppm, the total count of lithium-bearing samples in the Smackover Formation is 145.

High-grade mineral deposits are often times identified based on very few values, and possibly only a single value (Wellmer, 1998). The identification of many wells in the Smackover with high lithium values is indicative of wide-spread lithium presence concentrated in the brine. The lithium sample concentrations from the Smackover do not follow a normal distribution, as is to be expected with ore deposits. One controlling factor may be the variations in lithium-rich detrital sediments deposited in the Norphlet, if that is indeed the source. Detailed vertical fluid sampling of the Smackover and Norphlet with a downhole fluid sampler could reveal which parts of the formation are host to the highest lithium concentrations.

Figure 4.5: The geographical distribution of lithium-bearing samples from the Smackover Formation are identified in two distinct regions.

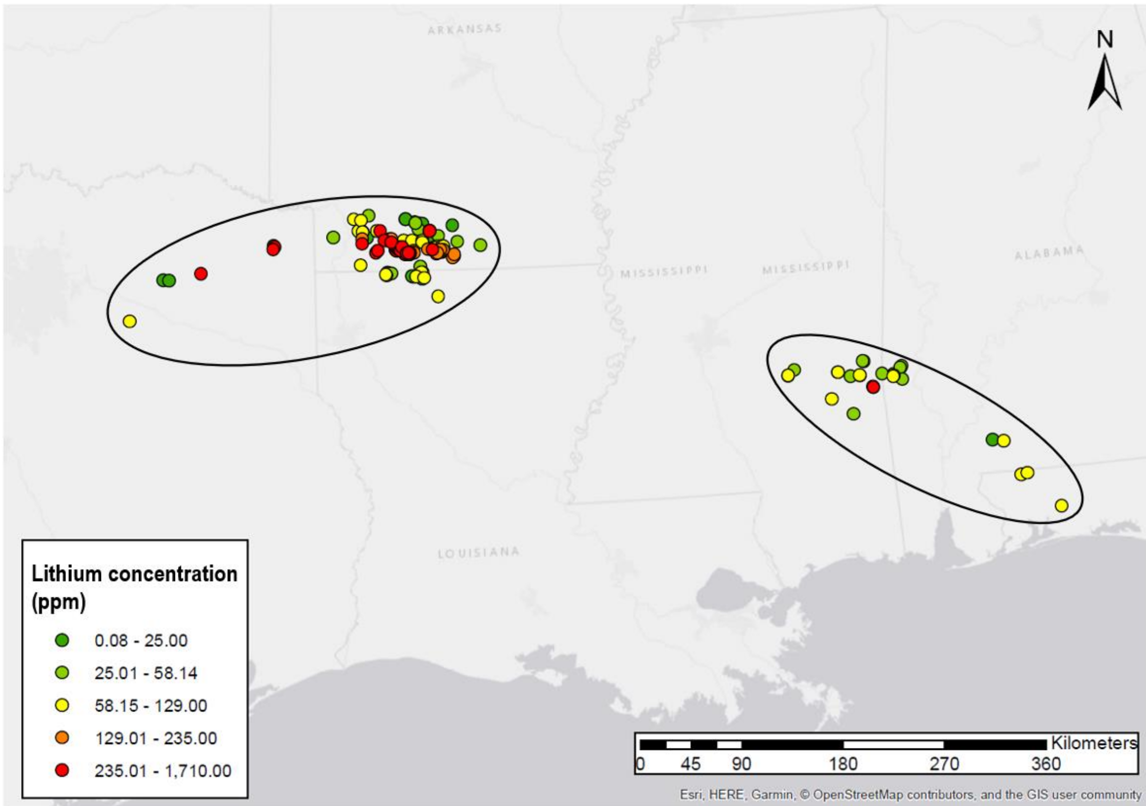
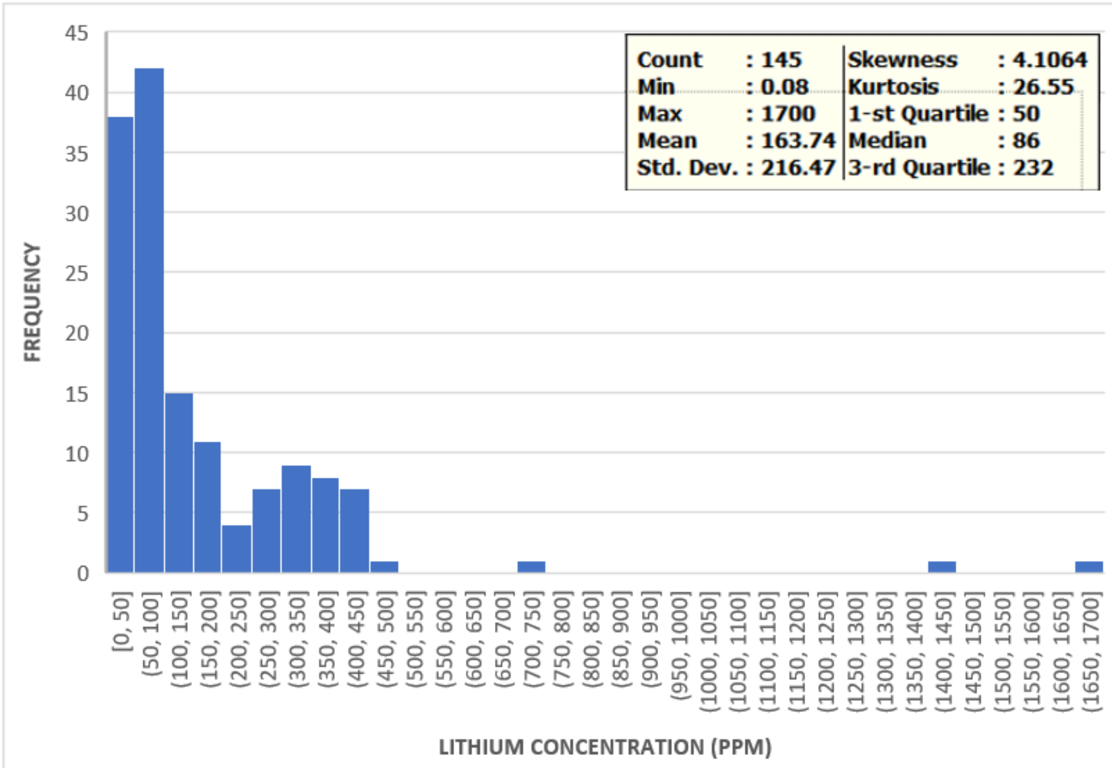


Figure 4.6: Histogram of lithium samples from the Smackover Formation.



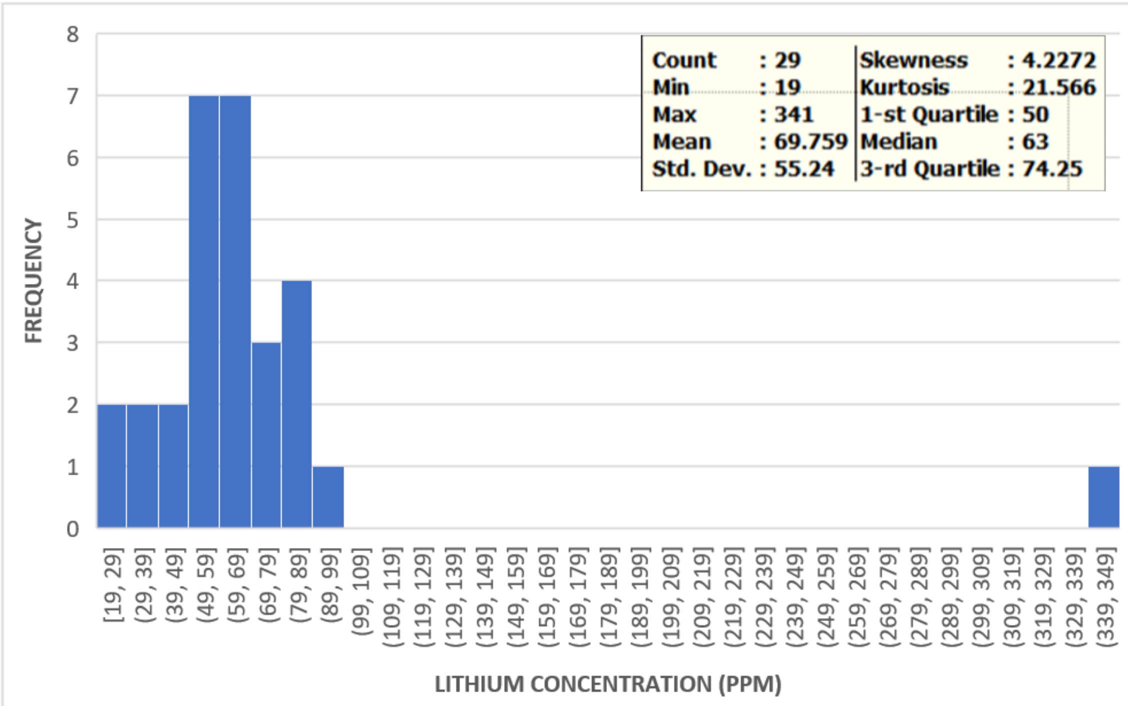
The extent of the samples from the Smackover Formation are shown in Figure 4.5. The statistics associated with the Smackover samples are provided in Figure 4.6. However, the samples have been collected in two distinctly separate regions. The first set of samples (Subset 1) is located in Mississippi and Alabama, with some samples extending into the panhandle of Florida. Subset 1 is comprised of 29 samples. The second set of samples (Subset 2) are found in Arkansas, Louisiana, and East Texas. Subset 2 is comprised of 116 samples. Both Subsets are evaluated separately to assess the regional lithium concentration, and their associated statistics can be found in Table 4.1.

Table 4.1: Statistics for the Smackover Formation, Subsets 1 and 2, and their adjusted subsets.

Name	Location	Area (km^2)	Sample count (n)	Avg. lithium (ppm)	St. Dev (ppm)	Range of lithium concentration (ppm)
Full sample set	Full Extent	213,430	145	163.74	216.47	0.08 – 1700
Subset 1	AL/MS/FL	13,226	29	69.76	55.24	19 – 341
Subset 1, Adj	AL/MS/FL	13,226	28	60.07	18.5	19 – 90
Subset 2	AR/LA/TX	9,850	116	187.23	234.84	0.08 – 1700
Subset 2, Adj	AR/LA/TX	9,850	114	163.06	147.02	0.08 – 740

In Subset 1, the lithium values range from 19 to 341 ppm. The average lithium concentration for this set of samples is 69.76 ppm, and the subset has a standard deviation of 55 ppm. Of the 29 samples, nine have lithium values greater than 70 ppm. One sample has a concentration of 341 ppm. The distribution of lithium samples in Subset 1 are shown in Figure 4.7. If the outlier sample of 341 ppm is removed from Subset 1 (Subset 1, Adjusted), the values of the mean and standard deviation become 60.07 ppm and 18.5 ppm, respectively, as shown in Table 4.1.

Figure 4.7: Histogram of lithium Samples from Subset 1 of the Smackover Formation, located in Alabama, Florida, and Mississippi.



The presence of a single high lithium measurement among twenty-eight lithium measurements with values less than 100 ppm warrants further investigation. Whether or not to remove the outlier lithium value was determined by comparing the lithium concentration and depth of sampling interval to adjacent wells. Two adjacent wells were used for the comparison, detailed in Table 4.2. The closest well, located 0.2 km NW of the outlier well, has a measured lithium concentration of 83 ppm. The second adjacent well, located 0.55 km NNW of the outlier well, has a lithium concentration of 85 ppm. Geochemical data for the two adjacent wells was sampled over a 41 m (134 ft) interval, while geochemical data for the outlier well was measured over an interval of 231 m (760 ft). The outlier well's sampling interval encompasses that of the adjacent wells. The sample interval of the two adjacent wells is included in the uppermost part of the outlier well's sampling interval.

Table 4.2: Nearby wells associated with outlier well in Subset 1.

Well (IDUSGS)	Distance from well	Li (ppm)	Well depth upper (m)	Well depth lower (m)	Total Interval depth (m)
100875	.213 km NW	83	3863	3904	41
100874	.546 km NNW	85	3863	3904	41
29337	**0.0**	**341**	**3867**	**4098**	**231**

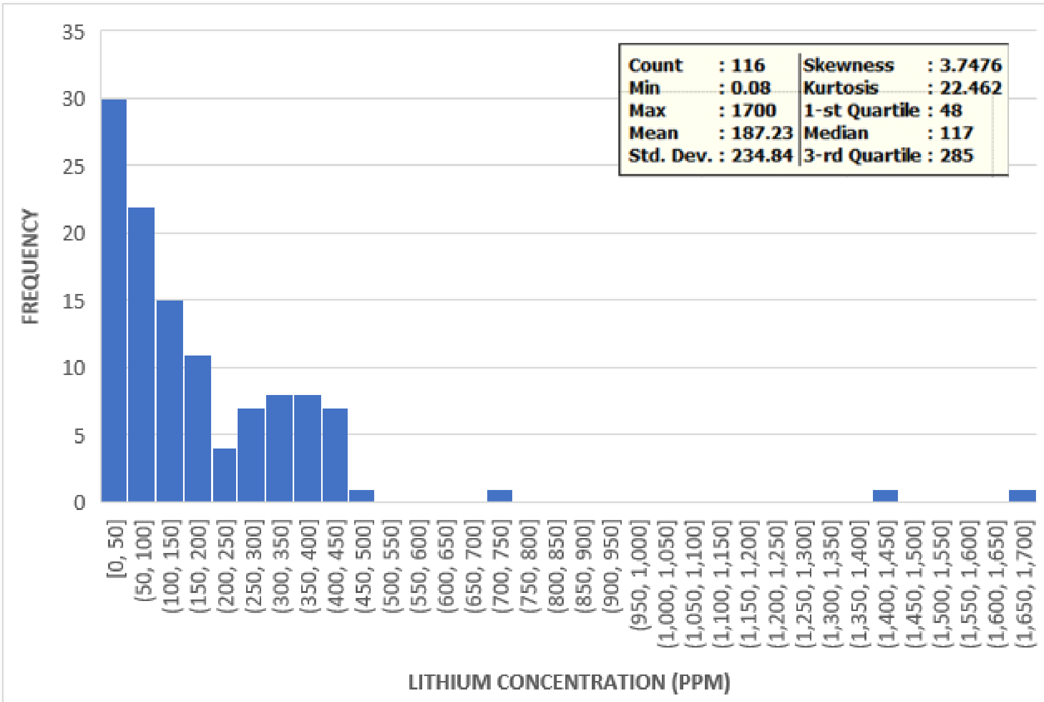
The Smackover Formation has been documented to reach an average thickness of 233 m in the area of Subset 1 (Wade, 1993). The outlier well sampling interval most likely extends across the entire Smackover Formation. The sampling interval of the adjacent wells most likely targets the Upper Smackover unit. Oil producers commonly target the Upper

Smackover unit because of the high porosity offered by the oolitic reservoir, and the structural traps created by the overlying Buckner anhydrite.

It is likely that the sampling interval of the adjacent wells do not penetrate the depositional layer that sources lithium for the Smackover, while the outlier well does penetrate this layer. Lithium will have diffused from the source throughout the formation, creating elevated lithium concentration throughout the Smackover. However, significant vertical variations in lithium concentration may exist in the Smackover. This would explain the contrast in lithium measurements between the outlier well's measurements and the measurements of the surrounding wells and suggests that lithium concentration may increase with depth. If the above reasoning is correct, this suggests that lithium may vary considerably depending on the specific interval of the Smackover. The significance of this observation will be of interest to geoscientists and exploration companies interested in exploiting lithium from the Smackover and selectively targeting the highest lithium concentrations. Therefore, Subset 1 (and not Subset 1, Adjusted) will be used for estimating the lithium resource of this area.

In Subset 2 the lithium concentration values range from 0.08 to 1700 ppm. Of the 116 samples, 78 samples have lithium values greater than 70 ppm, and 65 samples have a concentration greater than 100 ppm. Two samples have measured lithium concentrations greater than 1000 ppm (1430 and 1700 ppm). The statistics for the lithium samples from Subset 2, shown in Figure 4.8, have an average concentration of 187 ppm and a standard deviation of 235 ppm. If the wells with concentrations exceeding 1,000 ppm are considered as outliers and these samples are removed from Subset 2 (thereby creating Subset 2, Adjusted), the mean lithium concentration becomes 163 ppm, with a standard deviation of 147 ppm.

Figure 4.8: Histogram of lithium samples from Subset 2 of the Smackover Formation, located in Arkansas, Louisiana, and Texas.



In order to evaluate whether the two outlier samples should be removed from Subset 2, the concentration and sampling intervals of the outlier wells were again compared with adjacent wells. Within a 10 km radius, the well sample with a value of 1430 ppm has two adjacent wells, as detailed in Table 4.3. The nearest adjacent well is 3 km W and has a lithium value of 86 ppm. The next closest well is 9.4 km SE and has a lithium concentration of 371 ppm. The geochemical data from the first adjacent well (Li = 86 ppm) was taken across a sampling interval of 19 meters. This sampling interval ends 3 meters before the sampling interval of the outlier well begins. Geochemical data for the outlier well was sampled from a seven meter interval. This interval is just below that of the first adjacent well's sampling interval, but more than 175 meters above that of the second adjacent well's sampling interval. This information implies that the sampling interval of the outlier well either broaches, penetrates, or comingles with the lithium-rich source of the Smackover Formation in this area.

Table 4.3: Nearby wells associated with outlier value Li = 1430 ppm in Subset 2.

Well (IDUSGS)	Distance from well	Li (ppm)	Well depth-upper (m)	Well depth-lower (m)	Total Interval depth (m)
74232	3 km W	86	2193	2212	19
74231	**0.0**	**1430**	**2215**	**2222**	**7**
108401	9.4 km SE	371	2400	Unknown	Unknown

Furthermore, the elevated concentration of the second adjacent well (Li = 371 ppm) at a lower depth than the outlier well supports the interpretation that lithium concentrations increase with depth. This again suggests significant vertical variation in the concentration of lithium. There is not sufficient data to disprove that the sampled lithium value of 1430 is inconsistent with surrounding well samples. It will be included in the data set used for averaging the lithium concentration of the area.

The outlier sample with a lithium value of 1700 ppm was compared to 9 wells found in a ~5 km radius of the area, as shown in Table 4.4. Within the ~5 km radius, all wells had lithium values greater than 100 ppm. Similar to the previous outlier well in Subset 2, the geochemical data for this outlier well was taken over a relatively small sampling interval of six meters. Two of the adjacent wells have sampling intervals that encompass the six-meter interval of the outlier well. If the lithium concentration for the outlier well is highly elevated due to penetrating the lithium-rich source, then the two adjacent wells that encompass the sampling interval of the outlier well illustrate the effective diffusion of lithium throughout the formation. This outlier sample will be included in the data set analyzed for an average lithium concentration because of its inherent similarities to the first outlier analyzed in Subset 2.

Table 4.4: Nearby wells associated with outlier value Li = 1700 ppm in Subset 2.

Well (IDUSGS)	Distance from well	Li (ppm)	Well depth-upper (m)	Well depth-lower (m)	Total Interval depth (m)
108422	5.05 NE	122	2180	Unknown	Unknown
108420	2.97 NE	107	2190	Unknown	Unknown
108421	1.95 NNE	109	2195	Unknown	Unknown
74210	5.02 SE	125	2298	2335	37
74209	5.18 SE	140	2304	2347	43
108418	2.16 W	191	2330	Unknown	Unknown
74214	4.92 SE	170	2352	2404	52
74212	0.67 E	122	2364	2398	34
74211	**0.0**	**1700**	**2385**	**2391**	**6**
108417	4.01 W	186	2430	Unknown	Unknown

4.5 Smackover Resource Prediction Maps

Figure 4.9 shows the trend of the Smackover Fairway, as illustrated by Collins (1976). After investigation of the outliers concluded that all lithium samples should be included in the analysis, a predictive model was created in GIS to estimate the lithium resource in the areas of the Subsets. Two methods were used to predict lithium concentrations in Subsets 1 and 2. Because normal distribution is an assumed parameter in these modeling techniques, the accuracy of the prediction maps is dampened. Thus, multiple methods were used for analysis. It should also be noted that, due to many unknown sample depths, the depth of the samples is not accounted for in the prediction maps.

Method A uses Inverse Distance Weighted functions for the prediction map. This is a deterministic function that creates surfaces from measured values according to similarity of the measured values. It is a local technique that will use point proximity to influence the resulting interpolation. In essence, this interpolation method assumes that points which are closer to one another are more similar and will have a greater effect on the surface that is created. Consequently, Inverse Distance Weighted interpolation also assumes that points which are farther away from one another are less similar to one another and will have less of an effect on determining the surface.

Method B uses ordinary kriging to generate surfaces. Kriging is a geostatistical technique that incorporates the statistics of a measured data set to create a surface. This method not only creates a prediction surface, but also predicts the error and uncertainty of the surface that has been created. Kriging therefore allows one to assess the accuracy of the prediction and to make adjustments to the prediction. Adjustments include accounting for data trends and data transformations. A trend is a geospatial alignment identified by the software, whereas a transformation of the data is used to manipulate the data into a normal distribution. A second-order polynomial trend was identified in Subset 1, and a third-order

Figure 4.9: Approximate geographic extent of the Smackover Fairway, as illustrated by Collins, 1976.

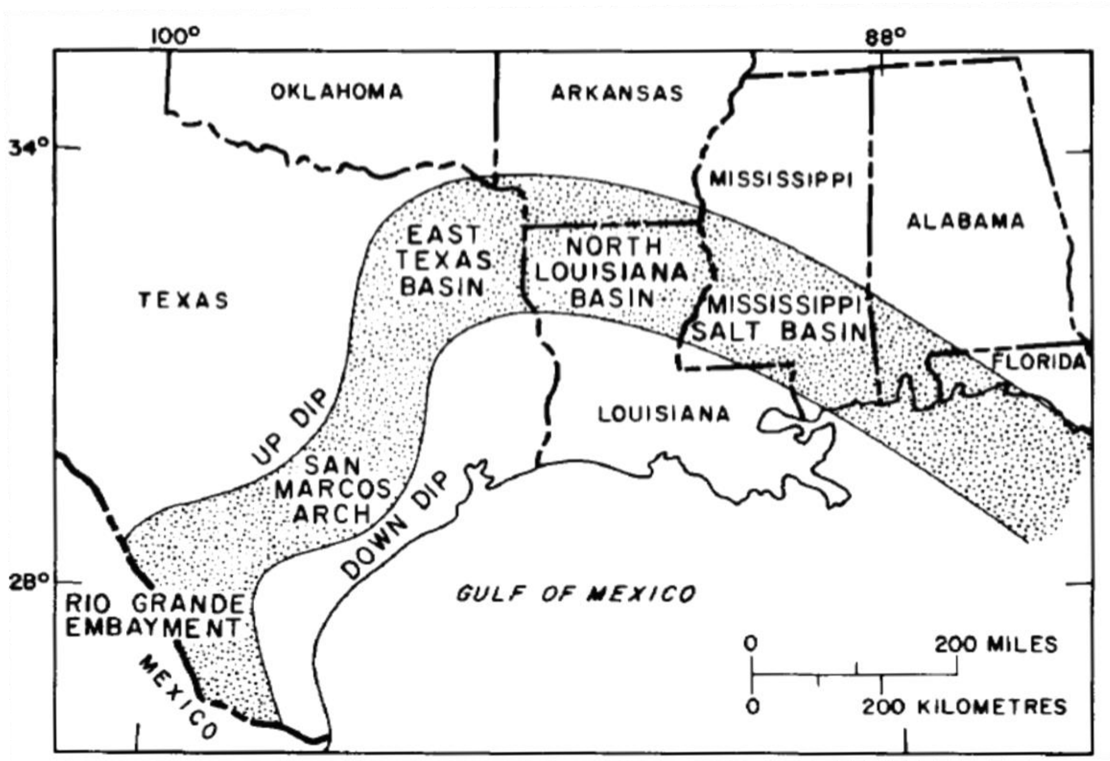


Figure 4.10: Prediction maps of lithium concentrations in the Smackover Subset 1 using different methods of computing: A) Inverse Distance Weighting; B) Ordinary kriging with a second-order trend removal and a logarithmic transformation.

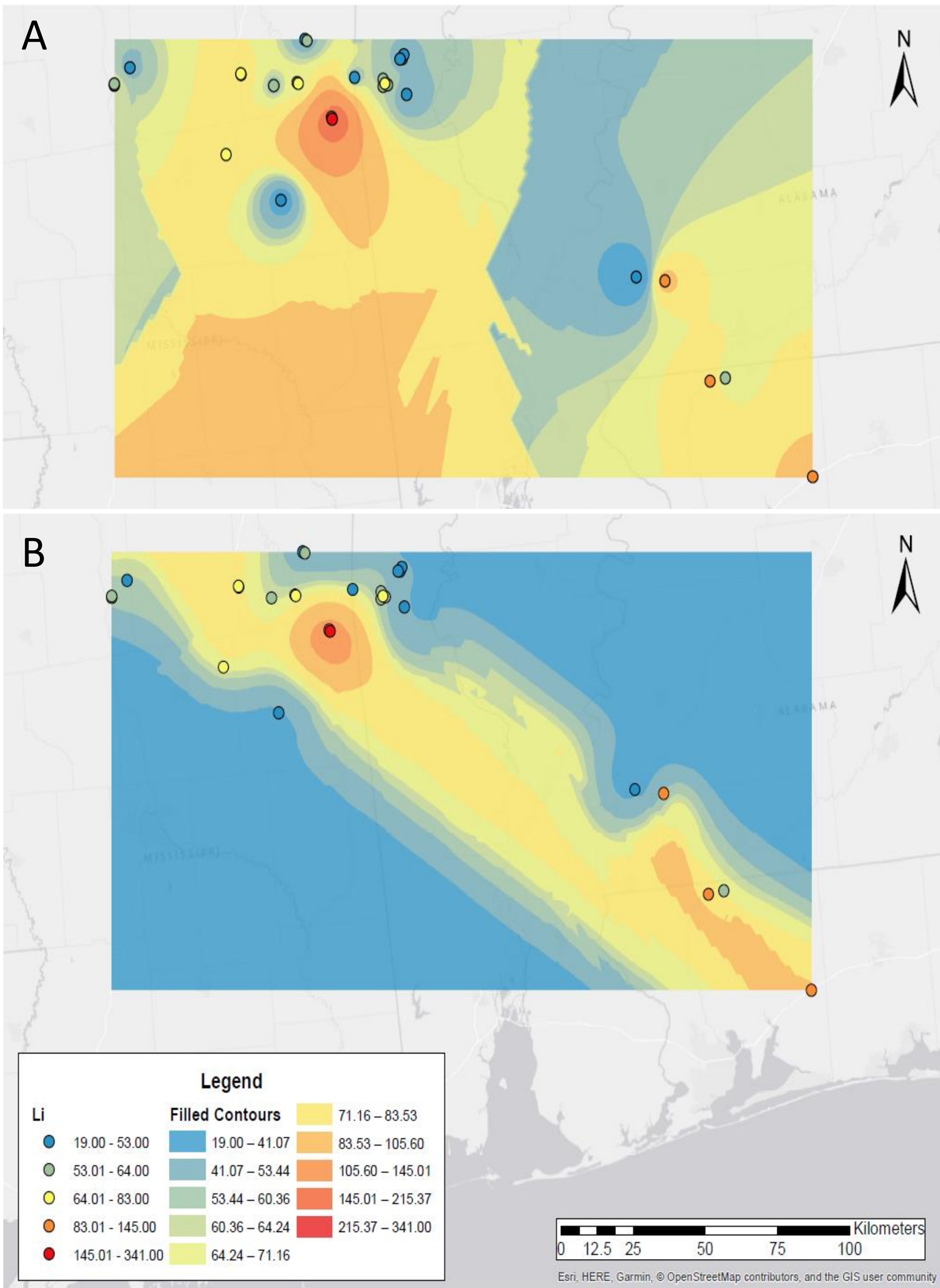
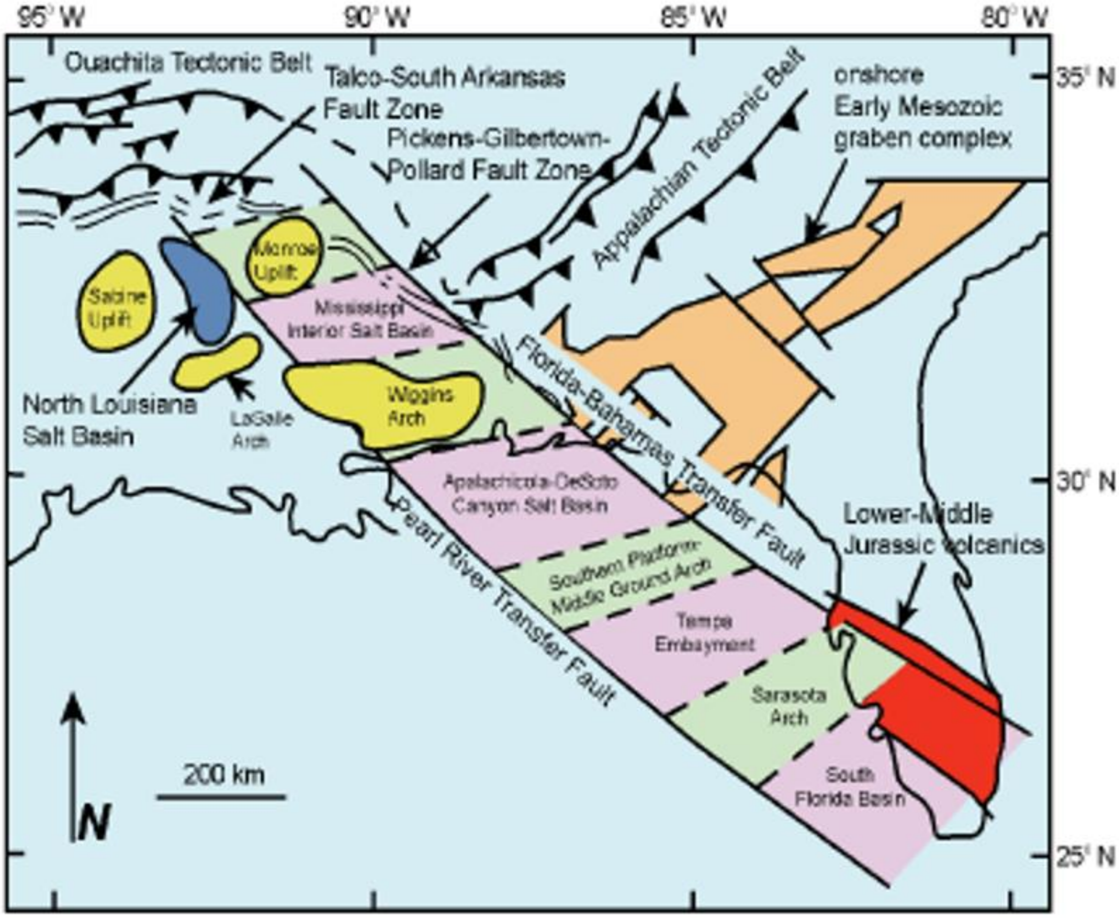


Figure 4.11: Regional faulting in the Gulf of Mexico. From MacRae and Watkins, 1996.



trend was identified in Subset 2. A logarithmic transformation was imposed on Subset 1. A transformation was not applied to Subset 2 due to an insignificant effect on the Subset.

Figure 4.10 shows prediction maps for Subset 1 using Inverse Distance Weighted interpolation (A) and ordinary kriging (B). Figure 4.10-A prediction map using Inverse Distance Weighted interpolation shows no spatial continuity in the region. This method of interpolation contradicts the continuity of the Smackover Fairway. In Figure 4.10-B the interpolation method of ordinary kriging shows spatial continuity in lithium trends. Figure 4.10-B shows a NW-SE trend in high lithium concentration that bisects a low lithium landscape. The trend of the high-lithium concentration areas in yellow to orange are similar to the trends of the Norphlet dunes and interdune sabhkas shown in Figure 3.5. Figure 4.11 illustrates regional faulting in the Gulf Coast area that would also explain the trend exhibited in Figure 4.10-B.

Figure 4.12 shows prediction maps for Subset 2 using Inverse Distance Weighted interpolation (A) and ordinary kriging (B). Inverse Distance Weighted interpolation used in Figure 4.12-A shows some spatial continuity between the measured lithium values. However, this spatial continuity cannot be explained by the Smackover Fairway exhibited in Figure 4.9. Figure 4.12-B shows a SW-NE trend that bends to the SE in Louisiana. In addition to following a similar pathway to that proposed by Collins, this trend also parallels the multiple fault zones illustrates in Figure 4.13. These fault zones offer a geological explanation behind the Kriging results. According to Vestal (1950), the Smackover formation is approximately 40 km wide as it moves across northern Louisiana into southern Arkansas. The width of the Smackover Formation as predicted in Figure 4.12-B is about 50 km wide where the data points begin. Ultimately, the ordinary kriging interpolation method was chosen to be representative of the Smackover Formation. The predictive maps of lithium concentration for both subsets can be found in Figure 4.14.

Figure 4.12: Prediction maps of lithium concentrations in the Smackover Subset 2 using different methods of computing: A) Inverse Distance Weighting; B) Ordinary kriging with and third-order trend removal and no transformation.

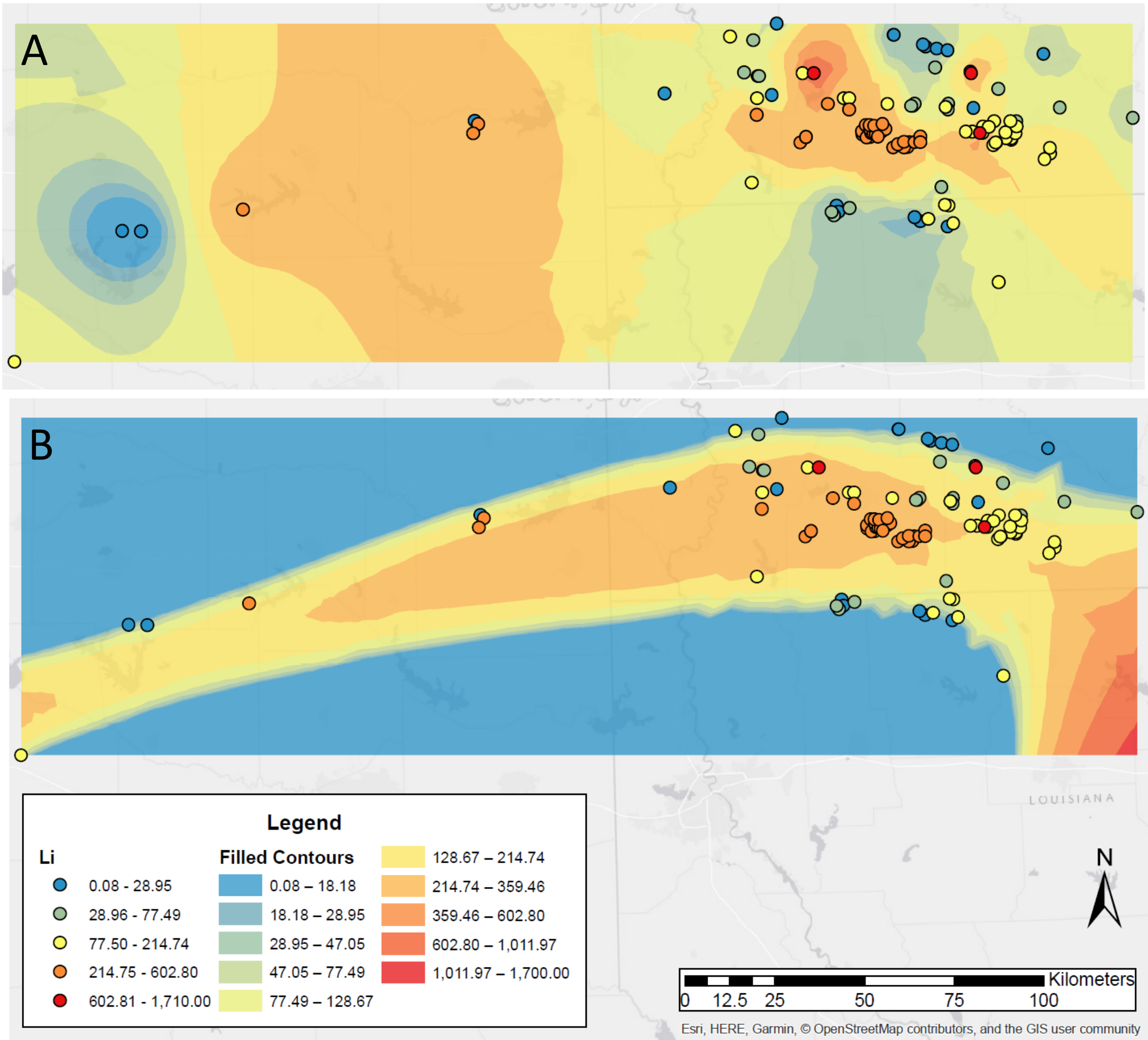


Figure 4.13: Fault zones influencing potential control on the predicted lithium pathways in Subset 2 area. Modified from Hammes and Frebourg, 2012.

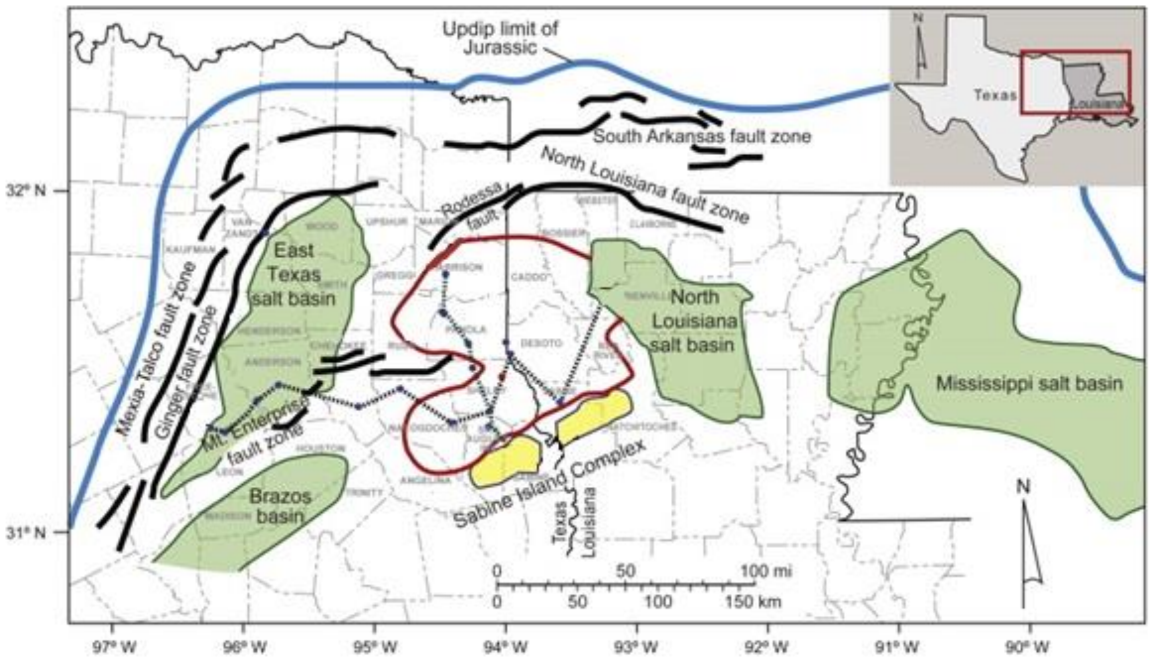
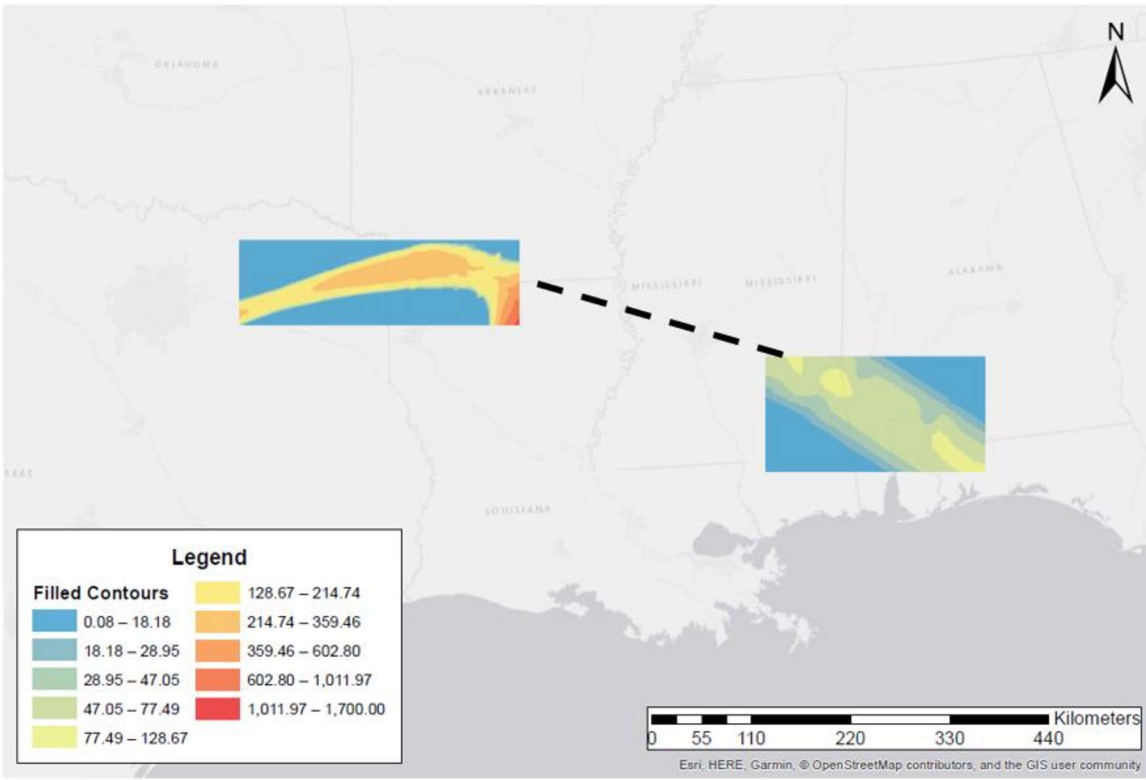


Figure 4.14: Predictive map of lithium concentration in the Smackover Formation Subsets. The Smackover Fairway connects both of the modeled areas but has not been modeled here due to lack of available data.



The proposed model by Chuchla (2018) for multiple sources of lithium align well with the enriched lithium intervals observed in Subset 2. The measured lithium concentrations of 1700 ppm and 1430 ppm were sampled over a well interval of six meters and seven meters, respectively. These samples exist at intervals measured at over 100 m difference, and the wells are located 49.25 km apart in a NW/SE trend. The Smackover formation is tilted in a southwestward direction with a maximum dip of 28.4 m/km (150 ft/mi) (Vestal, 1950). This suggests that there is one or many specific intervals in the Smackover Formation that hold the highest amount of lithium. It is possible that these are in fact two distinct intervals, and that there was more than one instance where lithium-enriched sediments entered the Smackover system. This hypothesis has major exploration and development implications for lithium production.

Collins found certain minerals to be enriched in the Smackover formations as compared to seawater and others to be depleted. Samples from Subsets 1 and 2 were compared to the ion concentrations measured by Collins (1976) in Table 4.5. The averages from each subset were gathered and compared to the concentrations found in seawater. A concentration ratio of the amount in brine to the amount in seawater is exhibited in Table 4.6. The concentration ratios in Table 4.6 support Collins' findings.

Additionally, regression analyses were performed to examine whether any relationships exist between lithium and other selected ions in the Smackover brine. The regressions were executed for the entire Smackover data as well as Subsets 1 and 2. The results can be found in Tables 4.7, 4.8, 4.9. The data used for comparison can be found in Appendix A. The ion with the strongest variance with respect to lithium is bromine. This statement holds true across all three subsets and is particularly evident in Subset 1 of the Smackover data. This correlation is unsurprising, as the Smackover brines have been used

Table 4.5: Comparison of average concentrations in Smackover formation to seawater.

	Collins (1976)		USGS Data		
	Seawater	**Smackover**	**Smackover**	**Subset 1**	**Subset 2**
Li	0.2	174	164	70	187
Ba	0.03	23	19	27	17
Ca	400	34534	32249	36251	31248
Cu	0.003	1.1	0.47	0.2	0.5
Fe	0.01	41	29	49	25
I	0.05	25	16	12	17
Mn	0.002	30	14	25	11
Sr	8	1924	1732	1471	1797
B	4.8	134	122	84	132
Cl	19000	171686	160880	181029	155843
K	380	2841	3285	7138	2321
Mg	1300	3465	3179	3548	3086
Na	10600	66973	61141	67165	59635
SO_4	2690	446	276	391	248
Br	65	3126	3378	1887	3750

Table 4.6: Comparison of concentration ratios measured in the Smackover to that observed in seawater. The ratio is written as Smackover: Seawater.

	Collins' Smackover	**USGS Smackover**	**Subset 1**	**Subset 2**	
Li	870	819	349	936	**Enriched**
Ba	767	640	890	577	
Ca	86	81	91	78	
Cu	367	156	80	175	
Fe	4100	2948	4864	2469	
I	500	315	233	335	
Mn	15000	7082	12722	5672	
Sr	241	217	184	225	
B	28	26	17	28	**Depleted**
Cl	9	8	10	8	
K	7	9	19	6	
Mg	3	2	3	2	
Na	6	6	6	6	
SO_4	0.17	0	0.15	0.09	
Br	48	52	29	58	

Table 4.7: Averages of selected ions from USGS Smackover data (in ppm) and respective regression statistics.

	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
Averages	164	19	32,249	0.47	29	16	14	1,732	122	160,880	3,285	3,179	61,141	276	3,378
R	--	0.21	0.34	0.01	0.14	0.09	0.14	0.36	0.31	0.34	0.06	0.15	0.30	0.03	0.49
R Square	--	0.04	0.11	0.00	0.02	0.01	0.02	0.13	0.09	0.11	0.00	0.02	0.09	0.00	0.24

Table 4.8: Averages of selected ions from Subset 1 of USGS Smackover data (in ppm) and respective regression statistics.

	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
Averages	70	27	36,251	0.24	49	12	25	1,471	84	181,029	7,138	3,548	67,165	391	1,887
R	--	0.08	0.18	0.27	0.08	0.03	0.15	0.25	0.12	0.33	0.05	0.09	0.20	0.10	0.74
R Square	--	0.01	0.03	0.07	0.01	0.00	0.02	0.06	0.01	0.11	0.00	0.01	0.04	0.01	0.55

Table 4.9: Averages of selected ions from Subset 2 of USGS Smackover data (in ppm) and respective regression statistics.

	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
Averages	187	17	31,248	0.53	25	17	11	1,797	132	155,843	2,321	3,086	59,635	248	3,750
R	--	0.32	0.41	0.05	0.15	0.08	0.27	0.36	0.34	0.40	0.33	0.28	0.35	0.19	0.44
R Square	--	0.10	0.17	0.00	0.02	0.01	0.07	0.13	0.12	0.16	0.11	0.08	0.13	0.04	0.20

for commercial recovery of bromine since 1957 (“Brine Resources,” 2015). In fact, bromine produced from the Smackover brine once supplied over 40 percent of the world’s bromine supply, from 1986 to 1990 (“Brine Resources,” 2015). It continues to account for a large portion of global production capacity (Schnebele, 2018). The continued production of bromine from Smackover brine creates the unique opportunity for the bromine producer (Albemarle) to simultaneously extract lithium.

Chapter 5: Financial Model Assumptions

5.1 Scenario overview

For commercial production of lithium from the Smackover Formation to commence, the following resources must be available: a lithium brine reserve; well(s) to access the brine reserve; a processing and extraction facility; a method to transport brine between wells and facility; storage tanks; and disposal or re-injection wells. The following sections of Chapter 5 detail the associated volumes, costs, and constraints of the required resources. The parameters were applied to a financial model that evaluates three possible scenarios for beginning commercial operation:

- Scenario 1: Produced water is gathered from active wells producing from the Smackover Formation.
- Scenario 2: Produced water is gathered from active wells producing from the Smackover Formation, with the eventual purchase of the producing wells from the operator when well costs for operator exceed well revenues.
- Scenario 3: Lithium producer drills purpose-designed well targeted to gather brine from a preferred location.

For simplification of the analysis, the company that will be focused on producing lithium will be referred to as LithiumCo, and the oil-producing well owners and operators will be collectively referred to as OilCo. The results of the financial analysis will be presented and discussed in Chapter 6.

5.2 Reserve estimates

The total volume of lithium metal in a brine can be estimated using the following relationship, modified from Gruber et al., (2011):

$$Lithium\ Reserve = A\ x\ T\ x\ \phi\ x\ (1 - S_{w,irr})\ x\ C$$

A = area of the aquifer

T = thickness of aquifer interval being measured

ϕ = porosity of the aquifer

$S_{w\ irr}$ = irreducible water saturation in aquifer

C = concentration of lithium in brine

Collins (1976) first estimated the lithium reserves in the Smackover formation to be 750,000 tons. The assumptions behind this are:

A = 25,000 km^2

T = 0.06 km

ϕ = 5%, effective

C = 100 mg/L

Collins does not provide an irreducible water saturation associated with porosity of the Smackover, but instead references an effective porosity. An irreducible water saturation value represents the amount of water that cannot be extracted from the aquifer due to being bound by capillary forces. Applying the parameters specified by Collins to the above formula for lithium resources does not yield the predicted amount of 750,000 tons.

The reserve estimates for the Subsets 1 and 2 were calculated using the above formula and can be found in Table 5.1. The Smackover area was determined by following the high-concentration trends identified in ArcGIS. The reserve estimate for the total formation has not been calculated, as the fairway region between these subsets is not clearly defined.

Table 5.1: Lithium reserve calculation for Subsets 1 and 2 of the Smackover Formation.

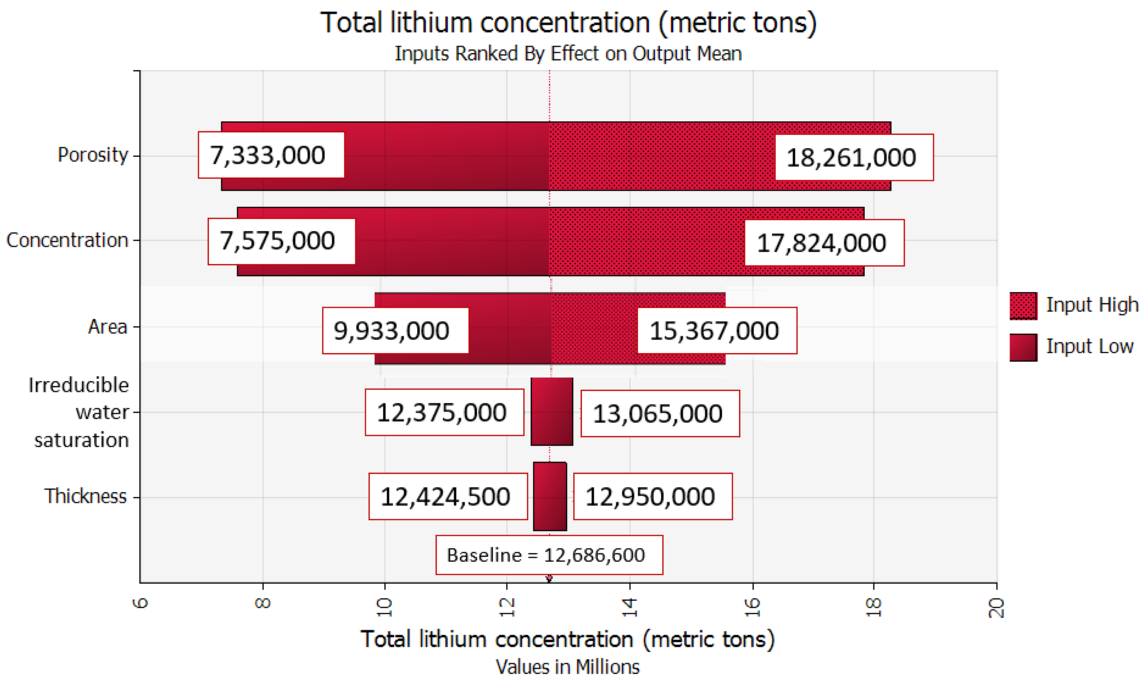
	Subset 1	**Subset 2**
Smackover Area (km^2)	13,226	9,850
Avg. Thickness (km)	0.0579	0.0579
ϕ	14%	14%
$S_{w\ irr}$	16%	16%
Li Concentration (mg/L)	70	187
Total extractable vol. (km^3)	86.8	64.6
Total Li (metric tons)	6,076,180	12,088,764

If Collins' parameters are applied to the formula used to estimate the reserves of the Subsets, this would yield a reserve of 6,750,000 tons. Compared to the reserves calculated in the area of the Subsets, this amount is slightly greater than Subset 1 and less than that of Subset 2. Subset 2 predicts a reserve amount almost twice that of Collins' estimation. Factors that are responsible for these differences include the formation thickness, area of the formation, porosity, irreducible water saturation, and concentration of lithium. It is also possible that hydrocarbon migration pathways have decreased the effective porosity of the formation. Figure 5.1 demonstrates that porosity and lithium concentration have the greatest effect on the reserve estimate.

5.3 Well production capacity

The production capacity of lithium is limited by access to brine resources. Oilfield brine can be obtained by gathering brine from currently producing wells, re-entering

Figure 5.1: Tornado diagram of factors that impact reserve estimates.



abandoned wells or drilling new wells to produce brine from the Smackover. However, the hydrogen sulfide (H_2S) that is produced in conjunction with hydrocarbons produced from the Smackover is extremely corrosive and can potentially deteriorate the well casing. Failed casing can result in environmental disaster. The likelihood of re-entering and producing from abandoned wells in the Smackover Formation is given a low probability of success. Therefore, the brine resource available for lithium extraction is constrained by either 1) the number of actively producing wells that access the Smackover formation and their flow respective flow rates or 2) the maximum flow potential in a newly drilled well.

Using DrillingInfo, historical production data was found for 15 wells of the 145 wells in the sample set. A more detailed breakdown of well production was found by accessing each state's oil and gas production website. Only four wells were currently operating for production, and all of the wells were found to be located in the area of Subset 1. For the scenarios where lithium is extracted from existing producing wells, these will be the wells used for the assessment. The historical production from one of the active wells was used to extrapolate future production of oil and brine from the well for the next 20 years. For simplification, the same rate of production was applied to all active wells in the subset. The historical and forecasted well production data can be found in Appendix B.

An additional scenario evaluates how the economics of extracting lithium differ when a new purpose-designed well is drilled to gather the brine. If a new well is drilled, the most economical production would take place at the highest source of lithium. The highest source of lithium is concentrated in Subset 2 of the Smackover. Therefore, lithium production capacity estimation for the scenario of a purpose-drilled brine well will be conducted using the average lithium concentration for Subset 2. It is also assumed that no hydrocarbons are produced in this scenario.

The amount of brine a new well produces can be calculated using the ideal specific flow rate. The equation for ideal specific flow rate can be described using the following formula (*A Survey of the Subsurface*, 1972):

$$Q = \frac{0.2065 k_w h (P_e - P_w)}{\mu \ln \left({}^{r_e}/_{r_w} \right)}$$

Q = ideal flow rate in gallons per minute (gpm)

k_w = permeability in Darcies (D)

h = bed thickness, in feet (ft)

r_w = radius of the well-bore (ft)

r_e = external drainage radius (ft)

P_e = static aquifer pressure at r_e: a function of depth, specific gravity, and a constant of 0.433,in pounds per square inch (psig)

P_w = producing bottom hole pressure of aquifer, estimated to be 20% of P_w (psig)

μ = water viscosity (cp)

A compilation of measurements from various studies on the Smackover Formations were averaged to create the values for permeability, bed thickness, static aquifer pressure and bottom hole pressure. The Smackover averages and data used for this calculation can be found in Table 5.2. For this calculation, the well-bore radius is 0.5 feet and the external drainage radius is 2,640 ft (0.5 mi, or 0.805 km). Using these values, the flow rate for a newly drilled well in the Smackover formation will have a flow of 5,077 gallons per minute (gpm), shown in Table 5.3. This equates to more than 174,000 barrels per day of brine supply from one well. The well screen efficiency will reduce the well flow rate by 15 to 40

Table 5.2: Compiled averages of Smackover characteristics from surveyed research.

Compiled Averages of Smackover	
Avg ϕ	14%
$S_{w\ irr}$	16%
Specific Gravity	1.19 g/cc
Avg K_w	0.158 D
Bed thickness	190 ft / 57.9 m
Fmtn. Thickness	548 ft / 167.4 m
Avg Fmtn. Depth	12,946 ft / 3,946 m
Avg Temperature	126˚C / 252˚F
Viscosity	0.2312 cp

Sources: Guillotte et al., 1979; Vestal, 1950; Wade, 1993; Mancini, 2008; *A Survey of the Subsurface,* 1972; *Annual Report of Production*, 2017.

Table 5.3: Ideal specific flow rate of a newly drilled well in the Smackover Formation.

k_w	0.158 D
h	190 ft
r_w	0.5 ft
r_e	2640 ft
P_e	2033.26 psig
P_w	406.65 psig
μ	0.2312 cp
Q =	5077.4 gpm

percent of its ideal flow rate. This reduced flow rate is accounted for in the model. However, the facility's processing capability for the model is a fraction of the flow potential from the purpose-drilled well. For this reason, the annual number of barrels of water produced by the well and processed by the facility appear to remain steady in the financial model.

5.4 ASSOCIATED COSTS

5.4.1 Rights to brine and oil

Before mineral extraction from oilfield brine can occur, the mineral producer is required to have the rights to access the brine. The rights to the brine can be owned or leased by landowners, government, oil producers, or other third parties. The rights can be sold or leased to another party. For this model, the brine rights are assumed to be owned by a third party from which LithiumCo will lease the brine rights.

Table 5.4: Model of financial compensation for rights to access brine.

Brine rights holder:	Standard Lithium
Lessee:	Tetra Tech.
Net-Acres Brine:	33,000

	Payment			Royalty
Year 1	$1,000,000			
Year 2	$600,000			
Year 3	$700,000			
Year 4	$750,000			
Year 5	$1,000,000	OR	*Year 5*	2.50%
Year 6	$1,000,000		*Year 6*	2.50%
Year 7	$1,000,000		*Year 7*	2.50%
Year 8	$1,000,000		*Year 8*	2.50%
Year 9	$1,000,000		*Year 9*	2.50%
Year 10	$1,000,000		*Year 10*	2.50%

* Royalty is of gross revenue, subject to a minimum annual royalty payment of $1 million.

The payment schedule is modeled based on a brine rights transaction between Tetra Technologies and Standard Lithium for access to 33,000 net acres of brine in Arkansas ("Standard Lithium," 2018). The details of the agreement can be found in Table 5.4. The terms of the agreement require annual cash payments for the first four years from the date of purchase agreement. Subsequently, the lessee (Standard Lithium) will provide the lessor (Tetra Technologies) an annual cash payment of either $1 million, or 2.5 percent of the company's gross profit, subject to a minimum of $1 million through the tenth year. This series of transactions grants the lessee the rights to access and extract from the brine for the duration of ten years.

Because this analysis uses a 20-year operation lifetime, an accompanying royalty, albeit conservative, was included for the remaining ten years of operation. It imposes an annual cash payment of 2.5 percent of the company's gross lithium profit. There is no minimum payment this royalty should meet. An additional royalty payment is required for any hydrocarbons produced by LithiumCo. The model assumes that LithiumCo distributes a royalty payment of 12.5 percent of the gross oil profit to the mineral rights holder from any skim oil created from the brine. No royalty payments will be paid to the OilCo because of the discount price offered to OilCo for collection and disposal of produced water (see section 5.4.3).

5.4.2 Well costs

Brine production will ideally be sourced from vertical wells. The well costs and associated costs for this analysis are based on information provided by the 2016 EIA report on Trends in U.S. Oil and Natural Gas Upstream Costs. Because this study evaluates wells with a horizontal drilling component, the lower price points were assumed in the financial model for both operating expenses and capital expenses to mitigate the effect of horizontal costs in the breakdowns. Any new wells constructed for lithium extraction will be vertical wells. The lower price points are supported by discussions with industry personnel

(Alspaugh, 2018; Clay, 2018). The following assumptions were made to account for well costs:

- Purchase of a stripper well: $78,000
- Drilling and completion of vertical well to 12,000' with probable H_2S content: $2 million
- Well operation costs: 12% of total cost
- Lease operating expenses per barrel of oil: $3
- Gathering, Transport, and Processing costs per barrel of oil: $1.50

The cost of drilling and completing a vertical well for the financial analysis includes the costs for surface casing and intermediate casing. The lease operating expenses per well are subject to a minimum annual cost of $10,500 (Clay, 2018).

5.4.3 Transportation of brine

Like oil and gas produced from a well, brine can be transported from the wellhead to a treatment facility through pipeline or by trucking. Transfer through pipeline is a more cost-effective method than trucking when the resource to be transferred has an extended lifetime of supply. Trucking enables flexibility and access to multiple wells that may not have a large reserve but are still operational. Storage facilities are required for both transportation methods at either the wellhead or the processing facility.

The scenarios to be evaluated assume trucking as the method of brine transportation. Companies producing hydrocarbons often outsource the disposal of their produced water to saltwater disposal (SWD) companies. These companies collect and transport the produced water to a facility for processing. Processing of the produced water is characterized by decontamination of the brine to levels required by federal and/or state standards. This is a necessary step to prevent the injection of contaminants such as volatile organic compounds (VOCs), or substances used in drill production and completion. Removal of these contaminants contributes to a prolonged life of the transportation equipment, processing facilities, and wells used for reinjection or disposal.

The costs associated with disposal of produced water vary on average between one to eight dollars per barrel (EIA and IHS, 2016). Factors that determine the price per barrel include number of barrels of water produced per barrel of oil, proximity to SWD facility, costs of transportation, and method of disposal. Clay (2018) estimates that in producing fields similar to the Smackover, producers pay disposal costs of $1.85 per barrel of water, including trucking costs.

LithiumCo has the opportunity to enter the SWD industry and gain market share by offering hydrocarbon producers a water disposal fee that is less than the competing market price of $1.85 per barrel. The lower price not only creates a customer base for LithiumCo, but it also increases the profit margin for the hydrocarbon producers who sell produced water to LithiumCo. The increase in profit margin for the hydrocarbon producers incentivizes the producers to employ LithiumCo.

5.4.4 Facility and extraction technology

Advancements in production technology of lithium from brine has created the opportunity to extract lithium from highly enriched brine contaminated with organic matter such as oil and natural gas. Currently there are five companies that have begun utilizing advanced technology to extract lithium from brines: MGX Minerals, Petrolithium, Standard Lithium, Albemarle, and POSCO. Each company uses a different technique to extract the lithium from the highly mineralized and/or contaminated water. In essence, each technology goes through multiple filtration steps that remove non-lithium elements from the solution. The goal of the filtration is to eliminate as many dissolved solids and organic matter from the brine that could inhibit the recovery of simple lithium compounds. The rates of lithium recovery have been documented between 70 to 80 percent for these companies, and the lithium product can be created in as little as 8 to 36 hours ("POSCO Opens," 2017; McEachern, 2017).

The cost of extracting lithium from oilfield brine is based on details provided by the CEO of MGX Minerals, Jared Lazerson, in a published interview ("A Critical Q&A with MGX," 2017). The following information was used to construct the financial model:

- Capital expense for commercial treatment facility with processing capacity of 7,000 barrels per day with heavy mineral and hydrocarbon contaminants: $3,000,000
- Average cost per barrel to treat brine: $1
- Average transportation cost per barrel to facility: $0.50
- Lithium recovery rate from brine with lithium concentration of 70 mg/L: 70%
- Magnesium recovery rate: 99%

The interview also states that the final product could be converted to lithium carbonate "for a modest fee" ("A Critical Q&A with MGX," 2017). This fee was modeled as part of the cost to treat each barrel of brine and is assumed to be less than $0.05.

Because the exact method used to separate hydrocarbons from the brine are unknown, the model assumes that the facility has the capability to successfully process hydrocarbons in small quantities. The model assumes that an increased cost of maintenance and replacement parts is required to continue operation if the quantity of oil increases. However, if additional infrastructure were required to separate oil from brine, as may be the case in Scenario 2, LithiumCo can purchase floating oil skimmers or oil water separators for less than $2,000 to extract about 12 gallons of oil per hour. Maintenance costs for this additional purchase would be negligible.

5.4.5 Disposal of residuum

For the purpose of the proposed scenarios, all brine that has been processed for lithium extraction will be disposed or reinjected through disposal or reinjection wells that access the Smackover Formation. Disposal wells typically refer to cleaned water being put into the ground at an interval deeper than the producing formation. Injection wells are wells used to reinject water into the producing formation to create an enhanced recovery of the hydrocarbons. For this analysis, the company should seek a disposal well that will reinject water into the Smackover Formation for conservation and recycling of the lithium-bearing brines after processing. This will allow the 30 percent of lithium not yet recovered by the extraction process to be subject to potential recovery. However, this reinjected and relatively lithium-poor fluid will dilute the unprocessed lithium brine over time. This factor has not been accounted for in this analysis.

The removed contaminants that are not sold for profit are obtained by centralized waste treatment facilities. After lithium has been extracted from the brine, the resulting brine will meet or exceed the standards required by federal and/or state regulations for disposal and reinjection. The recycling of the brine into the Smackover Formation is important because it will maintain the water level and pressure of the confined aquifer. The costs of reinjection and disposal are accounted for in the price paid by hydrocarbon producers to dispose of the produced water.

5.5 COMMODITY PRICES

5.5.1 Lithium prices

As discussed in section 2.2.3, the future price of lithium proves difficult to forecast because of the multiple factors that pull the price in different directions. For this analysis, the price of lithium is modeled as increasing until 2020, at which time additional lithium projects come online and increase market availability of lithium. The price increase for this period follows that created from the regression coefficients of historical prices shown in section 2.2.3, Table 2.2. From 2020 to 2037, prices are modeled to decrease by five percent annually and revert to a price of about $14,000 per metric ton of LCE. This is the approximate price of lithium observed in 2017. Pursuant to the Deutsche Bank forecast, prices will not fall below $10,000 per metric ton of LCE in this model (Graves, 2017). Model lithium prices can be found in Table 5.5.

Table 5.5: Prices per metric ton of LCE used in analysis.

Year	LCE Price per metric ton
2018	$ 20,510
2019	$ 28,220
2020	$ 27,460
2021	$ 26,690
2022	$ 25,930
2023	$ 25,160
2024	$ 24,400
2025	$ 23,630
2026	$ 22,860

Table 5.5, cont'd	
2027	$ 22,100
2028	$ 21,330
2029	$ 20,570
2030	$ 19,800
2031	$ 19,040
2032	$ 18,270
2033	$ 17,500
2034	$ 16,740
2035	$ 15,970
2036	$ 15,210
2037	$ 14,440

5.5.2 Oil prices

It is necessary to include forecasted oil prices in the analysis because oil price will affect the outcome of the lithium operation in two of the scenarios analyzed. In Scenarios 1 and 2, the price per barrel of oil affects the profit from the sale of skimmed oil, which is an additional revenue stream for LithiumCo. In Scenario 2, the point at which OilCo sells the wells to LithiumCo depends on OilCo's profit margin, which is dependent on the spot market price per barrel of oil.

Three methods were used to predict future oil prices and assembled into price decks. The first price deck, Base Case, models oil prices increasing at the annual U.S. inflation rate of two percent. The second price deck, Dynamic Case, used the regression coefficients of historical oil prices to forecast price. The third price deck, Future Case, used the regression coefficients of future market oil prices to forecast price. Little variation was observed between the three price decks, as can be seen in Figure 5.2. Thus, an average was taken of the three prices and was used for the analysis. The averages of the oil price decks can be found in Table 5.6.

Figure 5.2: Oil price decks constructed for assessing future oil price.

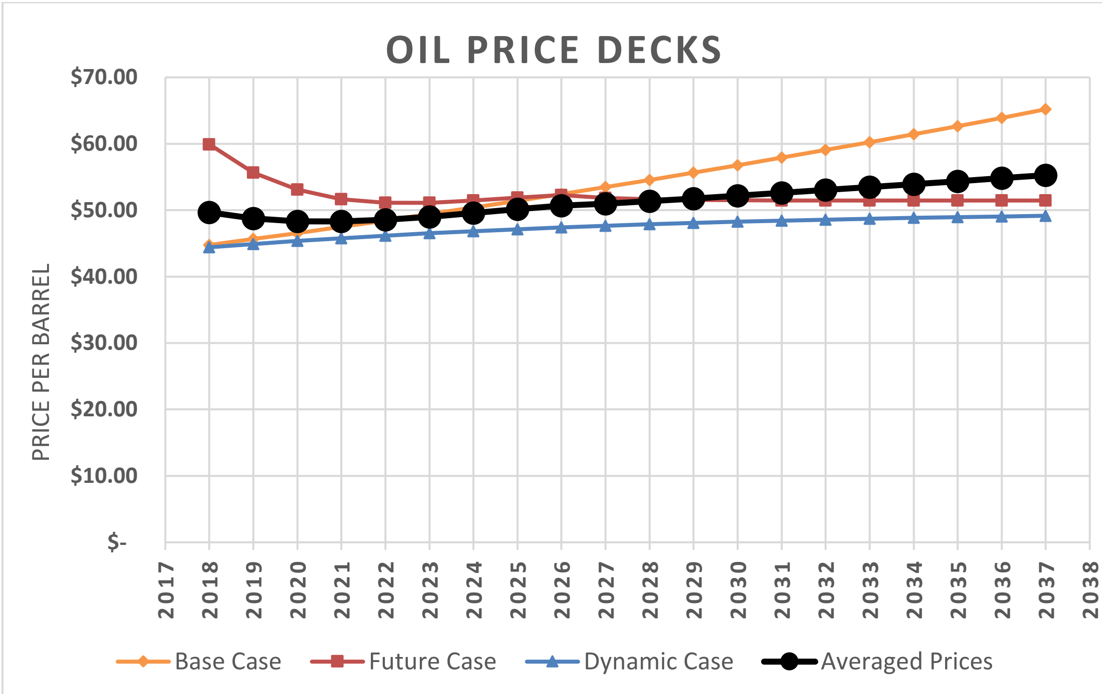


Table 5.6: Prices per barrel of oil used in analysis.

Year	Averaged prices per BBL of oil
2018	$ 49.70
2019	$ 48.74
2020	$ 48.34
2021	$ 48.31
2022	$ 48.58
2023	$ 49.01
2024	$ 49.57
2025	$ 50.14
2026	$ 50.71
2027	$ 50.99
2028	$ 51.35
2029	$ 51.75
2030	$ 52.17
2031	$ 52.60
2032	$ 53.03
2033	$ 53.47
2034	$ 53.91
2035	$ 54.36
2036	$ 54.81
2037	$ 55.27

Chapter 6: Commercial Analysis

6.1 Scenario 1: Produced water acquired from operators

Scenario 1 evaluates commercial lithium production from produced water of actively operating wells producing from the Smackover Formation. This scenario was chosen to assess the value impact of using existing well infrastructure to access the lithium reserve. It can be viewed as a hypothetical scenario, for in this scenario hydrocarbon producers are assumed to continue producing from the four Smackover wells for the next twenty years and the produced water is sold to LithiumCo. It is assumed that no new wells are identified nor drilled into the Smackover that can provide additional produced water from the Smackover.

In Scenario 1, LithiumCo's revenue stems from three sources: by collecting produced water from oil producers, from the sale of lithium carbonate, and from the sale of skim oil. Revenue for Scenario 1 is modeled in Figure 6.1. Revenue rises in Year 2 of the financial analysis because of the increase in market lithium price. After Year 2, gross revenue appears to remain stable, although the amount of revenue from each source changes. Revenues from lithium carbonate sales gradually decrease in response to a decrease in lithium sale price.

In contrast, revenues from produced water collection and skim oil sales are increasing. Revenues from produced water increase because more produced water is available for collection over time. This is because the wells used to gather the brine are modeled to have increasing quantities of produced water for sale as hydrocarbon production declines. This is a natural phenomenon that occurs in hydrocarbon production. The increased produced water creates in an increased amount of skim oil that is sold

Figure 6.1: Sources of revenue in Scenario 1.

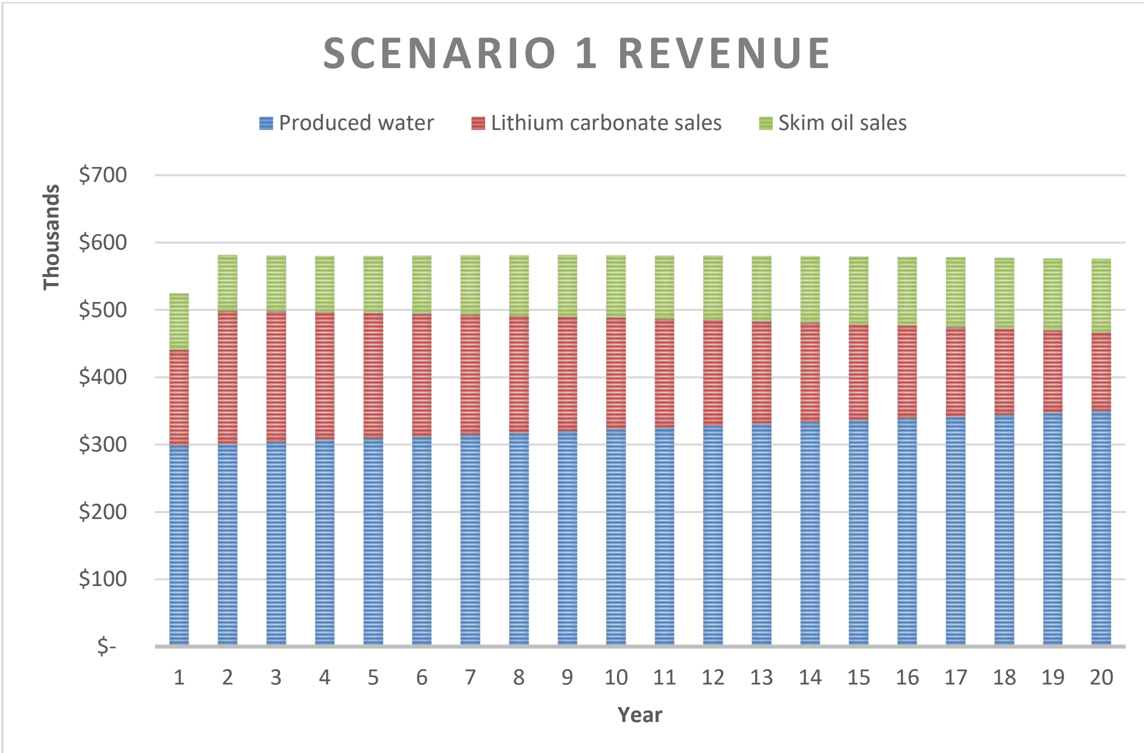
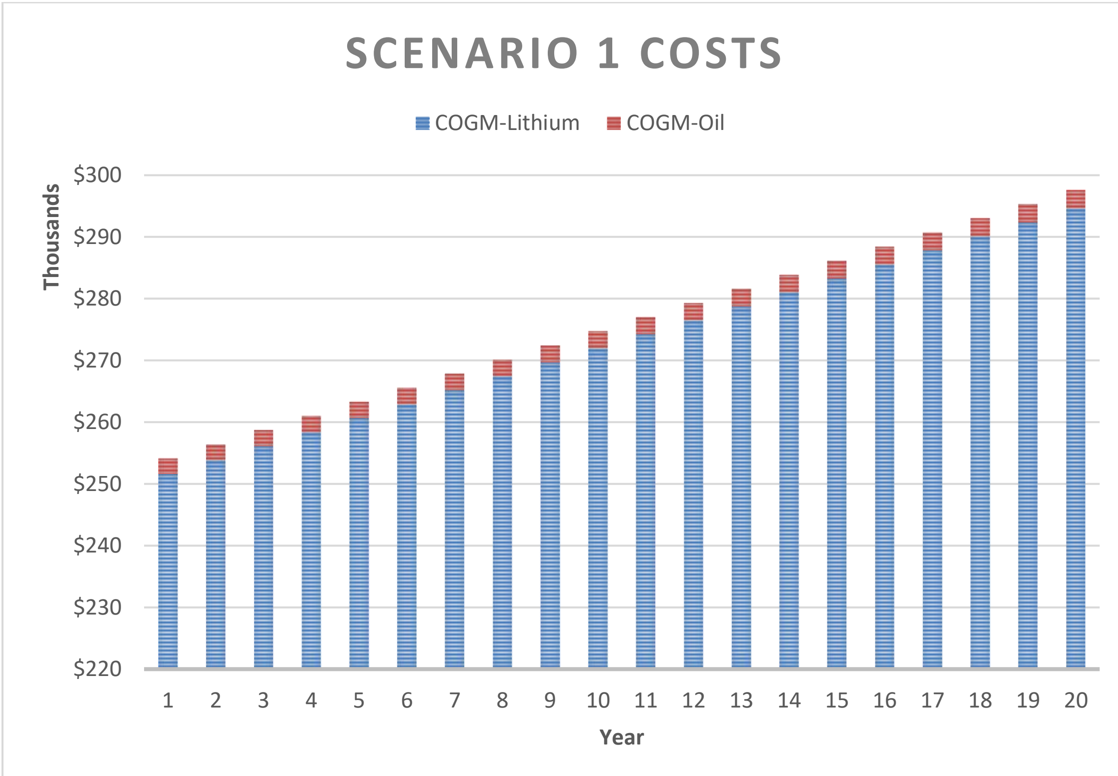


Figure 6.2: Breakdown of costs for Scenario 1.



because skim oil is modeled as one percent of the total produced water collected. In conjunction with more skim oil for sale, the price of oil increases over time, resulting in increasing revenue from the skim oil sales.

The costs associated with Scenario 1 are displayed in Figure 6.2. In Scenario 1, costs were saved by not owning any wells, nor incurring operational costs (i.e. power costs), nor lease operational costs (i.e. costs for land use) associated with wells. The majority of the costs are attributed to lithium extraction and processing. Costs gradually increase over time as more produced water is collected. The costs of producing skim oil corresponds to the increase in skim oil that is collected.

An additional cost for LithiumCo is the royalty payment for oil and brine rights. Oil royalty payments are deducted from the gross oil profit, and the brine right royalties are deducted from the gross lithium profit. The impact of the royalty payments on LithiumCo's profitability is shown in Figure 6.3 along with company's free cash flow (FCF). FCF is the total profit or loss created by the company each year. The calculated FCF is a summary of the annual revenue, costs, capital expenses, taxes, and depreciation incurred by the company.

LithiumCo does not make a positive FCF until Year 11 of the operation. At this point in time LithiumCo is no longer subject to paying a minimum brine right royalty of $1 million. LithiumCo continues to pay brine rights royalties throughout the lifetime of the operation, but the amount is substantially less than the amount that was owed in the first ten years of the lease. Oil royalty payments are less than $10,000 annually and have little impact on the FCF. Figure 6.3 juxtaposes FCF against the brine rights royalty payments to demonstrate the effect of these payments on LithiumCo's FCF. It is the abating cost of the brine rights royalties in Year 11 that enables the FCF to remain positive for the remainder of the operation's lifetime.

Figure 6.3: Overview of free cash flow in Scenario 1 with respect to oil and brine rights royalty payments.

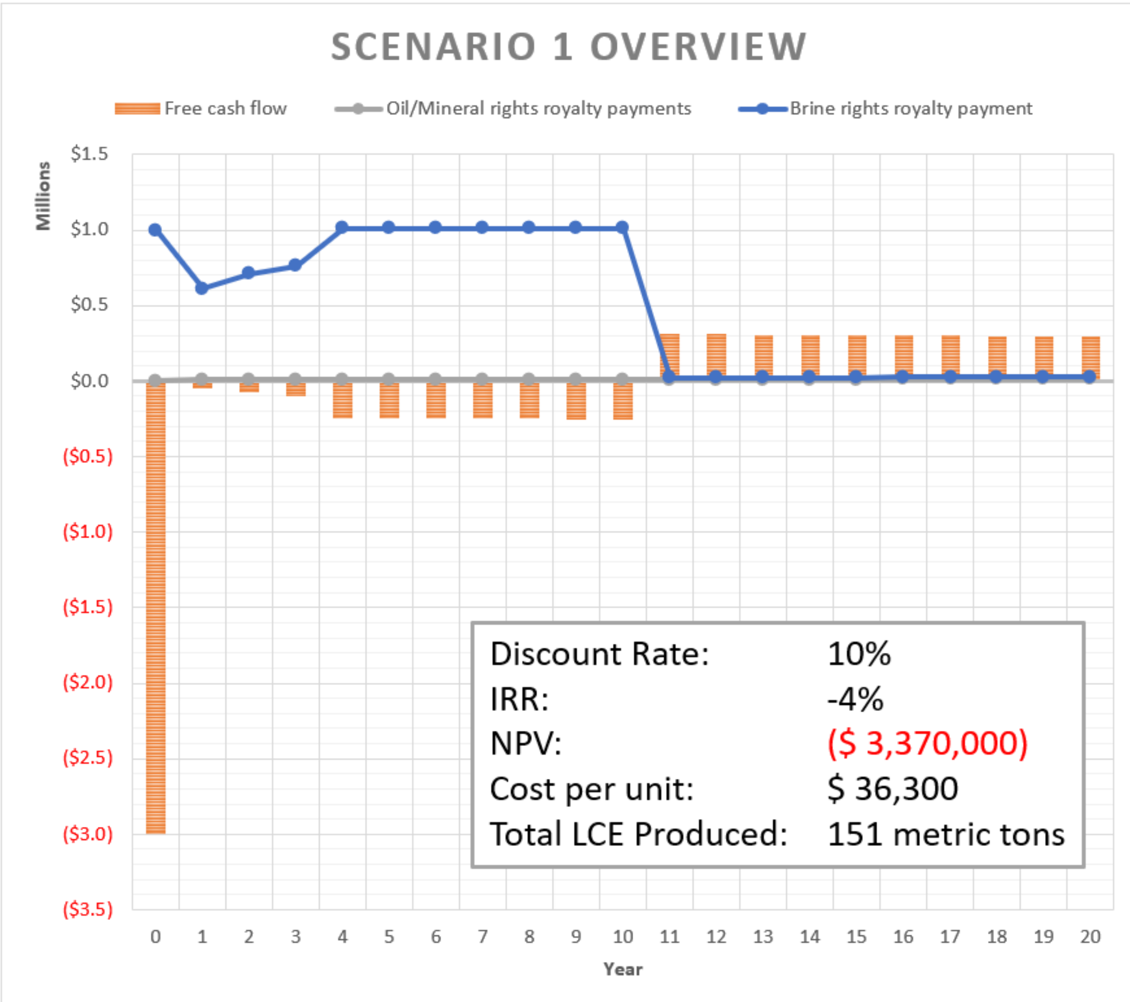
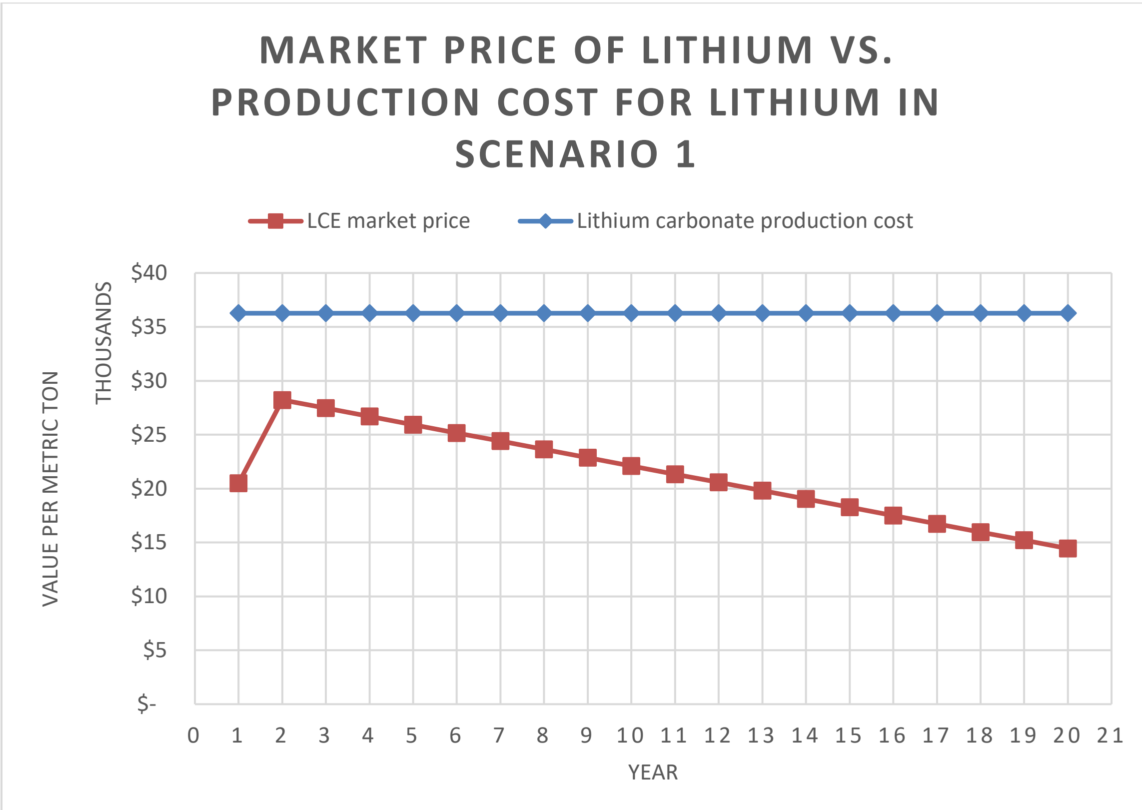


Figure 6.4: Scenario 1 production cost per metric ton of lithium carbonate compared to market price of LCE.



At the end of the 20-year life of the operation in, Scenario 1 produces 151 metric tons of lithium carbonate from the Smackover. The unit cost per ton of lithium carbonate manufactured is $36,300. However, the maximum price paid per ton of lithium carbonate in the spot market is $28,220 in Year 2. Figure 6.4 illustrates that in this scenario, the unit production cost of lithium carbonate is always greater than the sale price. Unless the cost of production is reduced, it is not possible for Scenario 1 to achieve an NPV10 (net present value at a ten percent discount rate) greater than zero at the end of 20 years.

The unit cost of production is dependent on the lithium concentration of the produced water. The produced water supply in this scenario is gathered from the 4 active wells in the Subset 1 area with an average lithium concentration of 70 ppm. At this lithium concentration, the facility must process more than 24,000 barrels of brine to produce one metric ton of lithium carbonate. The cost to manufacture lithium carbonate will only decrease when the concentration of lithium in the brine increases. Unfortunately, over time the lithium concentration in the Smackover is more likely to decrease, rather than increase, as reinjected brine dilutes the lithium concentration for this area.

6.2 Scenario 2: Oil company sells producing wells to lithium company

Scenario 2 evaluates lithium production from the produced water of active wells in the Smackover Formation. Unlike Scenario 1, Scenario 2 assumes that the producing wells in the Smackover Formation have a finite quantity of recoverable hydrocarbons, and therefore OilCo will eventually cease production from all of the Smackover wells. If OilCo abandons all four of the wells, then LithiumCo will need to source its brine by either purchasing the wells from the OilCo, or, if possible, by finding other wells from which produced water can be collected. This analysis assumes there are no more wells from which produced water can be gathered, and thus LithiumCo must purchase the wells from OilCo.

Evaluating this scenario is essential to the analysis for two reasons. First, the acquisition of the wells results in a greater amount of oil that LithiumCo can sell, enabling the company to focus on both oil and lithium production for revenues. However, owning the wells then increases the operating costs for LithiumCo to produce lithium, which can negatively impact the company's bottom line. This especially holds true if the additional source of revenue, in this case oil sales, is finite. Secondly, this scenario will be a situation that is likely faced by some, if not most, of the existing wells used to gather produced water. Therefore, it is important to demonstrate the impact of well acquisitions on the overall profitability of lithium production.

OilCo will consider abandoning the Smackover wells when the expected costs of operating the wells exceeds the expected revenues made from producing the wells. Figure 6.5 shows the expected revenues and costs for OilCo when operating the four Smackover wells. These values are based on the predicted oil prices shown in Table 5.6, which increase steadily over time. However, the amount of oil produced each year by the four wells decreases at such a rate that revenue loss cannot be offset by the gradual increase in oil price. In Year 11, OilCo experiences a financial loss when well costs exceed well revenues.

If an oil producer experiences a prolonged loss or believes a prolonged loss is inevitable, the producer must consider an exit strategy. There are three possible exit strategies: 1) to plug and abandon the well, 2) to continue producing oil at a loss, or 3) to sell the well to an interested party. The costs of plugging and abandoning a well are likely greater than the costs of continuing oil production at a loss. Alternatively, by selling the

Figure 6.5: Expected revenues and costs for OilCo from Smackover producing wells.

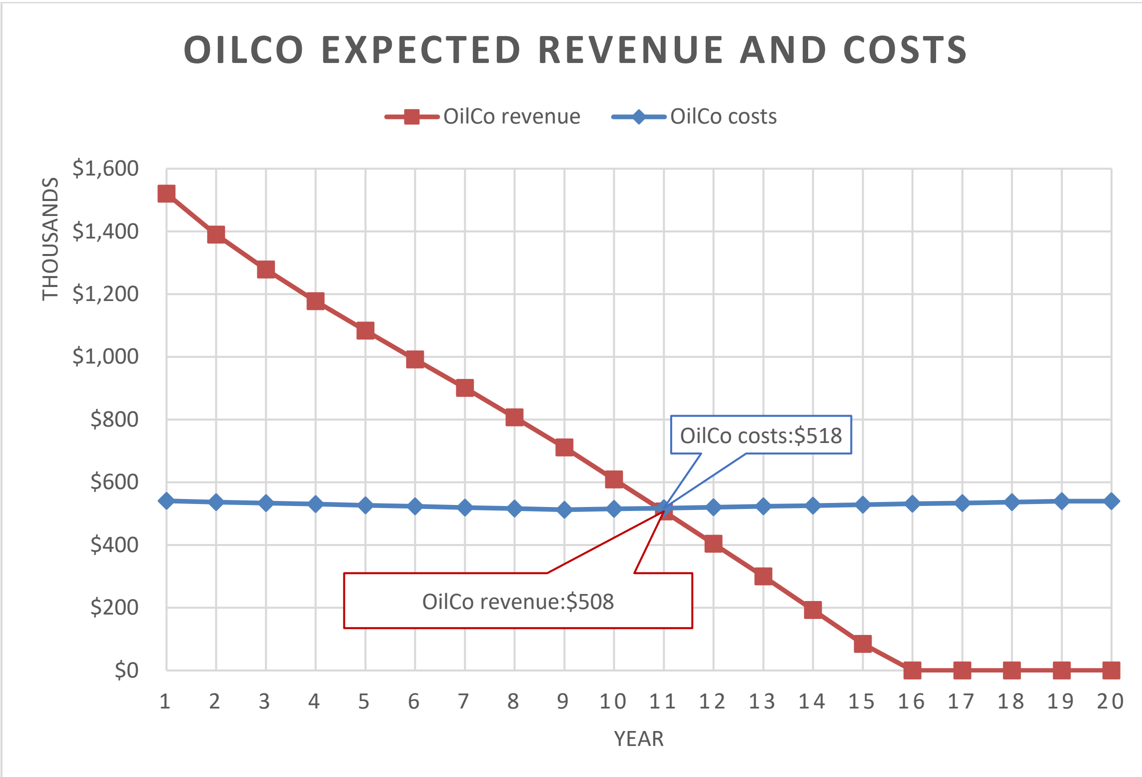
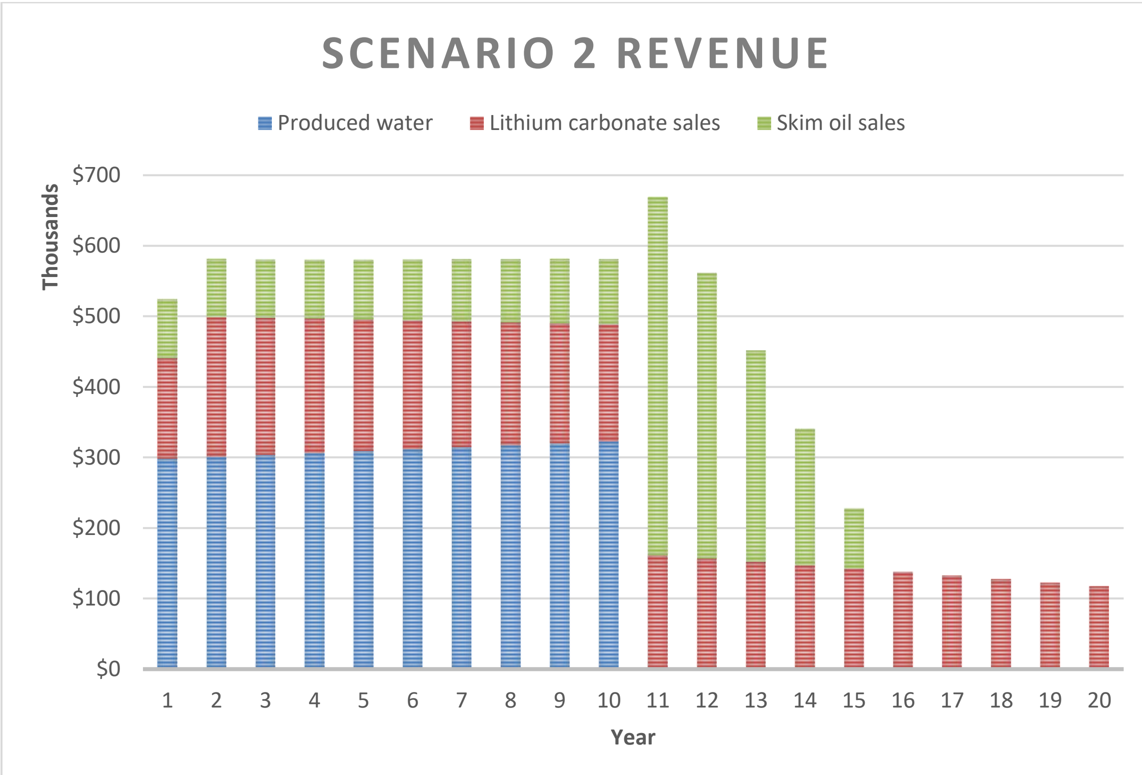


Figure 6.6: Sources of revenue for LithiumCo in Scenario 2.



wells to an interested party, an oil producer can mitigate the financial loss or possibly even recover some of the loss. For this analysis, selling the wells is the best exit strategy for OilCo.

Due to the anticipated financial loss that OilCo will experience in Year 11, the model assumes that OilCo preemptively sells the wells to LithiumCo at the beginning of Year 11 so as to avoid any loss. LithiumCo purchases all four wells from OilCo for a total price of $313,000, or a per well cost of $78,000. The sale value was calculated by finding the total profit (annual forecasted oil production of the wells multiplied by the forecasted oil prices each year) and subtracting from it the operational costs, lease expenses, and payable royalties.

Figure 6.6 shows the sources of revenue for LithiumCo in Scenario 2. In the beginning of the scenario, LithiumCo sources its revenue from collecting produced water, the sale of lithium carbonate, and the sale of skim oil. Beginning in Year 11, LithiumCo no longer makes revenue from collecting produced water but instead has an increased revenue from oil sales. Oil production from the Smackover wells ceases by Year 16. Hereafter lithium carbonate sales become the only source of revenue for LithiumCo, and LithiumCo experiences a decline in revenue directly relating to the LCE spot market price decreasing.

After the Smackover wells are purchased, LithiumCo has higher costs associated with lithium extraction and oil production as shown in Figure 6.7. This is due to the operational costs incurred by owning the producing wells, for lease operational expenses incurred for land use, and the increased oil royalty payments associated with hydrocarbon production. Lease operational expenses and operational costs of the well are modeled as costs attributed to lithium production because lithium extraction from the produced water is the sole reason for acquiring the wells. These additional costs therefore increase the

Figure 6.7: Breakdown of costs in Scenario 2.

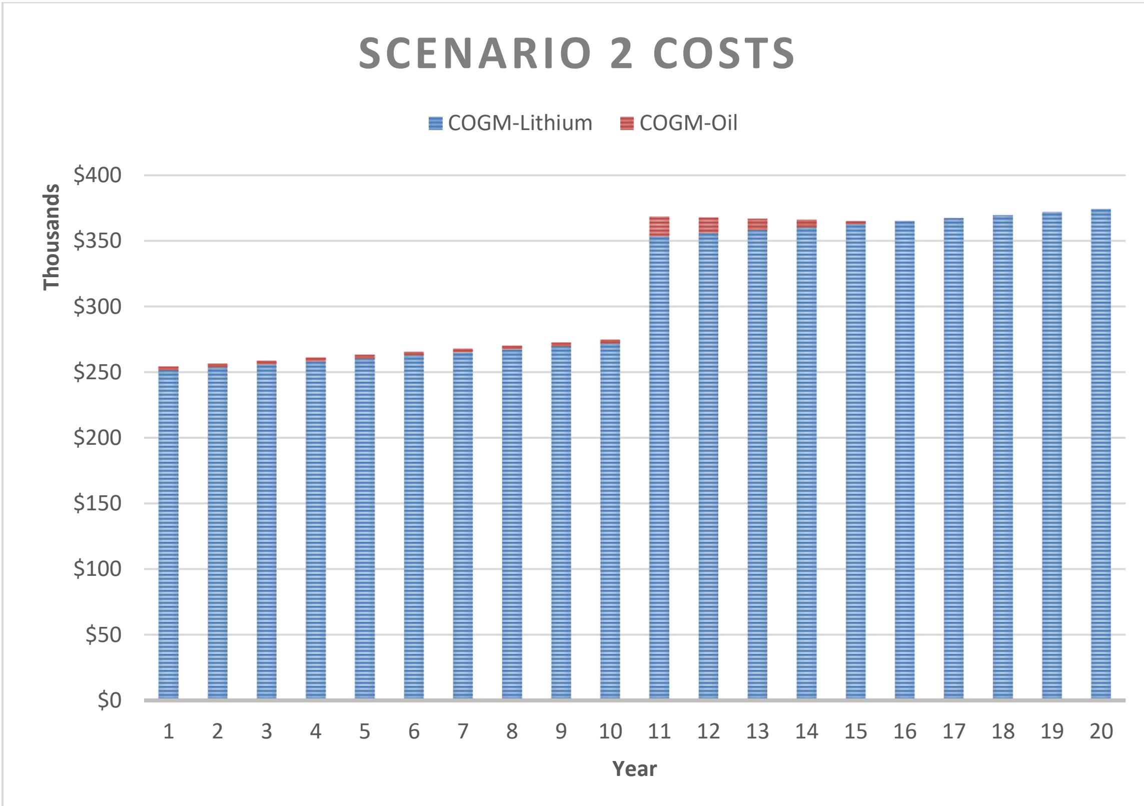
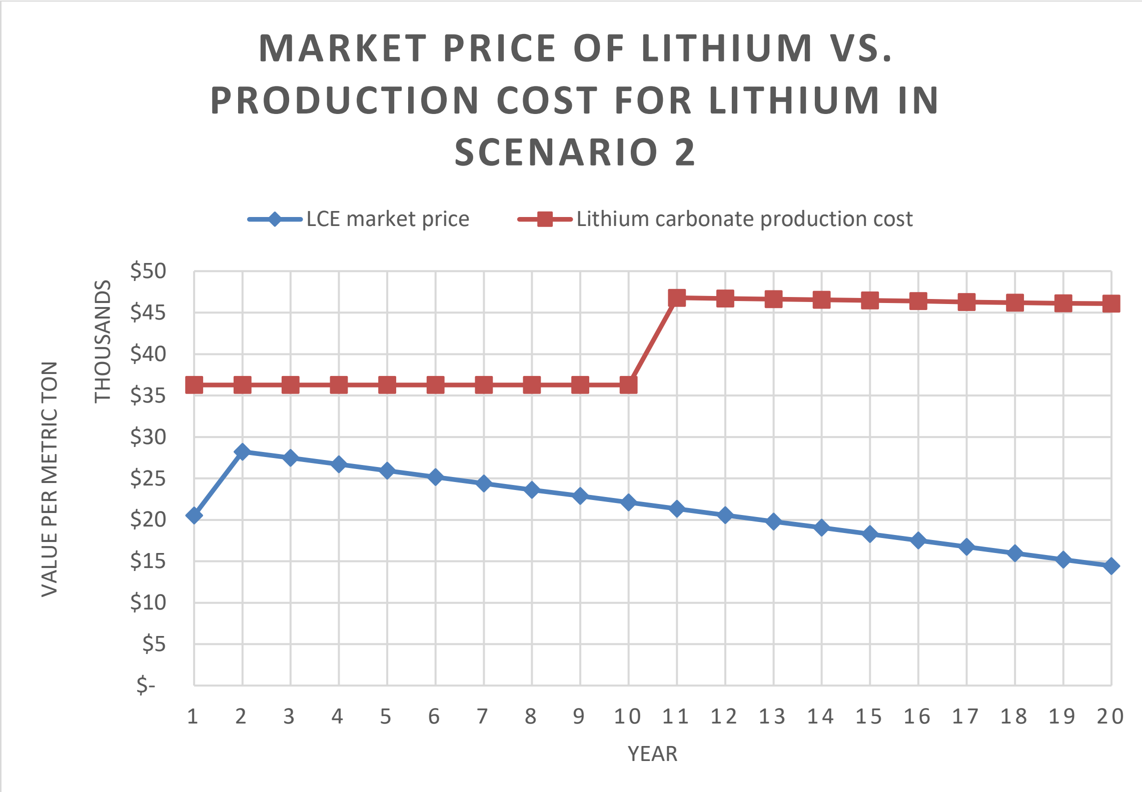


Figure 6.8: Scenario 2 production cost per metric ton of lithium carbonate compared to market price of LCE.



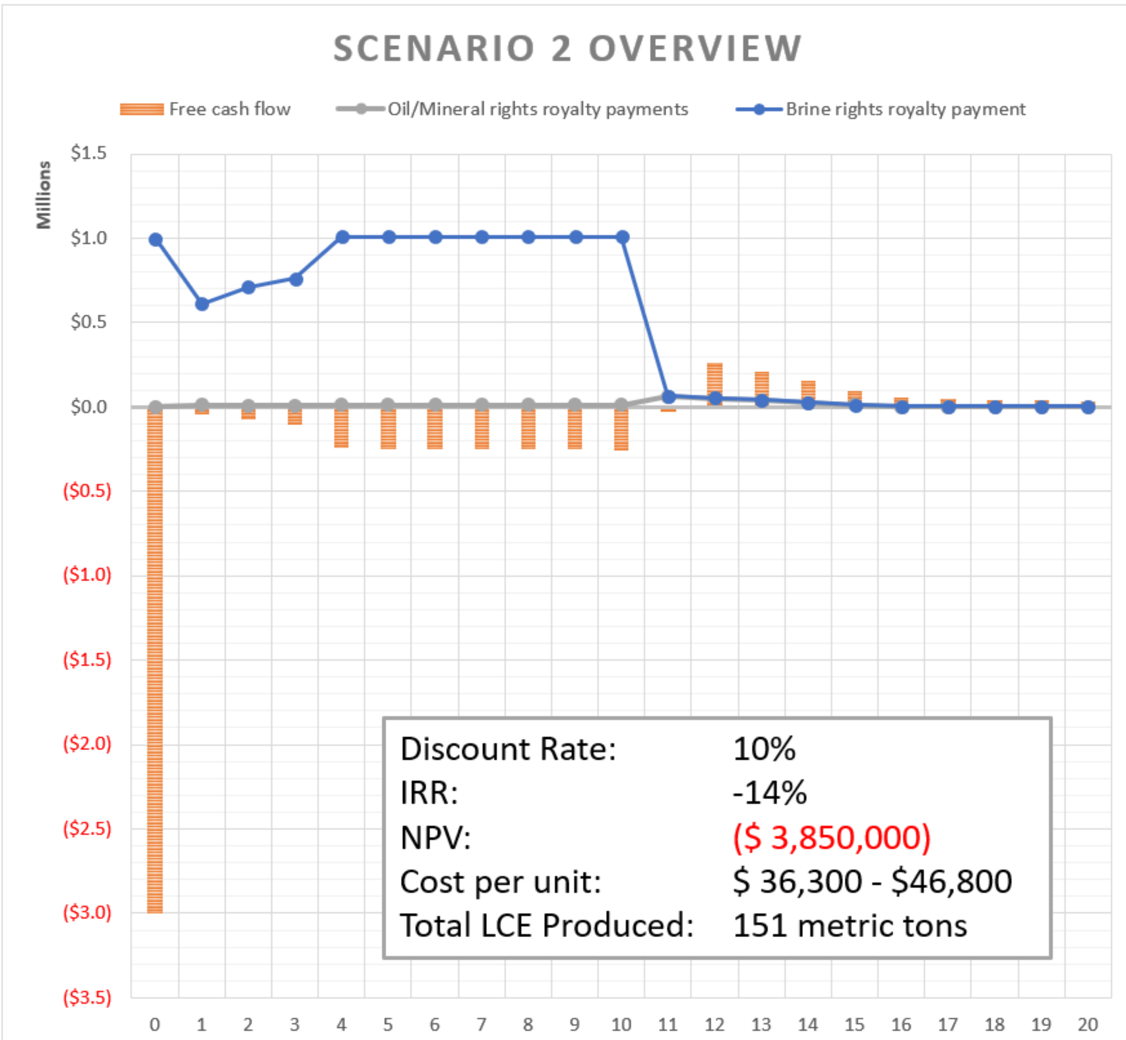
cost per metric ton of lithium carbonate produced, as shown in Figure 6.8. The initial cost per metric ton of lithium carbonate manufactured is $36,300. After the wells are purchased by LithiumCo, the cost per metric ton of lithium carbonate manufactured increases to $46,800.

The effect of oil and brine royalty payments on FCF is shown in Figure 6.9. As can be expected, LithiumCo's FCF increases when brine royalty payments are no longer subject to a minimum of $1 million. The wells are acquired in Year 11 and LithiumCo experiences its first positive FCF in Year 12 of $265,000. However, once the wells are acquired, LithiumCo's FCF begins to deteriorate due to the diminishing revenue from oil sales. When lithium carbonate sales provide the only source of revenue from Year 16 onward, the FCF falls from $50,000 to $30,000. It is expected that the FCF would fall below zero if the operation continued after 20 years.

In Scenario 2, the total lithium production over the 20-year lifetime of the operation is 28 metric tons, or 151 metric tons lithium carbonate. This is the same amount of lithium produced in Scenario 1. The cost per metric ton of lithium carbonate manufactured is initially the same as in Scenario 1, at $36,300, but the acquisition of the wells increases the cost per ton manufactured to $46,800. It still takes more than 24,000 barrels to manufacture one metric ton of lithium carbonate.

The acquisition of the wells from OilCo ultimately put LithiumCo in a precarious position. Even though LithiumCo secures access to the production of Smackover brine, the cost of owning the wells not only increases the cost per ton of lithium carbonate manufactured, but also results in substantial reduction to the FCF. It is possible that if the flow rate of the wells were increased then LithiumCo could produce a reliable source of income. The lithium extraction and processing facility was built to process up to 2.2 million barrels of water annually, but the annual rate of brine production from all four wells is less

Figure 6.9: Overview of free cash flow in Scenario 2 with respect to oil and brine rights royalty payments.



than 200,000 barrels. In summary, Scenario 2 demonstrates that acquiring wells which produce from low lithium concentrations is not a profitable endeavor. The requirements to make Scenario 2 NPV positive will be discussed in Chapter 7.

6.3 Scenario 3: Lithium producer drills well

Scenario 3 evaluates commercial lithium production when LithiumCo drills a purpose-designed well specifically to gather brine from the Smackover Formation. In this scenario, the lithium producer creates its own supply of brine. This scenario was selected to compare the profitability of LithiumCo when upfront capital expenses are made to create the necessary infrastructure for operation. This relieves the company from any dependence on oil operators, on produced water from oil wells, or on oil price. Furthermore, because LithiumCo is no longer limited to produce from active wells in Subset 1, in this scenario LithiumCo drills a new well in the area of higher lithium concentration, Subset 2.

The financial model accounts for a well drilled in Year 0 at a cost of $2 million. The well would be drilled in close proximity to the processing facility and a disposal well. The proximity of the well to the processing facility is accounted for in the model by a reduced cost of transportation. Transportation costs will be 20 percent of that incurred in Scenarios 1 and 2.

The flow rate from the drilled well used in Scenario 3 has an ideal specific flow rate of 60.9 million barrels per year. However, the efficiency of the well decreases over time by obstructions to the well screen. A well efficiency loss factor of 15 percent was applied to the flow rate of the drilled well in Year 1, producing a flow rate of 51.7 million barrels per year. The well efficiency loss factor increases by 1.5 percent annually through the lifetime of the well. By Year 20, the well efficiency loss factor reaches 43.5 percent, and the well produces 34.4 million barrels per year.

The facility built for the financial model has a maximum processing capability of 2.45 million barrels per year when the operation runs at 100 percent capacity. To account for maintenance and operation downtime, the facility was given a 90 percent operation capacity in the financial model. Applying this factor yields a maximum processing capacity of 2.2 million barrels per annum.

This leaves between 32.2 and 49.5 million barrels of brine accessible to LithiumCo but beyond feasible production limits. However, the flow rate for the well is dependent on a static pressure of the confined Smackover aquifer. Producing the maximum potential of barrels from the aquifer would require the equivalent amount to be reinjected back into the aquifer. LithiumCo will need to act prudently when calculating rates of extraction and injection so as to minimize formation damage and well-related problems.

The use of the facility to maximum capacity creates a total of 4,873 metric tons of lithium carbonate over the twenty-year lifetime of operation. This amount is 32 times greater than the amount of lithium carbonate produced in Scenarios 1 and 2. This increase in lithium carbonate production stems from a higher lithium concentration and a higher annual flow rate from the well. The lithium concentration is 2.7 times greater in Subset 2 than in Subset 1, and the annual flow rate in the newly drilled well is 11 times greater than the flow rate from the existing wells used in Scenarios 1 and 2.

Figure 6.10 shows the revenue versus costs in Scenario 3. Revenue in Scenario 3 come from only the sale of lithium carbonate. The model assumes that no hydrocarbons are produced from this well because the placement of the well pump will be well below the hydrocarbon traps at the top of the formation. Similarly, the only costs incurred are for

Figure 6.10: Revenue and costs in Scenario 3.

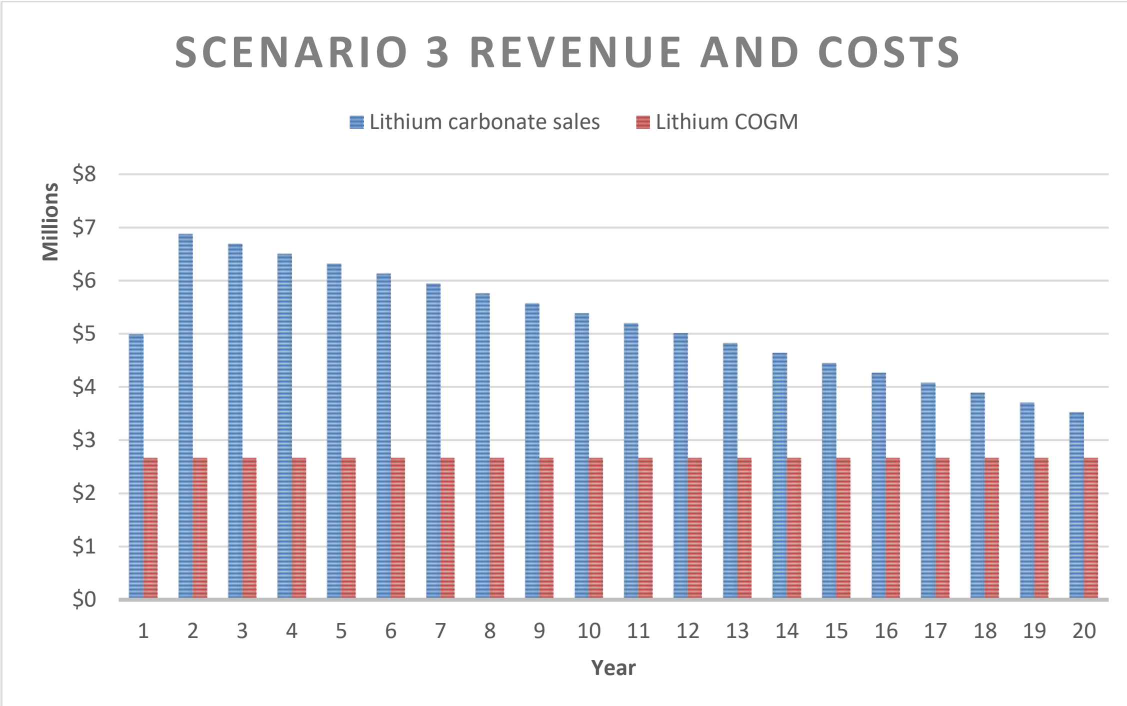
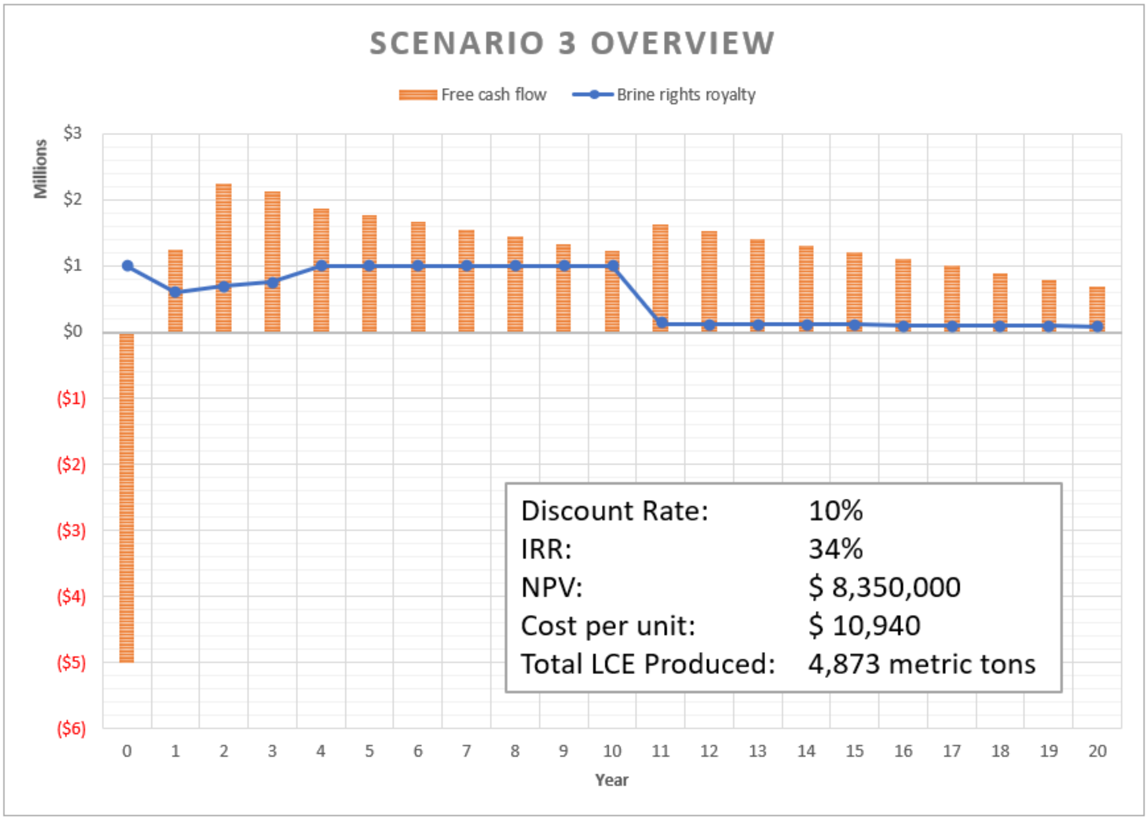


Figure 6.11: Overview of free cash flow in Scenario 3 with respect to brine rights royalty payments.



lithium production. The costs to extract and produce lithium do not change over time in Scenario 3 because the same amount of lithium is produced each year.

In Scenario 3, LithiumCo begins earning a FCF profit in Year 1 of $1.2 million. In Year 2 the FCF profit exceeds $2 million when the market price of lithium increases from $20,510 to $28,220. The change in revenue is a direct result of the change in sale price for lithium. The company continues to yield a positive FCF over the lifetime of operation, as shown in Figure 6.11. Unlike Scenarios 1 and 2, LithiumCo's FCF is now constrained by the processing capacity of the facility, whereas in Scenarios 1 and 2 the FCF is limited by the supply of produced water.

Scenario 3 is the only scenario that achieves a positive FCF each year and a positive NPV. The positive cash flow is a result of a low cost per unit produced. The cost per metric ton of lithium carbonate manufactured in Scenario 3 is $10,940. This is the only scenario where cost per unit manufactured is always less than the lithium spot price, and therefore this scenario of lithium extraction and production always yields a profit margin. The cost per unit manufactured is lower than that of Scenarios 1 and 2 because this scenario evaluates a well that is drilled in the area of Subset 2, which has an average lithium concentration of 187 ppm. Scenario 3 requires 9,050 barrels of brine to produce one metric ton of lithium carbonate.

Scenario 3 could yield even higher revenue if produced water were purchased from nearby producing wells in the Smackover. Although the purpose-designed well produces enough brine to run the extraction facility at maximum capacity, this would be an additional source of revenue for LithiumCo. It would be highly recommended to collect produced water if the oil operators offer a produced water with a higher average lithium concentration than that produced at the purpose-designed wellsite. Additional revenue could be added if skim oil were produced from the collected barrels of produce water.

Chapter 7: Conclusion

7.1 Hypothesis

Commercial lithium production is a profitable endeavor in the Smackover Formation when the advanced technology extraction facility has access to large volumes of brine for processing. In this commercial analysis, this volume was only fulfilled when a new well was drilled to supply the facility with brine. Although drilling a new well created additional expenses for the operation, the cost per unit manufactured was reduced compared to facilities that gathered brine from existing production wells. In the model, this occurred because drilling a new well allowed it to be optimally positioned to access a higher average lithium concentration. If the existing wells were located in the area of high lithium concentration, the cost per unit manufactured would have been reduced, but it is highly likely that not enough lithium would have been produced from the limited amount of produced water collected from each well.

The sale of processed, cleaned water was not a possible source of additional profit in this analysis. Water was reinjected into the formation in order to 1) maintain pressure of the aquifer, 2) recycle unrecovered lithium into the formation, and 3) to ensure compliance with water policy regulations set forth by local and state governments.

7.2 Discussion

7.2.1 Break-even analysis

A break-even analysis was performed to determine at what conditions each scenario evaluated can be profitable. The results of this analysis are shown in Table 7.1. When Scenario 1 is conducted in an area where the average lithium concentration is 70 ppm, brine must be gathered from at least 14 wells for the company to have an NPV10 greater than zero. For the NPV10 to be greater than zero in Scenario 2, brine must be gathered from 20 wells when the average lithium concentration is 70 ppm. In order for Scenarios 1 and 2 to be profitable using the four identified active wells, these wells would need to have average lithium concentrations of 360 and 400 ppm, respectively. Scenario 2 requires either a higher concentration of lithium or more wells for brine gathering than Scenario 1 due to the additional costs of owning the wells.

Table 7.1: Break-even analysis of the conditions required for each scenario to have an NPV greater than zero.

	At an average lithium concentration (ppm) of:	These many wells are required to break-even:	Cost per metric ton of Li2CO3 produced:
Scenario 1	70	14	$ 36,300
	187	7	$ 13,600
	359	4	$ 7,100
Scenario 2	70	20	$ 36,300 - $ 42,800
	187	9	$ 13,600 - $ 16,500
	401	4	$ 6,300 - $ 8,200
Scenario 3	70	--	$ 29,200
	130	1	$ 15,800
	187	1	$ 10,900

For Scenario 3 to be profitable, the average lithium concentration must be greater than 130 ppm. Extracting at this lithium concentration or greater recovers the expenses required to drill a single purpose-designed well. Any concentration less than 130 ppm will yield an NPV10 less than zero. For this reason, there is no number of wells associated with extracting lithium at a concentration of 70 ppm because no break-even point is achieved.

In all of the scenarios evaluated, it is noted that the cost per metric ton of produced lithium carbonate responds to an adjustment in the lithium concentration. The change in well count has no effect on this metric. As evidenced in Table 7.1, cost per ton decreases as lithium concentration increases.

7.2.2 Production challenges

7.2.2.1 Existing infrastructure

Relying on existing infrastructure poses a risk to production supply for LithiumCo from the Smackover Formation. The Smackover Formation is an oilfield that has been producing since the 1920's. While many wells have been drilled over the course of almost a century to capitalize on the hydrocarbons contained in the formation, the active and producing wells used to evaluate the commercial production model were drilled between 1970-1980. Many of these wells will have likely been exposed to H_2S, leading to serious corrosion and well integrity problems. These fluids have also been expelled at high temperatures and pressures, contributing to the overall well erosion. Equipment maintenance and replacement is unknown for these wells, but this information could be procured by an interested party.

Additionally, existing well-bores may not offer the same production value that drilling a new well will offer. This difference in production value could stem from well-bore diameter or from the method used to drill the well. If existing wells are purchased from a well operator, as is considered in Scenario 2, the ideal specific flow rate is subject to that which is feasible using the existing well-bore radius. The purpose-designed well used in Scenario 3 assumes a 12-inch well-bore diameter to maximize fluid flow potential, which is potentially greater than the diameter of wells drilled for oil production. If recently drilled, existing wells could be drilled using unconventional methods. Unconventional wells will most likely limit the brine production potential of the well.

7.2.2.2 Supply interruption

Production from the Smackover has existed for almost a century. Activity in this formation may reduce the total estimate lithium reserves. Episodes of fracking have occurred in some Smackover fields, which can redirect aquifer flow in the formation while connecting it to surrounding formations. Produced water will ideally be collected from areas that have been subject to little or no fracking to ensure lithium concentrations represented in this investigation.

The stratigraphy of the unit can also pose a barrier to production if it is not thoroughly evaluated from a geological perspective. The Smackover Formation does not outcrop in the continental U.S., but its time-equivalent deposit outcrops in Mexico. Geological interpretation for the Smackover is accomplished through core samples. A thorough aquifer transmissivity assessment and geological interpretation should accompany the areas from which brine is intended to be gathered. Similarly, the Smackover's unidentified source of lithium threatens operation viability. The lithium source should be determined in conjunction with a geologic interpretation of the regional depositional environment.

7.2.3 Commercial competition and strategy

The assumptions in this commercial analysis indicate that over a 20-year operation, the maximum total lithium produced is 918 metric tons, or 4,873 metric tons of lithium carbonate, in Scenario 3. This translates to an annual production of 46 metric tons of lithium, or 244 metric tons of lithium carbonate. This amount produced in Scenario 3 is limited by the size of the facility used in the model. Compared to the lithium supply estimates calculated in this investigation, as well as that estimated by Collins (1976), the amount of lithium produced from this analysis is only a fraction of what can feasibly be produced from the Smackover Formation. Table 7.2 displays the current lithium carbonate equivalent (LCE) production from major lithium-producing countries (Verma et al., 2016). When compared to the current operations, the annual production of lithium carbonate from the Smackover under parameters detailed in Scenario 3 will have a negligible impact on both the domestic and global lithium market.

Table 7.2: Production capacity and utilization of lithium facilities from major lithium producing countries. From Verma et al., 2016.

Country	Capacity in place (metric tons of LCE)	Production in 2014 (metric tons of LCE)	Utilization
Chile	101,875	68,499	67%
Argentina	23,000	15,399	67%
Australia	120,000	69,030	58%
Brazil	2,300	2,124	92%
China	80,750	26,550	33%

The hypothetical company evaluated, LithiumCo, can achieve a competitive advantage and a global market share by enlarging the operation and using economies of scale to decrease costs. If the facility is enlarged, LithiumCo could leverage economies of scale to decrease the upfront capital expenses of the infrastructure. In combination with increased lithium production, LithiumCo would have a larger NPV10 and a higher internal rate of return (IRR). If the rights to the Smackover brine are acquired by or leased to a single company, then the company will have sole right to extract lithium from the

Smackover Formation. This will create a barrier to entry for any competitors interested in extracting lithium from the formation.

LithiumCo has a technological advantage of using a filtration technique that extracts lithium from a brine in 8 to 36 hours. The technology has a lithium recovery rate of 70 percent. The average lithium concentration of the Smackover Formation in Subset 2 is 187 ppm, which is a significantly lower average concentration than that found in commercial lithium brine operations that employ solar evaporation for concentrating the brine. If LithiumCo is processing comparatively low lithium brine concentrations, then to compete with large-scale lithium productions LithiumCo will need to increase annual brine processing capacity by a minimum of ten times as much of that evaluated in Scenario 3.

Processing a greater volume flow-through is an achievable and realistic goal for LithiumCo. As described in Scenario 3, a new well in the Smackover produces an annual flow between 34 and 52 million barrels. The processing facility built for the commercial analysis can only process 2.2 million barrels per year. If the processing facility were expanded to treat 15 times as much brine, the single new well could support the volume and would still produce an excess amount of brine, as shown in Table 7.3. An additional well would need to be constructed for LithiumCo to produce more than this. For LithiumCo to become competitive on a global scale, the company needs to process and extract lithium from at least 10 times the amount of brine processed in Scenario 3.

Table 7.3: Potential processing facility expansion and corresponding lithium carbonate production under Scenario 3 parameters.

<table>
<tr><th>Facility expansion factor</th><th>Facility processing capability (BBLS of brine)</th><th>Li_2CO_3 produced (metric tons)</th><th></th></tr>
<tr><td>x1</td><td>2,205,000</td><td>244</td><td rowspan="15">1 well required</td></tr>
<tr><td>x2</td><td>4,410,000</td><td>487</td></tr>
<tr><td>x3</td><td>6,615,000</td><td>731</td></tr>
<tr><td>x4</td><td>8,820,000</td><td>975</td></tr>
<tr><td>x5</td><td>11,025,000</td><td>1,218</td></tr>
<tr><td>x6</td><td>13,230,000</td><td>1,462</td></tr>
<tr><td>x7</td><td>15,435,000</td><td>1,706</td></tr>
<tr><td>x8</td><td>17,640,000</td><td>1,949</td></tr>
<tr><td>x9</td><td>19,845,000</td><td>2,193</td></tr>
<tr><td>x10</td><td>22,050,000</td><td>2,437</td></tr>
<tr><td>x11</td><td>24,255,000</td><td>2,680</td></tr>
<tr><td>x12</td><td>26,460,000</td><td>2,924</td></tr>
<tr><td>x13</td><td>28,665,000</td><td>3,167</td></tr>
<tr><td>x14</td><td>30,870,000</td><td>3,411</td></tr>
<tr><td>x15</td><td>33,075,000</td><td>3,655</td></tr>
<tr><td>x16</td><td>35,280,000</td><td>3,898</td><td rowspan="5">2 wells required</td></tr>
<tr><td>x17</td><td>37,485,000</td><td>4,142</td></tr>
<tr><td>x18</td><td>39,690,000</td><td>4,386</td></tr>
<tr><td>x19</td><td>41,895,000</td><td>4,629</td></tr>
<tr><td>x20</td><td>44,100,000</td><td>4,873</td></tr>
</table>

Annual well flow from one purpose-drilled well = 34,424,000 BBLs

7.3 Recommendations

7.3.1 Analysis

The author recommends improving the analysis in the following ways. To better illustrate the role of oil prices in the decision to sell or acquire producing wells, the author suggests that random price modeling for oil prices be incorporated into the evaluation of Scenario 2. Scenario 2 uses fixed oil prices to determine when OilCo sells the wells to

LithiumCo. In reality, OilCo will not know the price of oil in the following year nor will they be able to predict a loss due to the price of oil. Random price modeling would allow for the uncertainty in future price forecasts to dictate when the well is no longer profitable for OilCo and when OilCo would be willing to sell.

7.3.2 Implementation

The author recommends that a larger facility be constructed for a standalone lithium corporation to achieve significant cash flow and profit. The facility will need to have at least ten times the processing capacity of that modeled in this analysis for the company to have material production and be a serious player in the lithium market. It is plausible that the size and processing capability of the facility evaluated in this analysis could be a profitable endeavor for companies that already focus on commercial processing of water for purification. This includes companies such as bromine producers accessing the Smackover Formation brines, or by water disposal companies that seeks an additional revenue stream. Commercial water purification and extraction companies are well-positioned to capitalize on lithium extraction because the existing supply processes, resources, and equipment would enable decreased costs across all end products through economies of scope.

The next steps of this investigation would be to conduct testing of additional wells in the Smackover Formation. The retesting of previously sampled wells would be highly encouraged to understand the effects of hydrocarbon production in this formation. Retesting samples from the outlier wells identified in Subset 2 should be prioritized, as should the emphasis on geological interpretation of these two wells. Focusing on the geology of these wells can potentially identify a source of lithium for the Smackover. This would require analysis of both the Smackover and Norphlet intervals given the competing scenarios for the lithium source. Once a lithium source is identified, lithium and strontium isotope analysis could potentially be used to develop a model for deposition of lithium in the Smackover and target brines with highest lithium concentration for exploitation.

Appendix A

(Begins on following page)

Table A-1: Selected data from Subset 1 (in ppm)

IDUSGS	**Li**	**Ba**	**Ca**	**Cu**	**Fe**	**I**	**Mn**	**Sr**	**B**	**Cl**	**K**	**Mg**	**Na**	**SO4**	**Br**
2958	66	38	29300	0	0	9	0	1250	0	184000	5960	3010	69300	182	1740
2959	64	33	28900	0	0.75	9	2.78	1260	0	190000	5790	2950	69200	197	1760
2961	54	41	26100	0	0.53	6	9.98	1040	0	165000	4920	2560	63600	175	1670
2962	74	48	33900	0	0.47	8	1.64	1670	0	170000	6500	3350	54800	161	2080
2963	74	50	33900	0	0.07	7	1.46	1730	0	171000	6240	3380	54600	169	2080
12631	50	36	40980	1	50	23	60	2220	0	190260	12	4164	95130	165	1440
12636	61	9	40980	0	12	22	30	2561	282	203075	8000	1720	75370	177	1878
12707	50	36	40980	1	50	23	60	2220	0	190260	12	4164	95130	165	1440
12708	55	0	37000	0	0.11	2.1	0	0	0	180000	11200	3790	75000	580	1700
12709	56	30	55296	1	70	37	75	2613	0	204408	5520	1686	68690	123	1754
12712	49	11	40900	1	6	35	3	1910	25	186269	2730	22113	75720	33	2037
12718	52	0	35900	0	1.4	2.2	0	0	0	180000	10300	2570	82800	0	1630
12719	66	0	44600	0	0.13	2.8	0	0	0	248000	13500	4570	90400	699	2190
12733	90	0	37000	0	0	1.1	0	2300	320	200000	7800	3600	77000	400	450
12775	19	0	8100	0	0	3	0	600	650	46000	1800	540	18000	700	110
12791	26	0	17000	0	0	4.9	0	1000	110	82000	39000	1600	32000	6000	160
16167	89	25	27200	0	7	42	166	2530	168	144600	5900	1760	40000	330	1230
16168	64	30	25000	0	5	52	15	23	206	184700	5900	2140	75800	125	1880
16169	84	15	26400	0	6	19	7	35	200	199700	5470	1730	74400	198	3680
29333	48	27	54135	1	8	8	18	1650	150	198748	7300	3888	59893	0	2443
29337	341	34	45399	1	15	11	48	2345	220	217572	7000	2230	76500	513	5343
29339	75	11	44110	1	6	11	4	1910	99	197757	800	3645	70947	0	1911
100911	33	0	31800	0	60	0	12	1360	0	167300	2610	3520	60600	0	1740
100912	57	20	32600	0	379	0	0	1490	0	174200	5600	3650	64300	0	1980

Table A-1: cont'd

IDUSGS	**Li**	**Ba**	**Ca**	**Cu**	**Fe**	**I**	**Mn**	**Sr**	**B**	**Cl**	**K**	**Mg**	**Na**	**SO4**	**Br**
100936	64	80	45600	0	245	0	59	1670	0	195700	7640	2650	65100	94	2260
100937	63	80	47200	0	414	0	59	2190	0	207400	7860	2840	66700	36	2220
100873	31	75	55600	0	74	0	73	1620	0	203300	2030	3740	58300	121	2200
100874	85	25	32600	0	0	0	18	1730	0	184200	9520	2720	69500	0	1820
100875	83	20	32800	0	0	0	15	1740	0	184400	10100	2620	69000	0	1900

Table A-2: Selected data from Subset 2 (in ppm)

IDUSGS	**Li**	**Ba**	**Ca**	**Cu**	**Fe**	**I**	**Mn**	**Sr**	**B**	**Cl**	**K**	**Mg**	**Na**	**SO4**	**Br**
108395	132	23	37100	0	0	7	0	2483	137	173532	2285	3798	62500	103	5746
108396	423	49	29300	0	0	7	0	2258	358	176679	7100	2243	72500	107	4276
108398	364	50	36750	0	0	7	0	2868	308	201399	3830	3094	79925	124	5339
108399	338	43	36675	0	0	9	0	2643	286	192112	3335	3177	73975	143	4913
108400	316	40	35275	0	0	7	0	2512	281	189847	3013	3116	72925	144	4718
108401	371	41	39119	0	0	0	0	2565	290	216807	6071	3263	82039	108	4523
108403	149	14	41600	0	0	10	0	2713	156	204478	1843	4183	74875	132	6601
108404	136	11	43375	0	0	11	0	2712	164	203594	2038	4393	74000	145	6609
108405	327	39	41117	0	0	0	0	2686	263	217908	5096	3549	85160	0	6462
108406	244	40	38159	0	0	0	0	2609	199	195589	3045	3289	74249	122	5481
108407	288	51	39063	0	0	0	0	2692	236	207777	4200	3261	77747	121	5096
108408	116	10	38808	0	0	0	0	2407	136	195432	1940	3906	72150	131	5850
108409	269	48	38700	0	0	7	0	2732	225	202307	3690	3445	78525	128	5763
108410	165	34	36067	0	0	18	0	2415	166	182232	2088	3249	70833	154	4887
108411	228	31	38848	0	0	0	0	2572	186	201355	2765	3332	73803	158	5487
108412	223	26	38674	0	0	0	0	2560	187	197405	2672	3348	73330	166	5426
108413	227	26	38819	0	0	0	0	2591	186	201295	2819	3349	74770	138	5507
108414	76	2	33825	0	0	13	0	1884	123	176735	1303	4005	67825	175	5126
108415	74	2	30150	0	0	6	0	1628	111	171390	1195	3753	67600	199	4714
108416	67	0	31743	0	0	0	0	1689	104	171201	1120	3641	66458	174	4583
108417	186	12	38159	0	0	0	0	2364	176	193784	2409	3521	71713	151	5626
108418	191	11	38985	0	0	0	0	2395	178	196117	2446	3632	73408	162	5308

Table A-2: cont'd

IDUSGS	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
108420	107	2	32200	0	0	7	0	1713	135	172618	1150	3798	64800	191	4804
108421	109	4	32350	0	0	9	0	1750	140	174097	1475	3833	67900	186	4888
108422	122	2	34125	0	0	10	0	1810	156	173070	1508	3829	66000	192	4862
108423	162	4	35550	0	0	11	0	2035	176	177348	1980	3810	70350	172	4893
108424	144	3	33050	0	0	10	0	1855	161	175023	1720	3783	68450	183	4666
108425	169	4	35800	0	0	13	0	2043	169	180782	1885	3768	68750	175	4924
108426	105	0	31444	0	0	0	0	1622	126	166561	1299	3518	61806	179	3473
108427	72	1	29800	0	0	9	0	1515	127	164601	1195	3813	64500	215	4411
108428	90	2	29125	0	0	13	0	1453	113	165266	1003	3784	63550	220	4337
108429	177	0	34837	0	0	0	0	1852	168	176601	1753	3328	65771	157	4404
108430	179	1	34817	0	0	0	0	1927	185	177520	1977	3268	65190	0	4975
108431	179	3	35303	0	0	0	0	2003	178	176461	1918	3177	65636	157	4726
108432	36	1	24000	0	0	16	0	1103	88	146351	925	3460	61350	295	3221
108433	34	1	23175	0	0	16	0	1089	71	152030	1018	3266	65375	276	3129
108434	24	1	18300	0	0	12	0	762	56	132733	760	2774	59275	392	2401
73852	340	35	46694	1	11	15	47	2766	213	208714	6230	3965	64900	234	5725
73853	367	42	44441	1	21	14	46	3050	240	202046	4406	4337	74000	276	5725
73854	378	38	45670	1	10	12	48	3180	288	201834	6000	3600	79000	841	5686
73855	412	23	45056	1	12	16	49	1890	210	228218	7460	2602	73030	889	5664
73856	386	16	43900	1	15	20	48	2293	220	212891	6950	3500	77900	306	5720
73857	331	44	43300	1	19	17	34	2064	200	210615	5640	4110	78400	254	5652
73858	403	29	43967	1	14	9	45	2452	198	200220	5260	6815	73800	800	4897
73862	69.66	0	41416	0	0	0	0	1644	0	0	0	3711.09	0	82.87	0
74196	80	47	48811	1	5	8	25	4016	150	188874	650	2000	74500	0	1986
74197	28	5	19048	0	3	17	2	400	200	137212	672	2844	62623	273	2870

Table A-2: cont'd

IDUSGS	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
74198	24	1	17500	1	6	36	2	770	42	129400	716	2630	58230	320	2050
74200	21	4	20050	1	7	17	3	771	28	138612	388	3086	63226	416	2952
74201	12	7	18747	1	26	13	1	885	124	117874	307	2080	50900	325	5584
74202	15	2	18160	1	307	19	7	700	143	121130	520	2648	47250	222	1966
74203	16	5	19568	1	8	24	5	759	48	145963	928	2066	68951	294	2121
74204	91	8	1837	0	246	12	4	230	0	31111	218	123	15800	508	350
74205	62	15	27557	1	6	22	8	371	94	143930	1242	4141	43930	156	2322
74206	46	3	27719	1	10	14	32	1273	10	125155	1227	4530	46830	166	1935
74207	72	38	43997	1	30	11	81	2050	66	186836	1874	2555	58820	420	4112
74208	94	11	35488	1	12	12	15	1736	0	190066	1384	4836	75284	242	5584
74497	34	11	16900	1	12	10	21	168	144	61200	204	1470	21900	166	1081
74209	140	10	36090	1	11	12	5	2024	32	194617	1710	3766	79122	347	5878
74210	125	6	36700	0	6	11	6	1911	195	183194	1435	3712	70338	340	5212
74211	1700	23	37974	0	11	11	6	1707	0	192867	152	3986	75370	262	6057
74212	122	11	39592	0	19	12	8	2261	193	186844	1520	3750	68919	298	5531
74213	180	0	38520	0	0	5	0	0	150	180766	1940	3850	63900	440	2340
74214	170	0	36290	0	0	5	0	0	140	19730	1370	4040	63300	350	4024
74215	160	0	34500	0	0	5	0	0	140	178070	1840	3950	64200	650	2450
74216	5	6	28518	1	18	13	2	1723	45	184422	20	3907	77630	166	3850
74395	50	11	26402	1	58	16	4	168	75	133665	614	2779	55470	325	2130
74217	35	10	24911	1	73	21	8	1150	66	120000	471	3407	47450	432	4213
74218	740	6	23706	1	8	21	1	1300	44	161542	21	3285	68930	406	5000
74219	445	45	45670	1	35	14	50	2980	322	196110	8340	2973	71390	548	5845
74220	365	30	43500	1	25	10	36	4478	210	218670	4230	3360	73300	500	5300
74221	357	32	48600	1	45	18	54	2456	200	208474	5810	3280	78300	278	5454

Table A-2: cont'd

IDUSGS	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
74222	425	26	45194	2	15	8	52	2965	195	200220	4770	3593	78600	398	4774
74223	440	40	45056	1	20	16	39	2860	305	203153	4364	3469	69600	406	5544
74224	391	20	44851	1	10	10	46	2470	288	210715	6380	3841	70850	174	5249
74225	343	39	43558	2	14	10	47	2297	208	210231	5960	9540	77000	590	4548
74446	277	23	39825	1	10	13	3	2760	174	201500	3020	2123	62950	184	5642
73846	260	23	40060	0	15	17	28	2576	62	224370	2930	3256	94987	126	6184
74226	276	35	43354	1	30	9	28	2463	178	201555	4090	3964	76500	805	4786
74227	331	40	46890	1	12	11	40	3440	300	219643	5950	1858	70670	640	5667
74228	329	36	49898	1	26	9	40	1965	230	214235	5330	6938	76400	554	5412
74229	7	8	32208	3	15	12	2	1624	109	174587	1310	5238	68930	246	4735
74230	53	14	26526	0	25	18	9	1558	92	147922	921	3048	59479	230	3565
74231	1430	10	39403	0	14	10	10	2539	112	183727	1629	3008	68366	267	5569
74232	86	22	42226	1	14	11	22	2302	52	224370	1820	3694	91711	157	6575
74233	43	5	20667	0	17	13	2	882	92	148715	1020	2265	69450	863	2397
74234	26	2	25062	1	113	26	3	1025	22	132533	774	3171	59300	329	3092
74235	28	12	4424	1	92	15	6	125	24	43264	500	2275	20500	158	98
74337	118	9	39016	0	15	10	18	2085	218	191360	5292	6251	65550	238	5499
74338	282	12	42800	0	17	11	33	2800	45	227500	3540	3380	97700	144	6930
74339	55	5	35450	1	16	12	2	1731	98	177500	1040	1310	73000	18	4920
74340	78	6	32530	0	8	10	2	1712	182	180530	14840	2826	96320	1020	4526
73843	0.27	2	148	10	51	0	1	51	0	244	2	8	126	0	6
24624	56	56	36150	1	292	38	15	3512	4	160996	129	3300	43220	0	1347
24625	0.22	3	249	0	70	3	1	15	7	1030	2	0	339	0	4
24626	69	61	56300	1	9	61	9	4700	45	203200	1170	3560	70800	187	1380
24627	2.02	3	1.133	0	9	4	2	75	0	2390	43	74	1240	0	30

Table A-2: cont'd

IDUSGS	Li	Ba	Ca	Cu	Fe	I	Mn	Sr	B	Cl	K	Mg	Na	SO4	Br
24628	2	3	201	0	34	5	1	16	0	772	68	0	0	0	12
24632	64	9	30697	1	334	37	0	2262	28	133117	700	2746	32270	0	1074
24640	80	13	34000	0	79	65	5	2540	95	182000	1380	2760	82800	166	1730
24642	80	28	31984	1	31	88	4	1900	66	160200	908	1315	59854	13	1684
24644	116	6	29500	0	0	34	0	2370	84	172300	1139	2370	64810	433	1717
24650	101	9	39300	0	84	40	1	189	100	172000	1088	2690	67400	150	2069
24651	94	75	46400	0	0	56	0	4790	86	196300	1884	615	70000	23	1520
24654	4	0	573	0	12	4	0	2	13	10793	780	10	2430	0	57
24667	1.28	2	612	0	17	6	3	50	0	2145	0	71	454	0	14
26407	0.81	10	24	0	142	7	2	71	0	8115	37	6	1500	0	33
26505	0.2	4	208	0	21	0	1	11	33	1172	3	0	514	0	11
26508	0.39	43	21311	1	33	38	5	1756	0	96207	875	2064	34750	604	698
44333	473	37	25264	0	0	423	0	2291	100	105283	0	6913	26754	589	939
45204	2	0	163	0	12	0	3	1	13	320	28	48	248	70	230
45205	404	5	28302	1	20	39	24	2504	383	170670	6390	2726	69310	123	2371
45206	293	17	39859	1	6	18	97	1327	152	186162	4660	1217	49000	0	1995
45211	0.08	0	143	0	9	0	2	1	28	416	5	0	48	317	3
45212	3	1	340	0	3	0	2	26	27	2234	13	105	720	0	15
45242	100	28	9096	1	9	7	3	1715	135	71173	2860	2914	25300	0	976

Appendix B

Table B-1: Production data from a producing well in the Smackover Formation from Subset 1.

Historical Data			
	Oil	Water	Ratio
1997	20,411	24,830	1:1
1998	19,019	40,168	1:2
1999	16,033	28,751	1:2
2000	12,309	22,902	1:2
2001	17,093	34,481	1:2
2002	16,523	41,540	1:3
2003	16,097	41,945	1:3
2004	15,609	42,765	1:3
2005	14,427	39,515	1:3
2006	15,783	42,535	1:3
2007	12,826	41,750	1:3
2008	13,209	42,860	1:3
2009	12,014	40,290	1:3
2010	11,378	41,740	1:4
2011	9,950	33,043	1:3
2012	10,698	39,962	1:4
2013	10,943	41,307	1:4
2014	10,352	41,602	1:4
2015	8,924	37,540	1:4
2016	8,188	36,015	1:4
2017	8,422	37,882	1:4

Forecasted Data			
	Oil	Water	Ratio
2018	7,648	41,934	1:5
2019	7,131	42,311	1:6
2020	6,613	42,689	1:6
2021	6,095	43,066	1:7
2022	5,577	43,443	1:8
2023	5,060	43,821	1:9
2024	4,542	44,198	1:10
2025	4,024	44,576	1:11
2026	3,507	44,953	1:13
2027	2,989	45,330	1:15
2028	2,471	45,708	1:18
2029	1,953	46,085	1:24
2030	1,436	46,463	1:32
2031	918	46,840	1:51
2032	400	47,218	1:118
2033	-	47,595	
2034	-	47,972	
2035	-	48,350	
2036	-	48,727	
2037	-	49,105	

Rate of Oil Production: $y = -517.72x + 1{,}052{,}411.45$

Rate of Water Production: $y= 377.42x -719{,}699$

Historical data provided by the Mississippi State Oil and Gas Board.
API: 2315320014

Glossary

Brine: saline, mineral-enriched solutions that can occur both at the surface and subsurface

EV: electric vehicles

FCF: free cash flow

gpm: gallons per minute

H_2S: hydrogen sulfide

IRR: internal rate of return

LCE: lithium carbonate equivalent. 1kT of Lithium = 5.31kT of LCE

Li: lithium

Li_2CO_3: lithium carbonate

Li_2O: lithium oxide

LIB: lithium-ion battery

mg/L: milligrams per liter, also referred to as part per million (ppm)

NPV: net present value

NPV10: net present value at a 10 percent discount rate

ppm: parts per million, also referred to as milligrams per liter (mg/L)

Produced water: water that is produced as a byproduct of extracting oil and gas and is considered to be industrial waste

Reserve: the part of the reserve base which could be economically extracted or produced at the time of determination.

Resource: a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such a form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible

SWD: saltwater disposal or saltwater disposal company

Metric ton (tonne): 1,000 kg or 2,204.6 lbs.

tpy: metric tons per year or tonnes per year

VOC: volatile organic compound

References

"A Critical Q & A with MGX Minerals CEO Jared Lazerson." *The Critical Investor*, 30 Aug 2017, www.criticalinvestor.eu/analysis/lithium/critical-q-mgx-minerals-ceo-jared-lazerson.

A Survey of the Subsurface Saline Water of Texas. Vol. 1, Texas Water Development Board, 1972.

Ajdukiewicz, J. M. et al. "Prediction of Deep Reservoir Quality Using Early Diagenetic Process Models in the Jurassic Norphlet Formation, Gulf of Mexico." *AAPG Bulletin*, vol. 94, no. 8, 2010, pp. 1189–1227., doi: doi.org/10.1306/04211009152

Alper, Alexandra. "Bolivia Seeks Investors to Power Lagging Lithium Output." *Reuters*, 27 Dec 2017, www.reuters.com/article/us-bolivia-lithium-analysis/bolivia-seeks-investors-to-power-up-lagging-lithium-output-idUSKBN1EL1JB.

Alspaugh, Andrew. Expected Costs of Drilling. 2 Mar 2018. Telephone Interview.

Annual Report of Production 2016. Arkansas Oil and Gas Commission, 2017, www.aogc.state.ar.us/data/production/Annual/Reports/Annual_Report_of_Production_2016.pdf.

Benchmark Minerals. "Monthly Price Data-Lithium." 2017. *Microsoft Excel* file.

Benson, Thomas R., et al. "Lithium Enrichment in Intracontinental Rhyolite Magmas Leads to Lithium Deposits in Caldera Basins." *Nature Communications*, vol. 8, no. 270, 16 Aug 2017, pp. 1–9., doi: doi.org/10.1038/s41467-017-00234-y.

Berckmans, Gert, et al. "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030." *Energies*, vol. 10, no. 1314, 2017, pp. 1-20., doi: doi.org/10.3390/en10091314.

Blondes, Madalyn S., et al. "U.S. Geological Survey National Produced Waters Geochemical Database v2.2 (PROVISIONAL)." USGS Energy Resources Program: Produced Waters, USGS, 16 Feb 2016, www.energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data.

Blondes, Madalyn S., et al. "U.S. Geological Survey National Produced Waters Geochemical Database v2.2 (PROVISIONAL) Documentation." USGS Energy Resources Program: Produced Waters, USGS, 16 Feb 2016, archive.org/stream/USGSProducedWatersV2.2c/USGS%20Produced%20Waters%20Database%20v2.2%20Documentation_djvu.txt.

Bradley, Dwight, et al. "A Preliminary Deposit Model for Lithium Brines." A Preliminary Deposit Model for Lithium Brines Open-File Report 2013-1006, U.S. Geological Survey, 2013, www.pubs.usgs.gov/of/2013/1006/OF13-1006.pdf.

Bradley, D.C., et al. "Lithium, chap. K" *of* Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply: U.S. Geological Survey Professional Paper 1802, 2017, pp. K1– K21., doi: doi.org/10.3133/pp1802K.

"Brine Resources & Operations." *Arkansas Geological Survey*, 2015, www.geology.ar.gov/energy/brine_resources.htm.

Clay, David. "RE: An Urgent Question from a Student." Received by Richard Chuchla. 8 Mar 2018. Email Interview.

Clay, David. Follow-up Questions for Drilling Costs. 2 Apr 2018. Telephone Interview.

Chuchla, Richard J. "Some Ideas Regarding the Controls on Lithium Concentration in Smackover Brines." *In preparation*, 2018.

Collins, A. G. "Lithium Abundances in Oilfield Waters." *of* Lithium Resources and Requirements by the Year 2000: USGS Professional Paper 1005, 1976, pp. 116–123, pubs.usgs.gov/pp/1005/report.pdf.

Energy Information Administration, and IHS Global Inc. "Trends in U.S. Oil and Natural Gas Upstream Costs." Trends in U.S. Oil and Natural Gas Upstream Costs, U.S. Energy Information Administration, 23 Mar 2016, www.eia.gov/analysis/studies/drilling/pdf/upstream.pdf.

Evans, R.K. "An abundance of lithium." *North Carolina State University*, 2008, pp. 1-17, pdfs.semanticscholar.org/9b04/439bd3442f139dbbaf10d0def7e052fd03f3.pdf.

Filice, Livio. "Lithium Prices Reach Record High in China." *Seeking Alpha*, 19 Oct 2017, www.seekingalpha.com/article/4114616-lithium-prices-reach-record-high-china.

Garrett, D.E. *Handbook of Lithium and Natural Calcium Chloride: Their Deposits, Processing, Uses and Properties.* Academic Press, 2004. *Elsevier*.

Graedel, T. E., et al. "Criticality of Metals and Metalloids." *Proceedings of the National Academy of Sciences*, vol. 112, no. 14, Apr 2015, pp. 4257–4262., doi: doi.org/10.1073/pnas.1500415112.

Graves, Paul. "Deutsche Bank Lithium Supply Chain & Energy Storage Conference." 2017, New York City, pp. 1-14, www.phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9Njg0NTk5fENoaWxkSUQ9Mzk0NTMwfFR5cGU9MQ==&t=1.

"Greenbushes Lithium Mine." *Golden Dragon Capital*, 2018, www.goldendragoncapital.com/greenbushes-lithium-mine/.

Gruber, P. W., et al. "Global Lithium Availability." *Journal of Industrial Ecology*, vol. 15, 2011, pp. 760–775., doi: doi.org/10.1111/j.1530-9290.2011.00359.x.

Guillotte, J.G., et al. "Smackover Reservoir: Interpretation Case Study of Water Saturation versus Production." *Transactions-Gulf Coast Association of Geological Societies*, vol. 29, 1979, pp. 121–126.

Hammes, Ursula, and Gregory Frebourg. "Haynesville and Bossier Mudrocks: A Facies and Sequence Stratigraphic Investigation, East Texas and Louisiana, USA." *Marine and Petroleum Geology*, vol. 31, no. 1, Mar 2012, pp. 8–26., doi: doi.org/10.1016/j.marpetgeo.2011.10.001.

Hatcher, Robert D. "Tectonics of the Southern and Central Appalachian Internides." *Annual Review of Earth and Planetary Sciences*, vol. 15, 1987, pp. 337–362, adsabs.harvard.edu/full/1987AREPS..15..337.

Hocking, Matthew, et al. "Lithium 101." *Deutsche Bank Markets Research*, 9 May 2016, pp.1-179, www.resourceswire.com/wp-content/uploads/2016/05/Lithium-Report-May-2016.pdf.

Hunt, Bryan Wallace. "Regional Norphlet Facies Correlation, Analysis and Implications for Paleostructure and Provenance, Eastern Gulf of Mexico." *University of Alabama*, 2013.

Jaskula, Brian W. "Lithium." *Mineral Commodity Summaries 2016*. U.S. Geological Survey, 2016, pp. 100-101., doi.org/10.3133/70180197.

Jaskula, Brian W. "Lithium." *Mineral Commodity Summaries 2018*. U.S. Geological Survey, 2018, pp. 98-99., doi.org/10.3133/70180197.

Kesler, S. E., et al. "Global Lithium Resources: Relative Importance of Pegmatite, Brine and Other Deposits." *Ore Geology Reviews*, vol. 48, 2012, pp. 55–69., doi: dx.doi.org/10.1016/j.oregeorev.2012.05.006.

Kidwell, Albert L. "Mesozoic Igneous Activity in the Northern Gulf Coastal Plain." *AAPG Datapages/Archives*, GCAGS Transactions, vol.1, 1951, pp. 182-199, archives.datapages.com/data/gcags/data/001/001001/0182.htm?doi=10.1306%2F 2DC4097F-0E47-11D7-8643000102C1865D.

"Lithium-Ion Battery Inventor Introduces New Technology for Fast-Charging, Noncombustible Batteries." *UT News*, 28 Feb 2017, news.utexas.edu/2017/02/28/goodenough-introduces-new-battery-technology.

"Lithium Price." *Metalary*, Apr 2018, www.metalary.com/lithium-price/.

Lisi, Andrea, and Amy Weislogel. "Provenance of the Upper Jurassic Norphlet and Surrounding Formations from U-Pb Detrital Zircon Geochronology." *AAPG Search and Discovery Article*, 22 May 2013, www.searchanddiscovery.com/abstracts/html/2013/90163ace/abstracts/lis.htm.

MacRae, G., and J.S. Watkins. "Desoto Canyon Salt Basin: Tectonic Evolution and Salts Structural Styles." *Gulf Coast Association of Geological Societies Transactions*, vol. 46, 1996, pp. 53-61.

Mancini, Ernest A., et al. *Basin Analysis and Petroleum System Characterization and Modeling, Interior Salt Basins, Central and Eastern Gulf of Mexico*, University of Alabama and Louisiana State University, 2008.

Martin, G., et al. "Lithium Market Research – Global Supply, Future Demand and Price Development." *Energy Storage Materials*, vol. 6, 2017, pp. 171-179., doi: dx.doi.org/10.1016/j.ensm.2016.11.004.

McEachern, Preston. "Lithium Recovery from Oilfield Produced Water Brine & Wastewater Treatment." *MGX Minerals*, MGX Minerals, 2017, www.rockstone-research.com/images/pdfs/MGX_TechnicalReportRapidLithiumExtractionProcess.pdf.

Meridian International Research, "The Trouble with Lithium 2: Under the Microscope." Meridian International Research, 2008, www.meridian-int-res.com/Projects/Lithium_Microscope.pdf.

"Mississippi State Oil and Gas Board - Entity Information." *Mississippi State Oil and Gas Board,* gis.ogb.state.ms.us/msogbonline/entityinformation.aspx?EntityType=Well&EntityKeyName=api&EntityKeyValue=2315320014.

Moore, C.H. and Ezat Heydari. "Burial Diagenesis and Hydrocarbon Migration in Platform Limestones: A Conceptual Model Based on the Upper Jurassic of the Gulf Coast of the USA." *Diagenesis and Basin Development*, 1993, pp. 213-229.

Moore, Clyde H. and Yehezkeel Druckman. "Burial Diagenesis and Porosity Evolution, Upper Jurassic Smackover, Arkansas and Louisiana." *AAPG Bulletin/Archives*, vol. 65, no. 4, 1981, pp. 597-628, archives.datapages.com/data/bulletns/1980-81/images/pg/00650004/0550/05970.pdf

Munk, Lee Ann, et al. "Lithium Brines: A Global Perspective." *of* Rare Earth and Critical Elements in Ore Deposits, vol. 18, 2016, pp. 339–365. *Researchgate.*

Palmer, Timothy, and Rinat Gabitov. "Assessment of Lithium-Rich Brine From the Smackover Formation by Analyzing Core, Geochemical, Petrophysical, and Productivity Data: Insights From Deep Evaporite-Carbonate Transitions." *AAPG Datapages, Inc.*, *Mississippi State University*, 5 Apr 2017, www.searchanddiscovery.com/abstracts/html/2017/90291ace/abstracts/2606283.html.

Peiro, L.T., et al. "Lithium: Sources, Production, Uses, and Recovery Outlook." *JOM*, vol. 65, no. 8, 2013, pp. 986-996. DOI: 10.1007/s11837-013-0666-4.

"POSCO Opens Its First Lithium Production Plant for Battery Manufacturing." *The Steel Wire*, POSCO, 9 Jun 2017, globalblog.posco.com/koreas-first-lithium-production-plant/.

Saunders, J. A., and D. W. Harrelson. "Age and Petrology of the Jackson Dome Igneous-Volcanic Complex, Mississippi: Implications for the Tectonic History of the Mississippi Salt Dome Basin." *AAPG Datapages/Archives*, GCAGS Transactions, vol. 42, 1992, pp. 659-667, archives.datapages.com/data/gcags/data/042/042001/0659.htm.

Schnebele, Emily K. "Bromine." *Mineral Commodity Summaries 2018*, U.S. Geological Survey, 2018, pp. 38-39., doi.org/10.3133/70180197.

Simbol Materials, Simbol Materials, 2011, www.simbolmaterials.com/who_we_are.htm/.

"Standard Lithium Acquires Lithium Brine Exploration Rights in Productive Smackover Formation in Arkansas." Standard Lithium Ltd., 8 Jan 2018, standardlithium.com/2018/standard-lithium-acquires-lithium-brine-exploration-rights-productive-smackover-formation-arkansas/.

Stueber, A. M., et al. "A Strontium Isotopic Study of Smackover Brines and Associated Solids, Southern Arkansas." *Geochimica et Cosmochimica Acta*, vol. 48, 1984, pp. 1637-1649., doi: dx.doi.org/10.1016/j.oregeorev.2012.05.006.

Swain, Basudev. "Recovery and Recycling of Lithium: A Review." *Separation and Purification Technology*, vol. 172, 2017, pp. 388-403., doi: dx.doi.org/10.1016/j.seppur.2016.08.031.

Thompson, Justin C. Calculating Well Flow Rate. 5 Mar 2018. Personal Interview.

Tonietto, Sandra N., and Michael C. Pope. "Diagenetic Evolution and its Influence on Petrophysical Properties of the Jurassic Smackover Formation Thrombolite and Grainstone Units of Little Cedar Creek Field, Alabama." *GCAGS Journal*, vol. 2, 2013, pp. 68-84.

Trump, Donald J. "Presidential Executive Order on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals." *The White House*, The United States Government, 20 Dec 2017, www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/.

U.S. Bureau of Mines and U.S. Geological Survey. "Principles of a Resource/ Reserve Classification for Minerals." *Geological Survey Circular 830*, 1980, pp. 1-12, pubs.usgs.gov/circ/1980/0831/report.pdf.

Verma, R., et al. "Battery Materials Value Chains: Demand, capacity and challenges." *Think Corner Research Note*, Center for Energy Economics, 2016, pp. 1-30.

Vestal, Jack H. "Petroleum Geology of the Smackover Formation of Southern Arkansas." *State of Arkansas Geological Commission*, 1950, pp. 1-37, www.kgs.uky.edu/kgsweb/geothermal/ar/14_c.pdf.

Vikstrom, H., et al. “Lithium Availability and Future Production Outlooks.” *Applied Energy,* May 2013, vol. 1, no. 10, pp. 252-266., doi: dx.doi.org/10.1016/j.apenergy.2013.04.005.

Wade, William James. "Stratigraphy, Diagenesis, and Petroleum Geology of the Smackover Formation, Southwest Alabama." *LSU Historical Dissertations and Theses*, 1993, digitalcommons.lsu.edu/gradschool_disstheses/5680.

Weikel, Matthew. “RE: Masters Student Li Brine Testing Question.” Received by Pamela Daitch. 9 Mar 2018. Email Interview.

Wellmer, Friederich. *Statistical Evaluations in Exploration for Mineral Deposits*. Springer, 1998.

Zimmerman, R. K. “Fractured Smackover Limestone in Northeast Louisiana; Implications for Hydrocarbon Exploitation.” *AAPG Datapages/Archives*, GCAGS Transactions, vol. 42, 1992, pp. 401-412, archives.datapages.com/data/gcags/data/042/042001/0401.htm?doi=10.1306%2FA1ADDD71-0DFE-11D7-8641000102C1865D.