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GLOBAL TRENDS IN X-RAY CT IMAGING APPLICATIONS IN PETROLEUM ENGINEERING AND THE GEOSCEINCES FROM 1984 TO 2014

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ABSTRACT

While the use of x-rays originated in medical fields it has expanded through other disciplines. Petroleum and geological sciences are no exception. Beginning in the 1980's, x-ray computed tomography (CT) imaging has become an increasingly powerful tool used to better understand rock and fluid properties. Used by academics and corporations alike, CT imaging creates a more accurate picture of the interactions between rocks and fluids such as water, oil, and gas.

This paper explores trends in the history of CT imaging across several geophysical fields. By observing these trends a history of CT imaging can be compiled and further examined. Three main objectives were followed in order to generate insights into CT imaging. The first objective was to build a database that would serve as a representative sample of the papers that make up the current literature of CT imaging in petroleum engineering and the geosciences. The database was limited by the selection criteria and primarily relied on Web of Science to find CT imaging papers. Secondly the CT imaging papers were sorted into various categories such as country of publication and author affiliation. The third objective was to analyze the data and identify geographical institutional affiliations dominating the field of CT imaging in petroleum engineering and the geosciences.

CT imaging is a prime example of how technology can transcend disciplinary boundaries. While originating in the medical fields, CT imaging has successfully been adapted to petroleum engineering and the geosciences. This paper documents the impact CT imaging has had from 1984 to 2014 and offers CT imaging as a case study of how a technology created in one field can be a game changer in another.

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ACKNOWLEDGEMENTS

For those who have entered the world of X-ray CT imaging and never returned, may this thesis grant them solace and serve as a guide so that they may reach heights higher than I ever could.

Chapter 1

Introduction

Unlike a traditional medical X-ray which can only view an object from one angle, an X-ray computed tomography scanner rotates an X-ray source around the object, viewing the object from many different angles (Wellington & Vinegar, 1987). The projections generated by the X-ray source and the object are received by a detector opposite the source (Cromwell, Kortum, & Bradley, 1984). The detector then sends the projections to a computer which translates them into cross sectional images (Wellington & Vinegar, 1987). These cross sectional images can then be constructed to form a three dimensional object (Wellington & Vinegar, 1987). This process is nondestructive and enables researchers to see the inside of a specimen without damaging it (Cromwell et al., 1984). CT imaging is useful in a wide variety of applications from multiphase permeability analysis (Eleri, Graue, & Skauge, 1995) to studying solid invasion in drilling fluids (Bailey et al., 2000).

Computed tomography had its origins in the medical field. Godfrey Hounsfield and Allen Cormack developed the first CT scanner in the early 1970's to obtain a more accurate depiction of internal organs (Cromwell et al., 1984). Its success led to its utilization in paleontology and meteorite studies (Ketcham & Carlson, 2001).

The first use of a CT scanner for rock and fluid properties occurred in the early 1980's (Cromwell et al., 1984). Wang et al. were trying to generate a three dimensional computer image that could display how oil saturation changed with time and space (Wang, Ayral, & Gryte, 1984). Previous studies using techniques like microwave attenuation x-ray shadowgraph only gave qualitative oil saturation data that could not be used to develop mass balance equations (Wang et al., 1984). Using a Computer Assisted Tomography (CAT) scanner, the authors captured images of oil displacement in a Berea sandstone core (Wang et al., 1984). The cross sectional images generated by the CAT scanner enabled them to observe the oil saturation in time and space and develop spatial and time derivatives (Wang et al., 1984). The authors stated that these derivatives could be used to form mass balance equations and fluid streamlines to analyze oil flow following displacement, ultimately leading to more efficient oil recovery (Wang et al., 1984).

Expanding on the work of Wang et al., Cromwell et al. created several qualitative experiments in order to demonstrate the potential of CT scanning in core analysis and suggest modifications that could improve its imaging capabilities (Cromwell et al., 1984). Cromwell at al. demonstrated the use of CT scanning to show variations in rock matrix and fluid saturation (Cromwell et al., 1984). CT scanning was also useful in tracking fluid fronts and displacement (Cromwell et al., 1984). With regards to modifications, Cromwell et al. noted that medical CT scanners used low energy x-rays to limit harm to the patient, and as a result only small diameter cores generated high resolution images (Cromwell et al., 1984). Cromwell et al. suggested that the energy and strength of the x-ray be increased to scan larger, more complex cores (Cromwell et al., 1984). By demonstrating the use of CT imaging and suggesting improvements, Cromwell et al. helped pave the way for the creation of CT scanners used exclusively for core analysis.

One of the most influential papers written in the early years of CT imaging of cores was X-Ray Computerized Tomography by S. L. Wellington and H. J. Vinegar. This paper served as a summary of CT imaging in petrophysical and reservoir engineering applications (Wellington & Vinegar, 1987). While the work of Cromwell was primarily qualitative, Wellington and Vinegar also emphasized the quantitative data that CT scanning provided. The authors found that CT imaging was useful in observing density, mobility, viscous fingering and other important data (Wellington & Vinegar, 1987). CT imaging was also used to supplement existing data. By scanning a damaged core, the authors were able to correlate the CT data with that of the existing well log in order to determine the density of the core (Wellington & Vinegar, 1987). The petrophysical data obtained could be directly compared with numerical simulations for accuracy (Wellington & Vinegar, 1987). By discussing the benefits and uses of CT imaging, Wellington and Vinegar were able to introduce CT imaging to a general audience which helped spur on the use of CT imaging in petroleum and geophysical engineering.

CT imaging has progressed rapidly in the fields of petroleum engineering and the geosciences since 1984. With a solid foundation set forth by these early pioneers, CT imaging has since been used in a variety of petroleum and geoscience applications.

One such area is foam mobility control (Simjoo, Dong, Andrianov, Talanana, & Zitha, 2013). In *Novel Insight into Foam Mobility Control* the authors used CT imaging to determine how foam mobility depended on surfactant concentration and total injection velocity (Simjoo et al., 2013). Foam resulted when gas is forced into a surfactant media, resulting in a major decrease in gas mobility (Simjoo et al., 2013). This results in an increase in oil recovery during gas floods (Simjoo et al., 2013). The authors conducted two experiments with the CT scanner. In the first one they varied the surfactant concentration and in the second, they varied the gas injection velocity. By utilizing a CT scanner, changes in liquid saturation were recorded (Simjoo et al., 2013). The authors used the CT scanner images to determine that foam mobility decreases during the first forward foam propagation and that during secondary backward liquid saturation foam mobility decreased further in the presence of high surfactant concentrations (Simjoo et al., 2013).

Another application that has benefited from CT imaging is rock anisotropy (Yun, Jeong, Kim, & Min, 2013). Anisotropy in rocks refers to properties like permeability and porosity that change with direction. It impacts fluid flow and heat transfer and anisotropy may not always be visible (Yun et al., 2013). In *Evaluation of rock anisotropy using 3D X-ray computed tomography,* Yun et al. utilized a CT scanner to view rock anisotropy (Yun et al., 2013). By using the attenuation values of the CT scanner with cross-sectional slices, the authors created a technique for determining the anisotropy for a rock even if the anisotropy was invisible (Yun et al., 2013).

Lastly, CT imaging is useful when creating computer simulations. In, *Prediction of Non-Darcy Coefficients for Inertial Flows Through the Castlegate Sandstone Using Image-Based Modeling* CT imaging was used to generate data to input into a simulator to determine non-Darcy coefficients (Chukwudozie, Tyagi, Sears, & White, 2012). Non-Darcy coefficients are required to calculate the wellbore flow in some gas wells (Chukwudozie et al., 2012). The CT scanner created an image of a sandstone core (Chukwudozie et al., 2012). The authors then used pore-grain space data from the CT image as input into a lattice Boltzmann method (LBM) flow simulation (Chukwudozie et al., 2012). By comparing the non-Darcy coefficients generated from the simulator to existing values generated by other methods, the authors confirmed the validity of their method (Chukwudozie et al., 2012). They concluded that by using the LBM method with high-resolution image data, accurate predictions of macroscopic rock properties could be determined (Chukwudozie et al., 2012).

This is a sample of the numerous applications of CT imaging to petroleum engineering and the geosciences and shows CT imaging has been successfully adapted from its medical origins.

Chapter 2

Objectives

In order to create a solid foundation of CT imaging papers in the geosciences and petroleum and natural gas engineering and to cement the assertion that CT imaging has thrived in this new field, this thesis was broken down into three main objectives. These three objectives were to build a database of CT imaging papers that was representative of all the CT imaging papers published based on the criteria used to construct the database, classify the papers by sorting them into categories so that trends could be observed, and analyze the papers to determine what trends existed in CT imaging papers in the geosciences and petroleum and natural gas engineering.

The first objective was to build a database of CT imaging papers out of the thousands of published CT imaging papers. By using a rigorous methodology detailed in Chapter 3, the database was constructed so that trends could be drawn. The construction was important because the trends drawn are limited by the constraints of the database.

The second objective was to classify the CT imaging papers into relevant categories so that trends within the database could be observed. This was a crucial step in determining what trends would be relevant to this thesis. One of the categories was year of publication. All the papers were sorted by the year they were published so that the growth of CT imaging could be observed.

The third objective was to analyze the CT imaging papers based on the various categories in which they were placed in order to determine what trends existed in CT imaging. By analyzing the data generated by classifying the papers, trends such as number of CT imaging papers published over time and number of CT imaging papers published per continent could be determined. By determining trends in CT imaging papers through analysis of the database, the future of CT imaging can be more accurately predicted.

By building a database of CT imaging papers, classifying the papers, and analyzing the papers for trends, a foundation for CT imaging in the geosciences and petroleum and natural gas engineering was determined. Each of the three objectives is interlinked. The analysis of the trends in CT imaging papers was determined by how the papers were classified and the relevance of the trends observed was based upon how the database was built. The foundation for CT imaging in the geosciences and petroleum and natural gas engineering was built using these three objectives in order to determine current trends in CT imaging paper publication. In order to analyze trends, a database was constructed to be representative of the success of CT imaging.

Chapter 3

Database Construction

Despite being a relatively recent adaptation into the field of geosciences, the number of papers produced on CT imaging has grown exponentially. This is another indicator of the success CT imaging has seen in its adaption to petroleum engineering and the geosciences. Searching for papers in the Web of Science database in 2014 turned up more than six hundred papers on the topic while other databases found more than 10 times that amount. An analysis of a little over two hundred papers may seem like a drop in the bucket. By using a rigorous methodology, the papers selected are representative of the larger body of work.

Searching for CT imaging turns up all papers that use CT scanning: geophysical and otherwise. One of the initial challenges was to determine a search criterion that would exclude irrelevant papers while maximizing papers that used CT imaging for rock and core analysis.

The phrases used to locate articles included CT and computed tomography. Then phrases such as “rock porosity”, “permeability”, and “wettability” were employed in order to find geological and petroleum related articles. While terms like permeability and wettability could be applied to fields outside of the geosciences, the overwhelming amount of papers that these searches returned were relevant.

Due to the large amount of CT papers found using this criterion, citation index values were used in order to select which papers to include for the library. In Web of Science, the citation index is defined as the number of papers that cite a specific work (Thomson Reuters, 2008). Only papers from journals in the Web of Science database are utilized in the citation index calculation. According to Thomson Reuters, 10% of research literature accounts for 90% of citations (Thomson Reuters, 2008). The Web of Science database does not include all literature journals, only the journals that publish large numbers of high impact papers. Papers with high citation index values indicated that they had a significant impact while papers with low index values were excluded for having little influence on the literature. One of the issues with this approach was that papers from the 1980's to the early 2000's in general had higher citation index values than those from the late 2000's and onward. The earlier papers were cited more because they had been published for a longer period of time. Many of the papers from 2005 and onwards had very little citations and appeared at the bottom of the search results when organized by impact. Despite their low impact, these papers were still relevant because they were used to observe trends over time in CT imaging. Web of Science searches returned a large amount of these papers and the library reflected the growth of CT research in the past decade.

In order to expand the library and find papers that may have been ignored by the previous criterion, numerous journals were examined including several *Society of Petroleum Engineers* (SPE) journals, *Transport in Porous Media,* and *Water Resources Research*. With these search criteria, it was easier to find papers that fit specific fields. The SPE journals contained papers that dealt with petroleum aspects of CT scanning whereas the other two papers were concerned with the geophysical implications. This approach was limited to the names of the journals searched. A CT paper published in a lesser known journal would be overlooked using this method. The journals searched through were based on the journal names of prominent papers found using the previous search criteria.

After examining the papers in the library there seemed to be a lack of papers from the 1980's to the 2000's. The previous searches on Web of Science had recovered very few papers so a different search engine was used. By searching for papers in the one petro database the library became more complete. The drawback to using this database was that it did not record the citation index so there was no way to measure the impact of these papers. The CT papers most pertinent to petroleum engineering and geophysics were chosen out of the selected results in order to analyze trends without breaking the continuity established in the library.

Throughout the building of the database each paper was read in order to determine if CT imaging took place during the experiment or whether the authors were simply looking at CT images from a previous experiment. By focusing only on papers where the authors used a CT scanner as part of the experiment, major centers of CT scanning could be more accurately determined. In most of the papers, the location of the CT scanner is not stated. One such paper is *Multi-scale experimental study of carbonated water injection: An effective process for mobilization and recovery of trapped oil* (Alizadeh, Khishvand, Ioannidis, & Piri, 2014). The location of the scanner could be inferred from the acknowledgements, but since there was no definitive location given, CT imaging scanner location was not recorded as a category.

Once the library was complete the papers were organized to spot certain trends. The first trend of interest was the year of paper publication. This showed how CT scanning in the petroleum and geosciences expanded from its infancy in the 1980’s to 2014.

The second classification was CT imaging citation index. By recording the citation index from papers obtained through Web of Science the impact of CT papers over time was recorded. This trend did not show a complete picture. Several of the papers selected did not have a citation impact and many of the papers after 2010 had not been in circulation long enough to accurately determine what impact they had. Thus only papers prior to 2010 and in the Web of Science database were used to analyze this trend. Despite these limitations, the number of papers with citation index was significant enough to warrant this trend.

The third classification was country of publication. The country or countries where the CT experiment was conducted was based on the addresses of the authors. In some cases an author had two addresses in different countries. That author was counted twice, once for the first country address and once for the second address. A paper authored by researchers in France, Japan, and the USA originally counted as one paper for France, one for Japan, and one for the USA. The problem with this distribution was uncovered when the countries were grouped based on region in order to examine regional trends. One of the papers was written by two authors in England and one in France. Under the original authorship distribution, England would have authored one paper and France would have authored one paper. When grouped together in the European region, the paper would be counted twice, once for England and once for France. This resulted in Europe representing a disproportionality large percentage of the papers authored. This skewed the trends and decreased the integrity of the report.

In order to solve this problem, authorship per country was decided by fractions. A paper authored in only one country would receive a fraction of 1. If a paper had three authors that were from the USA and one author from Japan, USA would have authored 75 % of the paper while Japan authored 25 %. This approached assumed that each author contributed equally to the paper. Table 1 shows the amount of papers authored by the USA based on this fractional approach.

Table 1: Papers authored by the USA from 1984 to 2014

Fraction	Number of Papers	Total Paper Value
1	98	98

0.86	1	0.86
0.83	2	1.66
0.8	2	1.6
0.75	4	3
0.66	3	1.98
0.64	1	0.64
0.6	5	3
0.57	2	1.14
0.5	3	1.5
0.4	2	0.8
0.29	2	0.58
0.25	4	1
Grand Total	129	115.76

Table 1 shows that while the number of papers with at least one American author was 129, the actual contribution of American authors was 115.76. All decimals are rounded to the nearest whole paper. In this case the U.S. published 116 papers. This number gives a more accurate view of American involvement in CT scanning.

The fourth classification was affiliation. Each of the authors was given one of four affiliations. Corporation was given if the author worked for a corporation such as BP, Exxon, or Schlumberger. For authors conducting research at a college or university, “Academic” affiliations were given. Originally all the other remaining authors were given the designation of “Other” designation if the research they conducted was not part of a corporation or a college or university. However the percentage of papers in the “Other” affiliation was too large to ignore. The affiliation “Other” was split into two new ones: “U. S. National Lab” and “Other Research Centers.” “Other Research Centers” included organizations like the Alberta Research Council and the Commonwealth Scientific and Industrial Research Organization of Petroleum in Australia.

When the database was completed it held 221 papers on CT imaging in the petroleum geosciences. By following the rigorous methodology, these papers serve as a sample of some of CT imaging’s greatest milestones in its successful adaption from the medical field to the geosciences. With the database constructed, trends could now be analyzed to determine the papers, countries, and affiliations behind CT imaging’s success.

Chapter 4

Analysis and Trends

With the CT imaging papers classified, trends were observed from the constructed database. Four trends were observed based on the four categories created in the database construction. By analyzing the evolution of CT imaging papers published over time, the growth of CT imaging papers can be observed. The influence of CT imaging papers can be analyzed to find high impact papers within the field. Looking at the geographic distribution of papers determined the most prolific publishing countries. Lastly, author affiliation was analyzed to determine what entities published the most papers. The trends found support the growth of CT imaging in petroleum engineering and the geosciences. It is important to note that these trends and observations hold true within the constraints of the database. There were many papers in Web of Science that were not included, because the main focus of the database was high impact papers. There are also other papers that are not in the Web of Science database and did not have a citation index. Thus it was difficult to determine the impact of these papers.

4.1 Evolution of CT Imaging Papers Published from 1984 to 2014

By looking at CT imaging papers published over time, the pattern of growth can be determined. Figure 1 shows the number of papers published for a given year.

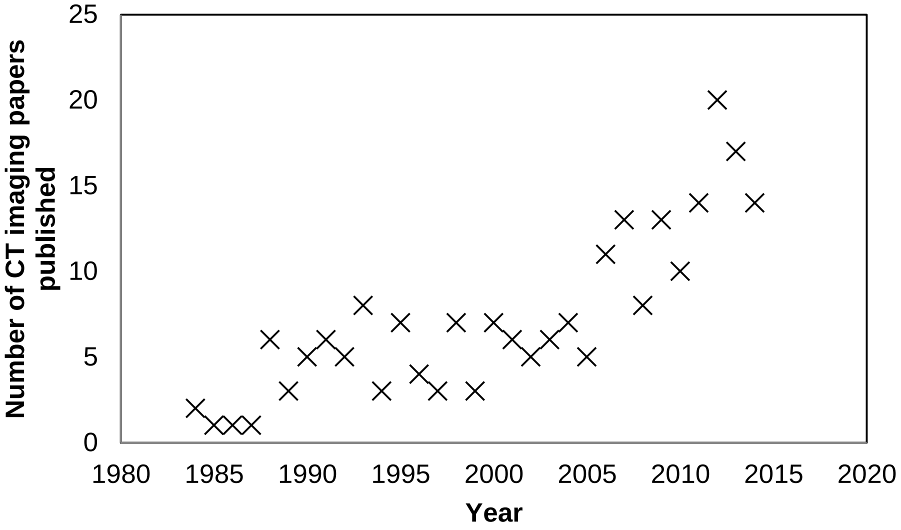

Figure 1: Number of CT imaging papers published from 1984 to 2014

From the graph, it appears that CT imaging research is growing, especially over the last decade. The extent of the growth is not as easy to determine. The fit line implies a rough exponential growth over the years, but it could be argued that the data is more of a linear fit. The R^2 values for both the linear and the exponential fit are roughly the same. The potential of a linear fit may be due to the fact that later on in the paper collection there was an effort to find some of the early papers because it was presumed that they would have a higher impact. The early papers would also fill gaps in the history that were left from the initial searches. This may have resulted in the years between 1984 and 2000 becoming overrepresented, diluting the strong exponential curve that was expected. Despite this the rapid growth is still evident in several of the years. In 2012 the number of papers published is close to one tenth of all the papers in the database.

4.2 Citation index of CT Imaging Papers from 1984 to 2010

Next the citation index of CT imaging papers over time was measured. Citation index measures how many papers have cited a paper. It is one way to measure the impact of a paper. By measuring the citation index over time, it could be determined if papers had high impact merely due to exposure time or whether there were other trends in play. Figure 2 shows paper impact over time from 1984 to 2010. Papers that were cited less than 10 times were not included.

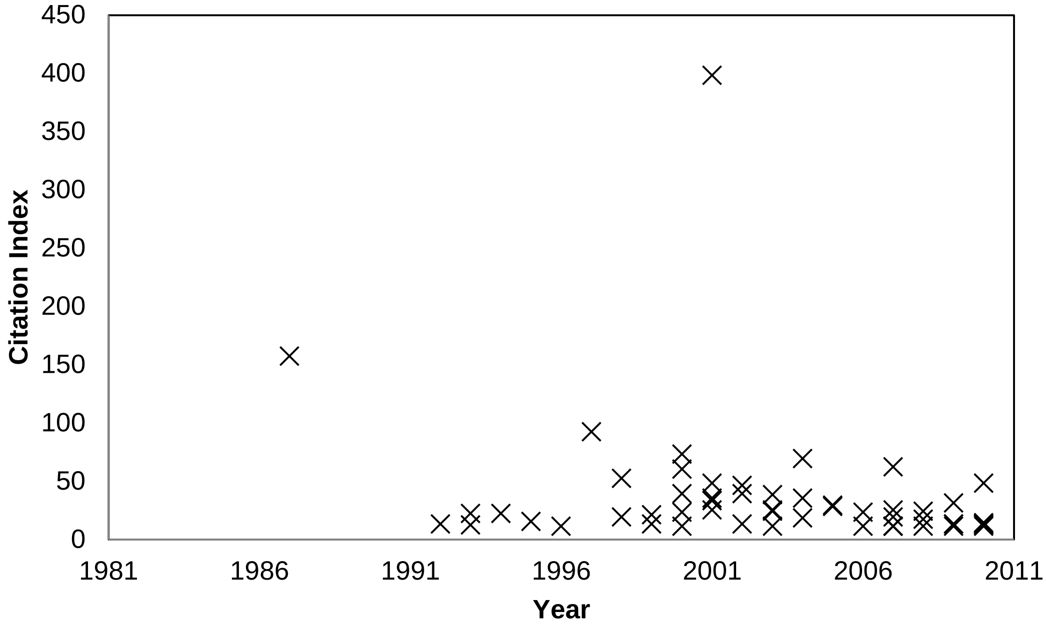

Figure 2: Citation index of CT imaging papers from 1984 to 2010

There is no clear decline in the citation index of CT imaging papers over time. In fact, paper impact in the 2000's is higher than in the early 1990's. Wellington and Vinegar's *X-Ray Computed Tomography* paper, published in 1987, was cited 157 times, while a paper in 1997 was cited 92 times. The two other papers discussed in the introduction do not appear in this graph for different reasons. The paper by Cromwell et al. was found outside of the Web of Science database and did not have a citation index. It could not be placed on this graph. *Computer-*

Assisted Tomography for the Observation of Oil Displacement in Porous Media by Wang et al. only had a citation index value of seven. This low citation value was interesting because this paper was cited in X-Ray Computed Tomography. It was also documented by Cromwell et al. as being one of the first papers written on the subject. It appears that Wellington and Vinegar were able to concisely summarize the work of Wang et al. in their paper. Instead of citing Wang et al. directly, researchers cited Wellington and Vinegar instead.

The outlier is *Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences* by R. A. Ketcham and W. D. Carlson. This paper cites *X-Ray Computed Tomography* as one of the first papers to document CT scanning in petroleum engineering. This paper is similar to the paper by Wellington and Vinegar in that it serves as an introduction to CT scanning in the geosciences. This paper draws on significantly more experience than Wellington and Vinegar due to the increase in research that occurred between the two papers publications. Ketcham and Carlson go more in depth on the history of CT scanning, how a CT scanner works, ways to optimize imaging, and various applications to the geosciences (Ketcham & Carlson, 2001). The high citation index is not surprising given the all-encompassing nature of the paper. Some of the papers that cite this work come from paleontology (Garwood & Dunlop, 2011) and human evolution journals (Ryan & Ketcham, 2002) . Despite this, the paper still has a high impact in relevant geosciences to warrant its inclusion.

Another paper of note is *Three-dimensional quantitative textural analysis of metamorphic rocks using high-resolution computed X-ray tomography. P2. Application to natural samples* (Denison & Carlson, 1997). This paper used CT imaging and numerical modeling to understand crystal development of metamorphic rocks (Denison & Carlson, 1997). This paper was considered on the cusp of being eligible for the database, because even though it uses CT imaging, it focuses on a topic that is not relevant to petroleum engineering nor rock and fluid properties. It is still a geological paper which is why it is included in the database.

4.3 Geographic Distribution of CT Imaging Papers

Using the authorship distribution method detailed in Chapter 2, countries were grouped by region in order to determine trends in regional CT experimentation. Table 2 shows the number of CT imaging papers published per country in alphabetical order and rounded to the nearest whole number. Countries that would round down to zero were kept as a decimal. Figure 3 shows the percentage of CT papers published based on region.

Table 2: Number of CT imaging papers published per country from 1984 to 2014

Country	**Number of CT Imaging Papers Published**
Australia	12
Belgium	2
Brazil	4
Canada	14
China	7
Croatia	1
Denmark	2
England	7
France	10
India	1
Israel	1
Italy	2
Japan	10
Mexico	2
Netherlands	10
New Zealand	0.2
Norway	7

Saudi Arabia	3
Scotland	2
Spain	0.3
Switzerland	0.3
Taiwan	0.1
Thailand	0.4
Turkey	2
UAE	2
USA	116
Venezuela	1

One of the trends is that North America is the leading region with regards to CT paper publication or about 133 out of 221 papers total. European countries come in second at 46 papers and Asia in third with 24 published CT imaging papers. The U.S. has published 87% of the North American papers or about 116 papers. U.S. authors account for slightly more than half of CT papers published at 52.5%. This may be due to the database construction methodology and the journals in the Web of Science database. The. U.S. may not be as dominant on a larger scale beyond the constraints of this database.

While only 11% of the papers in the North America region were published by Canadian authors, Canada published the second most papers at around 15 papers. The Netherlands published 23% of the papers in the European region, but the Europe region only accounts for 21% of all papers published. The Netherlands published about 10 papers overall which places it in fourth behind Australia. It is tied with Japan and France who also published 10 papers each.

Focusing on the Europe region, 26% of the papers are marked < 3 papers. This means that all the countries that published less than three papers each are placed in this category. This was the case for eight countries including Italy, Belgium, and Denmark. England and Scotland are separated in the European chart.

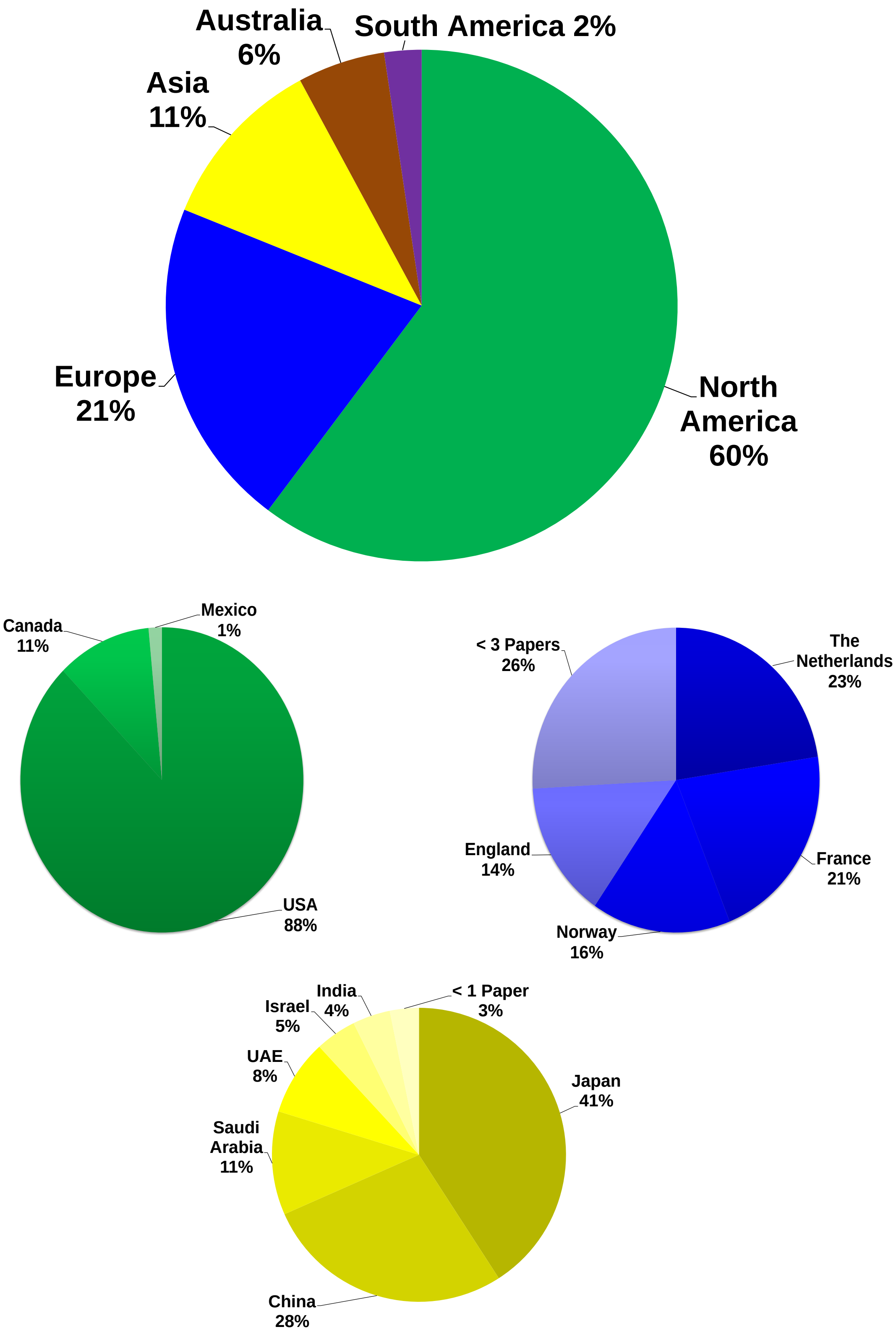

Figure 3: Geographic distribution of CT imaging papers from 1984 to 2014

The former country published 7 papers while the latter published 2 CT imaging papers. It is interesting to note that each of the major CT imaging paper publishing countries in Europe have major oil and gas companies headquartered in the country.

Australia is the major publishing force with 12 papers published. Neighboring country New Zealand is much less prolific, publishing less than one paper. It is not represented in Figure 4 nor is any other country that published less than one paper.

Japan is the highest CT imaging publisher in Asia with 10 papers and China is second with 8 papers. The Middle East region of Asia has published very few CT imaging papers. Saudi Arabia, UAE, and Israel combined published only 6 papers.

Figure 4 shows an alternative view of CT imaging papers published per country. The circle for one paper is 2 mm in diameter and increases by 50% for each subsequent paper. Transparency also increases as papers published increases. The USA published 116 papers and is the only country in the > 100 papers category. The CT imaging research in Europe is primarily clustered in northwestern Europe. France and The Netherlands published 10 papers each and are represented by the larger, more transparent circles. All other European countries published less than 10 papers.

Figure 4: World map showing the number of CT imaging papers published from 1984 to 2014

4.4 Author Affiliation of CT Imaging Papers

Lastly, the papers were grouped by affiliation in order to determine in what type of setting the CT research occurred. Figure 4 shows the percentage of papers based on the four affiliations: Academic, Corporation, U. S. National Lab, and Other Research Centers. The majority of the papers had academic involvement. Unlike the graphs of CT research per country, the papers were not given ownership. All papers with at least one college or university were given a 1 for academic. Likewise in the academic breakdown graph, each college or university was given one paper independent of the number of authors from that college or university. To increase the readability of the graph, some of the names of research centers, universities, corporations, and national labs have been abbreviated.

The majority of papers have had some academic involvement. 56% or 166 out of the 220 papers in the library involved at least one researcher from a college or university. It is important to note that 166 papers out of 220 papers equals 75%, not 56%. The total number of papers in the affiliation graph is greater than 220. This is because when computing the different affiliation sections, some papers were counted multiple times. A paper that had one author from a university and one author from a corporation was counted twice. As such, the graphs shown for affiliation are relative graphs. The percentages do not correspond to the actual amount of papers published under each affiliation. Rather it compares one affiliation to the other. When the number of papers is stated, it may not match the percentage in the graph. For a list of the acronyms and what they stand for, go to Appendix C.

When looking at the academic circle breakdown the top three schools are from the United States of America: Stanford, The Pennsylvania State University, and the University of Texas. Each of these schools comes from states that have a history of oil and gas production.

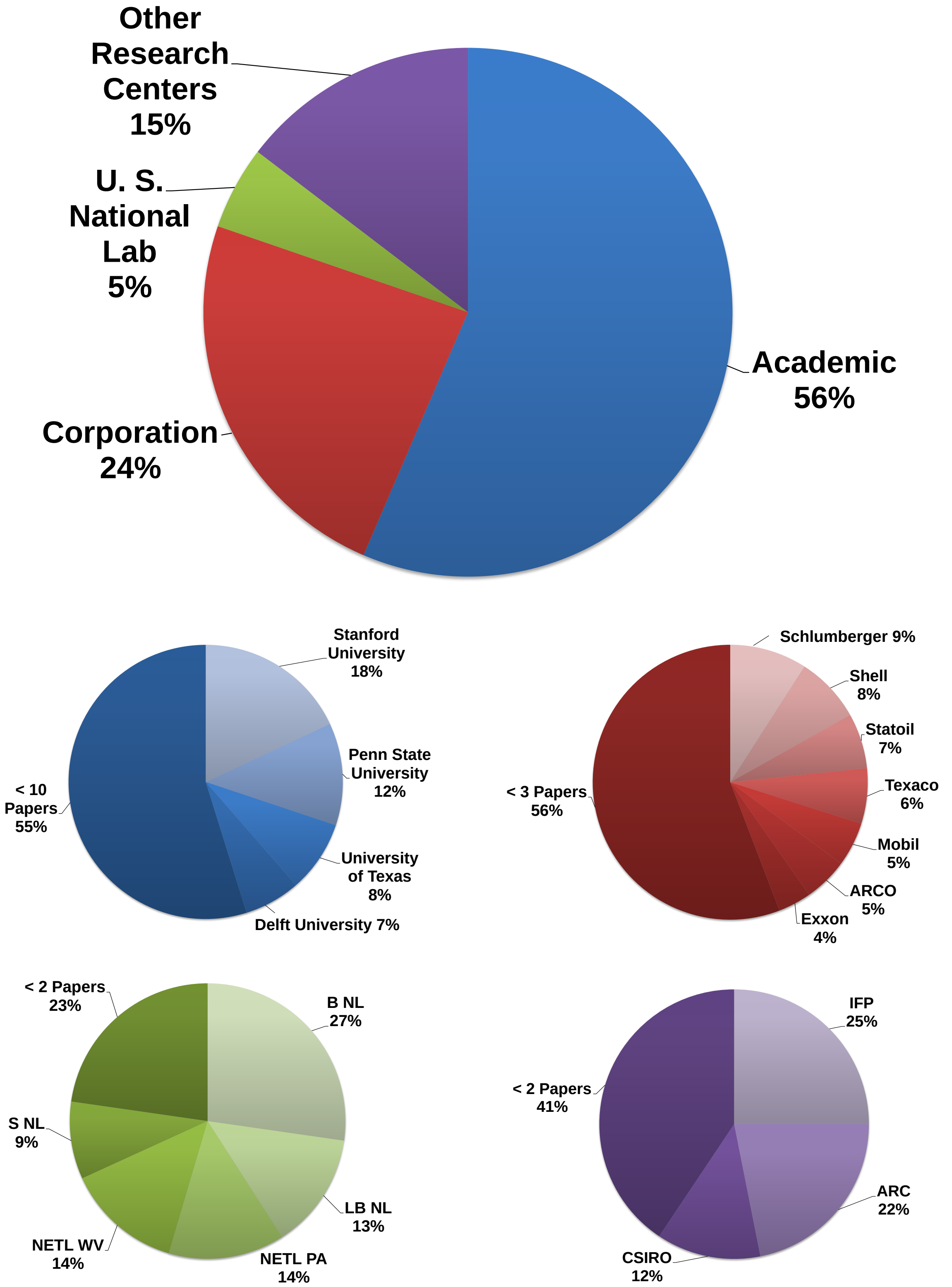

Figure 5: Percentage of CT imaging papers by affiliation and entity from 1984 to 2014

The fourth is Delft University in the Netherlands which also has a history of oil and gas production. The < 10 papers segment consists of almost 100 universities that published less than 10 papers.

The next largest sector is the corporation. Unlike the academic wedge, the corporations have been much less prolific in CT paper publication. Corporations were directly involved in the publication of 70 papers. The leader, Schlumberger, was only involved in the publication of seven papers. This is significantly less than the leading university, Stanford, which published 30 papers. Thirty-five other corporations published less than three papers each.

National labs in the U.S. accounted for 5% or 15 of the papers published. Brookhaven National Laboratory was the leader with 6 papers. Overall there were 10 national labs represented. These only represent U. S. national labs because it was difficult to determine whether or not a foreign research center was a national lab.

The last affiliation, Other Research Centers, consists of 37 papers that involved at least one author from a research center that did not fit in any of the other categories. The Institute Francias Petroleum (IFP) published the most at 8 papers. This is slightly more prolific than Schlumberger and Brookhaven National Laboratory.

Chapter 5

Concluding Remarks

X-ray CT imaging has had a significant impact on the geosciences and petroleum engineering and is a demonstration of a technology being successfully adapted from one field to another. By analyzing trends in CT imaging paper publication over time, citation index over time, geographic distribution, and institution affiliation the expansion in CT imaging from 1984 and 2014 can be observed. These observations are constrained by the database construction methodology

In order to monitor the growth of CT imaging applications in petroleum engineering and the geosciences, this work was divided into three objectives. A database was constructed to curate a sample of CT imaging papers from the thousands of papers published from 1984 to 2014. By following a rigorous methodology, the database was constructed with an emphasis on papers with high citation indices in Web of Science. By focusing on papers in the Web of Science database, there may be some biases that prevent the trends drawn from applying to all published CT papers. Only a small number of papers were chosen and further research would need to be done to determine if the trends observed were accurate on a larger scale. The papers were then categorized using keywords in order to create charts to look for trends. Once the data was categorized, the trends were analyzed. The extent of CT imaging was determined as well as which countries and affiliation were most involved with CT imaging publication. CT research has grown over time with more papers being written ever year. By looking at impact, papers written as detailed summaries of CT imaging have had the highest impact. This is due to the broad scope of the papers, and the thoroughness with which they address CT imaging. They are like milestones on the road of CT imaging. Looking at CT imaging on a regional basis has revealed that North America is the largest publisher of CT papers. In particular the U.S. has been involved with the publication of more than half of the CT papers in the library. Lastly, the majority of the papers published had at least one author from an academic institution. The amount of papers with academic involvement dwarfed all other affiliations at 166 papers. While 24% of the papers involved a corporation, the total paper count was only 70 papers. U.S. National Labs and Other Research Centers also had fairly low paper counts.

Academic institutions have been of particular importance from the mid 1980's to today. CT imaging research is also prevalent in Europe and shows how CT imaging in the petroleum and geosciences has had a global impact that goes beyond its country of origin. Its success is proof that a technology from one field can be successfully adapted to another. There may be other technologies out there from other fields that may prove useful in petroleum engineering and the geosciences.

By analyzing trends in the constructed database, CT imaging has achieved success in petroleum engineering and the geosciences. By looking at the evolution of CT papers over time, the growth of CT papers between 1984 and 2014 is readily observed. It is also apparent that paper impact is not correlated with time and that even recent petroleum engineering and geoscience CT imaging papers are influencing researchers beyond these fields. *Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences* is an example of a geosciences paper appealing to paleontology and human evolution. Like the adaption of CT imaging from medical fields to petroleum engineering and the geosciences, CT imaging may expand into other fields as well. The geographic distribution shows the global reach of CT imaging. Although the USA is the primary producer of CT imaging papers, several countries in Europe, Asia, and Australia have also made significant contributions. Lastly, affiliation shows that the majority of the authors who published CT imaging papers came from academic institutions. The universities and colleges were American which supports the geographic distribution data. American corporations and national laboratories also played a significant role in CT imaging paper publication.

Overall, CT imaging has succeeded in petroleum engineering and the geosciences and serves as a case study of how a technology developed in one field can be successfully adapted to another. These trends show the extent of CT imaging from 1984 to 2014 on a temporal and geographical scale and its impact on petroleum engineering and the geosciences within the database constraints.

Appendix A: CT Imaging Paper Database

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Appendix B: Affiliation Acronyms and Paper Counts

Affiliation	Acronym/ Abbreviation	Number of CT Imaging Papers Published
Academic Institution	Academic	150
Australia National University	ANU	5
Central University of Venezuela	CUV	1
China University Petroleum	CUP	2
Chinese Academy of Sciences (China)	CAS	2
Clemson University	Clemson	1
Colorado School of Mines	CSM	2
Columbia University	Columbia U	1
Curtin University of Technology (Australia)	Curtin	1
Delft University of Technology (Netherlands)	Delft	11
Ecole Natl Super Arts & Metiers (France)	ENSAM	1
Ehime University (Japan)	Ehime	1
Estado University of Rio de Janiero (Brazil)	EURJ	1
Federal Catarinense Institute (Brazil)	FCI	1
Federal University of Rio de Janiero (Brazil)	FURJ	1
Federal University of Santa Catarina	FUSC	2
Florida International University	FIU	1
Hebrew University Jerusalem (Israel)	HUJ	1
Heriot Watt University (Scotland)	HWU	2
Hokkaido University (Japan)	Hokkaido	1
Huxley School of Environment Earth Science and Engineering (England)	Huxley	1
Jiao Tong University (China)	JTU	2
King Saud University (Saudi Arabia)	KSU	1
Korea Institute of Construction Technology (Korea)	KICT	1
Kuwait Institute of Scientific Research	KISR	1
Kyushu University (Japan)	Kyushu	2
Louisiana State University	LSU	3
Lyon University (France)	Lyon U	1
Madrid Polytech (Spain)	MP	1
McGill University (Canada)	McGill	2
Middle East Technical University (Turkey)	METU	1
Middlebury College	MC	1

Mines Nancy (France)	MN	2
Montana Tech	Montana Tech	2
Montclair U.	Montclair	1
Old Dominion University	ODU	1
Oregon State	OS	1
Osaka University (Japan)	OU	1
Penn State University	PSU	20
Petroleum Institute Abu Dhabi (UAE)	PIAD	1
Qingdao University of Science and Technology (China)	QUST	1
Quebec university (Canada)	Quebec U	1
Seoul University (Korea)	Seoul U	1
Stanford University	Stanford	30
State University of New York Stoney Brook	SUNY SB	4
Swiss Federal Institute of Technology (Switzerland)	SFIT	1
Taiyuan Technical University (China)	Taiyuan U	2
Tech University of Denmark (Denmark)	TUD	3
Technion Israeli Institute of Technology (Israel)	Technion	2
Texas A&M	A&M	8
Texas Tech	TT	1
Tohoku University (Japan)	Tohoku	1
Tokyo Institute of Technology (Japan)	Tokyo	2
UAE U	UAE U	1
UNAM (Mexico)	UNAM	1
University New S Wales (Australia)	UNSW	5
University of Loughborough (England)	U Lou	1
University Bordeaux (France)	UB	1
University Ceara (Brazil)	Ceara	1
University of Central London (England)	UCL	1
University Estadual Londrina (Brazil)	UEL	2
University of Adeliade (Australia)	Adeliade	1
University of Alaska	UA	1
University of Arizona	U Arizona	1
University of Bergen (Norway)	U Bergen	3
University of Birmingham (England)	U Birm	1
University of Brighton (England)	U Brighton	1
University of Bristol (England)	Bristol	1
University of Calgary (Canada)	U Calgary	1
University of California Berkley	UCB	2
University of California Davis	U Davis	1

University of Chicago	U Chicago	2
University of Edinburgh (Scotland)	U Edin	2
University of Guelph (Canada)	Guelph	1
University of Houston	UH	5
University of Huelva	U Huelva	1
University of Idaho	U Idaho	1
University of Leuven (Belgium)	Leuven	1
University of Liverpool (England)	U Liver	1
University of London Imperial College of Science Technology and Medicine (England)	ULI	4
University of Manchester (England)	Man	2
University of Manitoba (Canada)	UM	1
University of North Carolina	UNC	1
University of Northern British Columbia (Canada)	UNBC	2
University of Notre Dame	UND	1
University of Oklahoma	UO	1
University of Pavia (Italy)	Pavia	1
University of Pittsburgh	UP	2
University of Science and Technology (China)	UST	1
University of Stavanger (Norway)	Stavanger	1
University of Texas	UT	14
University of Tokushima (Japan)	UTOKU	4
University of Tokyo (Japan)	U Tokyo	3
University of Trieste (Italy)	U Trieste	1
University of Tulsa	Tulsa	2
University of Waikato (New Zealand)	Waikato	1
University of Waterloo (Canada)	U Waterloo	2
University of Western Australia (Australia)	UWA	2
University of Wyoming	UW	5
University Oriente (Venezuela)	U Oriente	1
University Paris Sud	UPS	1
Vanderbilt	Vanderbilt	1
Yonsei University (Korea)	Yonsei U	1
Corporation	Corporation	70
Abu Dhabi Company for Onshore Oil Operations (UAE)	ADCO	1
ADAS (UK)	ADAS	1
Aera Energy LLC	Aera	1
AGIP (Italy)	AGIP	1
Amoco Production Co.	Amoco	1
ARCO Oil and Gas Co.	ARCO	4

Baker Hughes	Baker	1
BP	BP	2
China National Petroleum Corporation	CNPC	1
CPC Co. (Taiwan)	CPC	1
ENI	ENI	2
Esso (Canada)	Esso	1
Exxon	Exxon	3
FEI Lithicon	FEI	2
FEI Lithicon	FEI	2
Flint Canada Inc.	Flint	1
Geoquest Reservoir Technology LTD.	Geoquest	1
Hess	Hess	1
Huntsman	Huntsman	1
IKU SINTEF (Norway)	IKU SINTEF	1
INA (Croatia)	INA	1
Ingrain Inc.	Ingrain	1
Japan Oil Gas and Metals National Corporation	JOGMEC	1
Japan Petroleum Exploration Co.	JAPEX	1
Maersk	Maersk	1
Marathon Oil Co.	Marathon	1
Mobil E and P Tech Center	Mobil	4
Oil and Natural Gas Corporation (India)	ONGC	1
PEMEX	PEMEX	1
Petro Tech Services	PTS	1
Petrobas SA	Petrobas	1
PetroChina	PetroChina	1
Picker Inc.	Picker	1
Resevoir Management LTD	RMLTD	1
Saudi Aramco	Aramco	2
Schlumberger	Schlumberger	7
Shell Dev Co.	Shell	6
Sinopec (China)	Sinopec	2
Standard Oil	SO	1
Statoil	Statoil	5
Terratek	Terratek	1
Texaco	Texaco	5
URS	URS	2
National Lab	NL	21
Brookhaven National Laboratory	B NL	6
California Los Alamos National Laboratory	LA NL	1

Lawrence Berkeley National Laboratory	LB NL	3
Lawrence Livermore National Laboratory	LL NL	1
National Energy Technology Lab Morgantown, WV	NEL WV	3
National Energy Technology Lab Pittsburgh, PA	NEL PA	3
National Energy Technology Lab Washington D.C.	NEL DC	1
Pacific Northwest National Lab WA	WA NL	1
Sandia National Labs	SNL	2
<u>Other Research Centers</u>	<u>Other</u>	<u>44</u>
Agency for Innovation by Science and Technology (Flanders, Belgium public institution)	IWT	1
AIST (japan)	AIST	1
Alberta Research Council (Canada)	ARC	7
China Synchrotron Radiation Facility (China)	CSR	1
CSIRO Petroleum (Australia)	CSIRO	4
Department of Energy	DOE	1
European Synchrotron Radiation Facility (France)	ESR	1
Idaho National Engineering and Environmental Lab	NEEL	1
IFP Energies nouvelles (France)	IFPEN	2
Institute Francias Petroleum (France)	IFP	8
ISIS Facility	ISIS	1
Japan Marine Science & Technology Center (Japan)	JMS	1
Japan Synchrotron Radiation Research Institute (Japan)	JSR	1
Lab TREFLE (France)	TREFLE	1
Mexican Petroleum Institute (Mexico)	MPI	2
National Institute for Petroleum and Energy Research	NIPER	2
National Institute of Advanced Industrial Science and Technology (Japan)	NIST	2
National Science Foundation	NSF	1
New Mexico Technology Petroleum Recovery Research Center	NMTP	2
Research Institute of Innovation for the Earth (Japan)	RITE	1
RF Rogaland Research (Norway)	RFRR	1
Sezione di Pisa (Italy)	S Pisa	1
Sinctrotron Trieste (Italy)	S Trieste	1
US Geological Survey	USGS	2
VITO (Flemish Institute for Technological Research) (Belgium)	VITO	1
Western Australia Geothermal Center for Excellence (Australia)	WAGCE	1

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Education

Schreyer Honors College, Penn State University, Petroleum Engineering Major
Class of 2015

Work Experience

ConocoPhillips, Houston, Production Engineer Internship
May 2014-Aug 2014

Identified wells in the Panhandle area which could benefit from compression; Determined potential production uplift, associated lifting costs, and performed economic evaluations on utilization of permanent and rental compression; Presented recommendations to management

Penn State College of Earth and Mineral Sciences, Research and Teaching Assistant
Sept 2013-present

EMS Energy Institute Rock and Fluid Properties lab assistant

State of Alaska Oil and Gas Conservation Commission, Petroleum Engineering Internship
May 2013-August 2013

Identified by-passed gas pay on North Slope of Alaska by evaluating historical mud logs, wireline logs and drill stem test reports; documented findings with well cross sections and presented results and recommendations to
Commissioners for use in future lease sales; Evaluated applications from Alaska well operators to conduct drilling, well intervention, and Enhanced Oil Recovery injection operations

Holland America-Princess Cruises, Anchorage, Baggage Handler, Performance Award
May 2012-August 2012

Anchorage Fire Department Service Project: Created program to improve emergency response March 2010-June 2011

Mapped unnamed but frequently used trails; surveyed various user groups; created web site; Developed and presented computerized emergency response plan to officials

***Anchorage Press*, Writing Internship**
May 2009-August 2009

Participated in all aspects of the production of a weekly paper; Learned firsthand the importance of brevity, factual reporting and speed of delivery

Honors and Awards

SPE Scholarship, AADE Scholarship, College of Earth and Mineral Sciences Scholarship, Schreyer Honors College Academic Excellence Scholarship, AP Scholar with Distinction, Robert C. Byrd Honors Scholarship, Anchorage Running Club Scholarship