Dynamic capabilities in related diversification: the case of geothermal technology development by oil companies

by

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Abstract

During the peak oil price period of the 1970s and the first half of the 1980s, 12 major oil firms decided to diversify into the geothermal energy business under the assumption that they could easily leverage their upstream oil capabilities for that purpose. In this thesis I examine how oil firms achieve a successful related-diversification into geothermal energy technologies building on the case studies of Union Oil Company of California and Phillips Petroleum and encompassing 5 geothermal fields and 28 units of analysis that represent the knowledge sources and transfer mechanisms required to overcome the technological and managerial differences between upstream oil and geothermal. The evidence is constructed based on backward patent citation analysis, company reports, literature review and in-depth interviews with the engineers and managers that ran the geothermal business. The two case studies are used to demonstrate that core competencies inherited from upstream oil are necessary but not sufficient to diversify into a related business field. Correspondingly, this research introduces the concept of "dynamic capabilities" to explain how the main enablers of the successful diversification into geothermal energy in the two cases studied, were each firm's dynamic capabilities of: absorbing knowledge from the industrial ecosystem, developing and exploiting internal scientific knowledge, and empowering decentralized business units. Understanding the way that oil firms leveraged their own competencies to diversify into geothermal energy during the oil price crisis can provide important insights into how oil and gas and other extractive industries can meet the sustainability challenges they currently face, and to enhance technology transfer in general. An additional contribution of this thesis is to frame its propositions by integrating concepts from the technology strategy literature into a causal-loop representation of the different factors that influence the evolution of a firm's knowledge stock and its transition into related business fields.

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Acknowledgments

In the search for a master's degree, I knew I wanted to have the opportunity of learning what drives energy innovation and technology transfer, and I knew that no specific class would provide me an in-depth understanding of such issue. Once at MIT's Technology and Policy Program I found the correct people and the correct references to define this thesis topic and frame an exciting research question. Several individuals have guided and assisted me on this quest, and I want to express my profound appreciation to the most important.

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I. Introduction

Motivation

Oil and gas firms are currently exposed to a new set of challenges[1] that demand pushing the boundaries of their businesses and expanding the breadth of their capabilities. Researchers in the field of oil and gas industry strategy have stated that these challenges are the drivers of a "complete paradigm shift" in competitiveness, emphasizing the reduction of greenhouse gas emissions as one of the major pressures (Shuen & Teece, 2014; Teece, Shuen, & Feiler, 2014). Yet, committing resources in the low-carbon energy field could help oil and gas firms discover new sources of competitive advantage while creating positive externalities for the environment (Kolk & Pinkse, 2013). Whatever we can learn from earlier experiences of diversification into low-carbon energy can help guide these technology choices.

On another level, diversification efforts carried out by extractive industries can create positive externalities in terms of value creation and knowledge spillovers. Policymakers from resource-rich countries are taking important steps to expand the boundaries of their economies and transition from industries dependent on natural resources to knowledge-intensive industries. These industries create highly qualified jobs, thus contributing to high value output and reducing dependence on commodity price, thereby increasing global competitiveness (Hvidt, 2013; Kaplinsky, Farooki, Alcorta, & Rodousakis, 2012). Such is the case with countries that have historically relied on the exploitation of oil reserves (e.g. OPEC countries) and currently find low carbon energy technologies an attractive industry to incorporate into their "green growth" strategic plans (OECD, 2011; Popp, 2011).

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[1] Teece et al. identify the following challenges confronted by oil and gas companies (Teece et al., 2014) : 1) The increasing demand for oil and gas requiring increased production; 2) The opportunities to exploit unconventional oil and gas resources, by means of new technologies, at new geographies, and using new processes, drives the need for "ubiquitous learning"; 3) The rise of national oil and gas companies and large independents, are increasing the complexity of strategic decisions; 4) The increasingly challenging task of managing the Human Resource Strategy; 5) The permanent need to oversee and adress health, safety, security and environmental risks throughout the business ecosystem; 6) Rising macroeconomic pressure to divert resources to focus on low-carbon sources of energy.

This thesis is inspired by the opportunities for diversification triggered by low-carbon energy innovations from extractive industries, with special attention to the value that these can provide to the industry's knowledge stock. During the 2000-2010 period, U.S.-based oil and gas companies were responsible for 20% of the total U.S. renewable energy investments (Penha, 2010; Switzer, Lovekin, & Finigan, 2013). Part of that effort emerged from innovative activities based on these companies' existing capabilities (which from now on we will call "related-diversification[2]"). However, as early as the 1973 oil price crisis, oil firms also have been important knowledge contributors to the development of new energy technologies (C. E. Helfat, 1997; Teece, 1980).

One of the most interesting examples of diversification into alternative energy technologies (and the one that has been most studied) is that of the petroleum industry during the oil price crisis period (C. E. Helfat, 1997; Teece, 1980). The "oil price crisis" (named after the period encompassing two major oil price shocks in 1973 and 1978) spurred the diversification of many U.S. oil firms into alternative energy technologies, which increased the annual percent change of energy R&D intensity[3] by 6.3 on average between 1976 and 1981 (C. E. Helfat, 1997), and subsequently made available several innovations that expanded the energy technology portfolio at a pace that had not been seen before. A new wave of developments in alternative energy technologies began in this period, at least in part as the result of U.S. government sponsorship through policies like the Energy Security Act and several technology-specific regulations. However, the main driver for diversification emerged from the oil companies themselves, which considered these investments (e.g. synthetic fuels, solar, geothermal, coal gasification and nuclear) strategic opportunities[4].

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[2] This concept will be formally explained in Chapter II.

[3] R&D expenditures divided by firm sales.

[4] Some of the different ways that oil firms can approach the low-carbon energy technology market (which are defined later in Chapter II as bases of diversification) are, among others (Switzer et al., 2013): 1) Within the fence opportunities: Replacement of conventional fossil fuels for core or support services in operations; 2) Standalone low carbon energy businesses: Establishment of for-profit low-carbon technology production project development & deployment or support services; 3) Venture funds: Strategic investment in external businesses developing low-carbon energy technologies, projects and companies; 4) R&D support: Support for pre-commercial science, technology and data gap closure; 5) Public policy advocacy: Government relations and other communications to reduce barriers and enable low carbon energy growth; 6) Leveraging core competencies: Development of for-profit businesses in areas where O&G competencies are readily translated to the low-carbon energy sector. This is renamed "related diversification" throughout this thesis.

The first step in the research was to screen related-diversification cases from extractive industries into low-carbon energy technologies by number of cases. From all the cases collected, diversification from oil into geothermal represented the largest number of occurrences among different firms and also the oldest. Hence, I chose geothermal as the most suitable basis for making comparisons among different contexts and for testing propositions and hypotheses (Yin, 2009).

This thesis identifies the connections (or relatedness) between upstream oil operations and the development of geothermal energy technology, as well as the knowledge transfer mechanisms that enabled such diversification. The way that oil firms leveraged their own competencies to diversify into geothermal energy during the oil price crisis period can provide meaningful insights for today's green growth and competitiveness challenges, even considering the significant contextual differences in commodity prices or industry structure.

During the peak oil price period, some oil firms decided to diversify into the geothermal energy business under the assumption that they could effortlessly leverage their upstream oil capabilities for that purpose. I find that these operational capabilities were not enough to successfully diversify, and that firms also needed to exercise a set of critical "dynamic capabilities" (which are defined in Chapter II).

Research question

I define the research question for this thesis as: ***"How do oil firms achieve successful related-diversification into geothermal energy technologies?"***

It is important to distinguish this question from other inquiries that imply different methodological approaches. One such inquiry is "Why does an oil firm engage in a related-diversification process into geothermal energy technologies?" This query is not central to this research, yet it is embedded in the overall context of study. As I will show in Chapter IV, the main incentive for an oil firm to invest in geothermal energy technologies had more to do with exogenous factors such as oil price even if the firm's internal capabilities were readily available to support growth into new technology markets. The chosen research question focuses on the mechanisms of the transfer of knowledge between the oil industry and the then-nascent geothermal industry.

Structure

This thesis is organized into nine chapters: It starts with Chapter II, which includes an in-depth review of firm strategy and firm diversification theory, with the objective of defining related diversification and also introducing the concept of dynamic capabilities and their importance for leveraging the existing capabilities within a firm. In Chapter II, I also propose a causal-loop representation of the different factors that influence the evolution of a firm's knowledge stock, and its implications for related diversification. Chapter III explains the research methodology for this thesis, stating the propositions and hypothesis to be tested, so as to answer the research question posted. Chapter IV includes an overview of the historical context of the oil crisis period to explain the drivers that induced oil firms to develop new energy technologies and the role of government support. Chapter V provides a technical assessment of the challenges of diversifying from upstream oil operations to geothermal development. Chapter VI and Chapter VII include the complete case of related-diversification into geothermal energy for Unocal and Phillips Petroleum, respectively. Chapter VIII builds on the evidence provided by the case studies to analyze and test the validity of hypotheses presented in Chapter III, to reinforce the findings and improve the coherence of the theoretical propositions. Finally, Chapter IX consolidates the results of this thesis, extends the discussion of the legitimacy of results to a wider range of contexts (beyond the oil price crisis time frame and into other extractive industries) and proposes new topics for continuing research on this subject.

II. Theoretical framework

The first objective of this chapter is to explain how firms leverage their capabilities to enter a new business field, and to relate this to the definition of related diversification. The second aim is to introduce the concept of dynamic capabilities, one of the most influential approaches to explain a firm's strategic behavior. The third purpose of this chapter is to build a comprehensive system to explain the inherent factors and dynamic capabilities that influence the evolution of a firm's knowledge stock, and its implications for related diversification.

An introduction to related diversification

The traditional view of corporate diversification has explained entrance into a new business field as being based on the use of existing physical assets and tangible resources. This approach ignores intangible and internal resources, such as competencies or organizational routines, which are a source of uniqueness and competitive advantage (Chiesa & Manzini, 1997). This section presents a number of studies that emphasize the importance of these intangible resources in achieving business diversification (Døving & Gooderham, 2008).

The boundaries of corporate diversification can be framed based on two dimensions: the supply component, such as the internal competencies[5], assets or organizational routines available to the firm, and the demand component, represented by the external market (the products or services created from) for such resources. The chart in Figure 1 illustrates the different combinations that outline the boundaries of the firm, as a function of the competencies and the market it relies on (Penrose, 1996; Tidd, 2012). For example, if a company develops new competencies to sustain its current market position, this will result in market-related diversification (top left-hand side of the chart). To illustrate, consider the case of a conventional car manufacturing company that increases the boundary of its products and services by offering electric vehicles. The firm will be offering a new product to the same market, by developing new competencies. Instead, if a firm uses its existing skills (or similar competencies) to enter a new market (different product/service or

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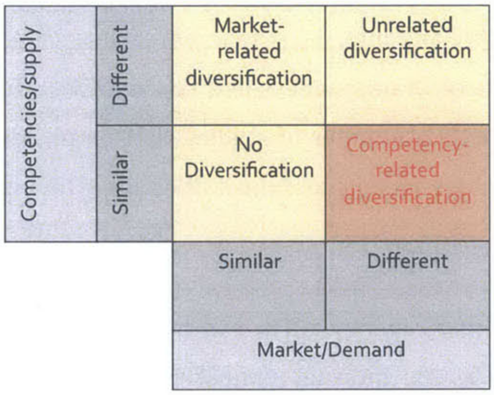
[5] Competencies are defined as the properties of the coordinating and learning routines of organizations (Dosi & Teece, 1998).

geography), it will be engaging in a competency-related diversification (bottom right-hand side). An example of such diversification is the same car manufacturing company using its capabilities in electronics and engine development to enter the aircraft market. We also have the scenario when the firm uses its existing competencies to enter a new market that is very similar to the one it has already mastered, with limited organizational implications to the firm, and thus no resultant diversification (bottom left-hand side). To represent this, think of the car company opening a new manufacturing plant in a neighboring country with similar market conditions, essentially replicating what it already does. Finally, we have the case when the diversification happens because of non-technological drivers like market power, brand, reputational assets, network of the firm, political power or entrepreneurship aspects of corporate management, which has been termed unrelated-diversification (top right-hand side) (Neffke & Henning, 2013; Tidd, 2012).

Figure 1: Two dimensions for business diversification (Tidd, 2012)



In discussing diversification, it is important to distinguish the concepts of **relatedness** and **basis of diversification**. The basis of diversification corresponds to the path chosen for driving the firm's diversification forward, which can, for example, be resource-based, technology-based (Tidd, 2012) or even based on the existing organizational routines within the firm (Pavitt, 1998). Figure 1 simplifies the basis of diversification on two dimensions: diversification driven by the market or the firm's competencies. Relatedness is the distance—on the basis of diversification chosen—between the core business and the diversification target. Relatedness is defined as the commonalities and connections among different businesses, like a common skill, resource, market or purpose (Døving & Gooderham, 2008). For example, the car manufacturer diversifying into aircraft manufacturing would have the knowledge the firm wants to leverage as the basis of diversification, while the relatedness would then be established by the overlap between both industries in terms of skills and disciplines. In contrast, the conventional car manufacturer diversifying into electric vehicles would select the passenger car industry as its basis of diversification, so the relatedness would be defined as the differences in attributes between the conventional-car demand and the electric-vehicle demand.

This thesis will emphasize and study related diversification, given that this type of diversification is recognized as a relevant source of value creation and performance growth (Miller, 2006; Teece, Pisano, & Shuen, 1997). Moreover, this thesis will focus on competency-related diversification (knowledge as the basis of diversification), given that firms are more likely to diversify into industries that have ties to the firms' core activities in terms of competency-relatedness (Neffke & Henning, 2013). Nevertheless, it should be recognized that companies concurrently integrate and leverage related and unrelated-resources for diversification, so there is seldom a pure competency-related diversification or a pure unrelated-diversification (Tidd, 2012). From now on, competency-relatedness will be termed "related diversification."

An introduction to dynamic capabilities

The dynamic capabilities view, one of the most recent and leading perspectives on corporate strategy (Teece et al., 1997), enables identification of the core underlying dynamics of diversification (Døving & Gooderham, 2008). In *From Knowledge Management to Strategic Competence,* Sussex professor Joe Tidd presents a consolidated definition for the term "resources": *"stocks of available factors that are owned, controlled, or accessed on a preferential basis by the firm"* (Tidd, 2012). Tidd also proposes a hierarchical structure for the resource base of the firm, classifying resources into increasing levels of sophistication or added value:

I. **"Having" resources**: These resources correspond to the assets of a firm that can be traded in a market so they are not exclusive to the firm and are not firm-specific. Some of these resources can be tangible (such as equipment, buildings, location or low-skilled workforce) or less tangible (like patents, databases or brand). "Having" resources are generally considered exogenous to the firm. If we use a cooking analogy, these would be the ingredients of a recipe (Lessard & Singh, 2014).

II. **"Doing" resources or operational capabilities**: These are skill-based intangible resources which do not have a specific market to be traded on, and that demonstrate the firm's potential for performing an activity *"on an on-going basis using more or less the same techniques on the same scale to support existing products for the same customer population"* (Stadler, Helfat, & Verona, 2013). Operational capabilities are similar to best practices that start in one or two companies and spread to the entire industry (Kleiner, 2013). Examples of these are product development, technology development or marketing. "Doing" resources or operational capabilities are generally considered endogenous to the firm. Continuing the cooking analogy, these operational capabilities are the skills needed to follow a cooking recipe. Core capabilities are the combination of some of these operational capabilities. If a firm places too much emphasis on exercising the core capabilities, it may become rigid and hinder innovation (Leonard-Barton 1993).

III. **"Dynamic Capabilities"**: The dynamic capabilities view states that a firm's competitive advantage lies in distinctive organizational processes, which are shaped by the firm's assets and the evolutionary path the firm has adopted or inherited; these capabilities are continuously and timely adapted to respond to changes in the market (Teece et al. 1997, Tidd 2012). A selected group of definitions of dynamic capabilities are consolidated in Table 1. Dynamic capabilities are what makes a firm distinct from others by sustaining competitive advantage based on a unique combination of resources (Dosi & Teece, 1998; Teece et al., 1997; Tidd, 2012). These are not meant to involve the production of goods or provide services; instead, their task is to continuously improve the execution of an activity by activating practices that continuously reconfigure existing operational capabilities, thus altering the scale and scope of resources of the firm in an effort to influence the firm's external ecosystem[6] (C. E. Helfat & Peteraf, 2003; Stadler et al., 2013; Zollo & Winter, 2002). As Berkeley professor David Teece points out, dynamic capabilities "allow an

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[6] There are several definitions and terms on the literature related with the concept of ecosystems (national systems of innovation, regional systems of innovations, clusters and ecosystems). All of these share the claim that firm-level innovation depends on the on the "the technological environment in which a firm innovates", which is determined by the supply of skilled workeers, universities, financial institutions , the legal system, the supply base, the domestic market and the presence of other firms in the same or related industries (Teece, 2010).

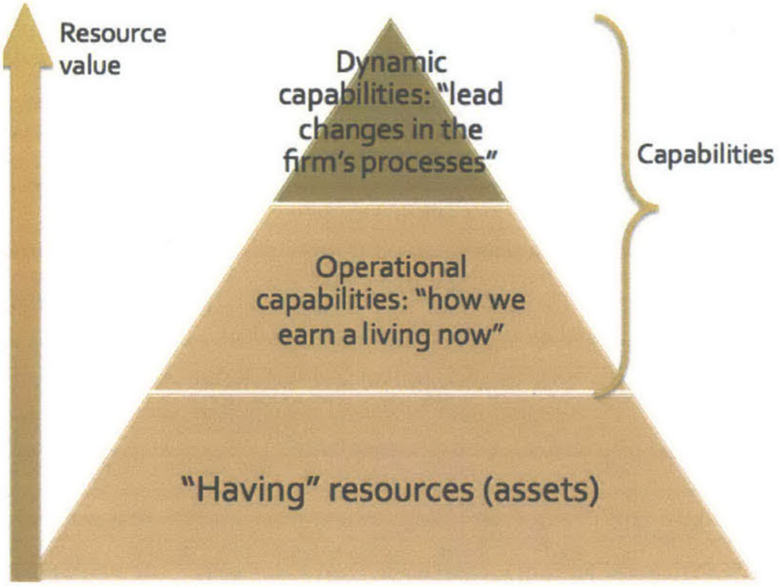
organization not only to do things right but also do the right things" (Shuen & Teece, 2014). Some examples of dynamic capabilities are creating and managing cross-functional R&D teams, quality control routines and technology transfer (Eisenhardt & Martin, 2000). Consistent with the cooking analogy, dynamic capabilities are the skills required to create new recipes.

Table 1: Selection of definitions on dynamic capabilities

Reference	Definition
(C. E. Helfat et al., 2007)	*"The capacity of an organization to purposefully create, extend, or modify its resource base"*
(Eisenhardt & Martin, 2000)	*"The organizational and strategic routines by which firms achieve new resource configurations as markets emerge, collide, split, evolve and die"*
(Teece et al., 1997)	*"The firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments"*
(Tidd, 2012)	*"Firm-specific and skill-based intangible resources that make the organization "continuously recognize, integrate, and leverage resources and connect them to the changing environment in order to create value"*
(Zollo & Winter, 2002)	*"A learned and stable pattern of collective activity through which the organization systematically generates and modifies its operating routines in pursuit of improved effectiveness"*

As can be seen in Figure 2, the concept of "dynamic capabilities" has the highest level of sophistication or resource value, followed by the "doing" resources, and then the "having" resources, which have the least value in the hierarchical structure. This hierarchy favors "dynamic capabilities," given that it enables a dynamic learning process (Teece et al., 1997) for creating new distinctive resources.

Figure 2 Hierarchical structure of the resources and capabilities of a firm (based on Tidd 2012)



The concept of dynamic capabilities is relatively new; therefore, there is limited consensus with respect to its definition or even its operational meaning. Still, this is the most appropriate approach to understand the role of resources as a driver of a firm's strategy (Teece, 2010; Tidd, 2012). To better understand the underlying rationale of dynamic capabilities and arrive at a more concrete definition, we need to refer to the operational terms that represent dynamic capabilities. Teece and other authors established these operational terms and termed them micro-foundations (Castiaux, 2012a; Eisenhardt & Martin, 2000; C. Helfat & Eisenhardt, 2004; Kleiner, 2013; Teece, 2007b). These are managerial activities classified into three main groups or classes: sensing, seizing, and transforming. The different types of micro-foundations and their nature are explained in Table 2. The column "Activities" provides examples of the operational terms of dynamic capabilities.

Table 2 Class, nature and micro-foundations of dynamic capabilities. Based on (Castiaux, 2012b; Teece, 2007a)

Class	Nature	Micro-foundations	Activities
Sensing	Explore, anticipate and create opportunities outside the boundaries of the firm	Cognitive and creative capacities of individuals.	Scanning and monitoring internal and external technological developments.
		R&D activity and networking.	Assessing existing or latent customer needs.
Seizing	Mobilize the firm's resources to capture value from those opportunities through new products and business models	Selecting product architectures and business models.	Determining technology and product architecture/ Designing revenue architectures/ Selecting target market/ Building mechanisms of value capture
		Selecting enterprise boundaries to manage complements and "control" platforms.	Analyzing: Appropriability regimes / Complementary assets/ Relative positioning/ Phase in industry development/ Assessing the systemic nature of products/services/ Evaluation of firm boundaries in this context
		Selecting decisions making protocols	Recognizing inflexion points and Complementarities. / Avoiding decision errors and anti-cannibalization fears/ Demonstrating leadership / Effectively communicating
		Building loyalty and commitment	Recognizing non-economic factors, values, and culture
Transforming	Adaptive and continuous renewal to respond to environmental changes and overcome constraints such as cognitive limitations and rigidities	Decentralizing	Adopting loosely coupled structures/ Embracing open innovation/ Developing integration and coordination skills
		Co-specializing	Managing strategic fit so that asset combinations are value enhancing
		Governance	Achieving incentive alignment/ Minimizing agency issues/ Checking strategic malfeasance
		Knowledge management	Blocking rent dissipation/ Learning/ Knowledge transfer/ Know-how integration/ Achieving know-how and IP protection

There are two microfoundations (or terms to represent the dynamic capabilities) from Table 2 that have been underlined. These represent three key dynamic capabilities that will be the focus of this research:

1. Shaping and capturing value from the ecosystem
2. Developing and exploiting internal scientific capabilities
3. Empowering decentralized units

The following section builds on the academic literature of strategy and management to propose these three dynamic capabilities as enablers for the diversification of oil firms into a related business field, and presents a systemic approach to explain how the firm becomes a dynamic repository of knowledge that can reach new markets.

A systemic approach to explain the evolution of related diversification.

The reader might ask what goes on inside a firm when it leverages existing capabilities and what are the drivers that shape the integration of capabilities and resources to engage into a new market. To answer this question, we need to analyze the system of interactions among resources and capabilities inside the firm (so we can unveil the path dependences) and the influences from external sources of knowledge. Figure 3 (at the end of this chapter) represents the causal loop diagram of this system that will be explained throughout the rest of this section. The purpose of Figure 3 is to sketch the interactions among the firm's resources that drive a related diversification and to show how the organizations become an integrator and repository of knowledge. Figure 3 consolidates different academic references and will not be used for modeling or forecasting. Therefore, it is a simplified version of the dynamic system, and as such does not include an accurate dimensioning of units.

Special attention has been given to the firm's dynamic capabilities and their influence on the system's underlying drivers for diversification (Døving & Gooderham, 2008). All of the different levels of resources and capabilities shown in Figure 2 are relevant technological resources for a competency-related diversification or, as we will call it from now on, a "related-diversification." Still, dynamic capabilities are the most relevant to sensing opportunities to leverage and "stretch" existing resources and competences into new pathways and integrate and reconfigure such assets and capabilities to create new knowledge. The dynamic capabilities framework claims that a related-diversification can be a viable choice for learning and improving in a new market (Teece et al., 1997; Tidd, 2012); it also claims that dynamic capabilities "determine the evolution of the intersectoral boundaries of the firm (scope of horizontal diversification and vertical integration)" (Dosi & Teece, 1998). Therefore, the stronger the dynamic capabilities of a company, the more prepared it will be for related diversification.

Taking advantage of a firm's relative strengths should pay off by increasing the scale of applicability for their knowledge base into different sectors (Chiesa & Manzini, 1997; de Oliveira & Roa Rubiano, 2011; Prahalad & Hamel, 1990). This notion has been called economies of scope. Economies of scope are present when the cost of producing different outputs (Y1 and Y2 below) together with common resources is less than the sum of the costs of producing each output separately (C. Helfat & Eisenhardt, 2004; Teece, 1980), as long as the resources are not fully used in current operations (Penrose, 1996). Equation 1 explains the rationale behind economies of scope.

Equation 1: Economies of scope for two products

$$C(Y_1, Y_2) < C(Y_1, 0) + C(0, Y_2)$$

where:

$C: Cost\ production\ function$

$Y_1: Output\ of\ product\ 1$

$Y_2: Output\ of\ product\ 2$

The economies of scope determine the relative importance of a particular type of relatedness during the development of a diversification strategy. This means that the closer a new product is to the previous business of a firm (relatedness), the less expensive it will be to enter this new business (better economies of scope) (Alonso-Borrego & Forcadell, 2010; Neffke & Henning, 2013). Economies of scope reflect the firm's relative position in terms of complementary assets and resources (Dosi & Teece, 1998). This feature of the system is represented by the link between "**economies of scope**" and "**decision to engage**

in related diversification" from Figure 3. That is, all else being equal, the higher the economies of scope, the more likely the firm is to engage in a related diversification.

Knowledge assets are generally tacit and context dependent, thus costly to transfer (Teece, 2010). In 1980, Teece first linked the concept of economies of scope and related diversification to identify the conditions in which the transfer of proprietary know-how tends to happen through firm diversification rather than through markets (Teece, 1980). These conditions are:

- When there are relevant transactional costs that hinder the allocation (or sale) of the knowledge resource to a third party. That is, business diversification should occur when the internal organizational costs are lower than the transactional costs of using the market to transfer this asset (C. Helfat & Eisenhardt, 2004).
- When there is no common use for the firm's underutilized assets.

Such conditions can be expected when there are few (or no) market actors that have the training, the organizational arrangements, or the absorptive capabilities to leverage the knowledge transferred. To illustrate this scenario, take the hypothetical example of a supplier for mining processes with strong electrochemistry capabilities, which owns several patents potentially applicable to develop new energy storage solutions (considered an immature energy technology) but finds neither the interest nor the experience on the part of external parties that could agree to buy the license for its inventions. Based on such conditions, the firm will tend to use its own organization to transfer such knowledge instead of relying on the market to commercialize these assets. Such transfer of knowledge from one business field to another will likely rely on the transfer of people within the organization, given that a large share of the intangible resources transferred can have a tacit nature[7]. Related-diversification is more likely to happen under highly specialized technologies that do not have a mature market. This relationship is illustrated by the links connecting "**Level of maturity**", "**Transactional costs**" and "**Decision to engage in related diversification**" from Figure 3. This means that, all else being equal, the lower the

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[7] A similar situation happens with tacit know-how that is difficult to trade and also difficult to develop as a competence when the firm lacks the proper organizational capabilities. Such difficulty in trading is what makes a resource 'sticky" (Teece et al., 1997).

level of maturity of a technology, the higher the transactional costs to market underutilized assets, and thus the more likely a firm is to engage in related diversification.

It is important to emphasize the influence of the external environment on the strategic decision of related diversification. The engagement of a firm into a new business field will be driven more by the opportunities (or threats) outside the firm's boundaries, than by the possible economies of scope (Dosi & Teece, 1998). This is represented by the link between the variable "**external opportunity/threat of environment**" and "**decision to engage in related diversification**". On this particular issue, Chapter IV explains that the sudden rise in the price of oil was the main driver of the diversification of oil and gas firms into new energy technologies during the 1970s.

A related-diversification into a new market pushes a firm to simultaneously pursue two effects: strengthen its capabilities and expand the breadth of its knowledge base[8] (Piscitello, 2004); hence, encouraging innovation becomes critically important[9] (Breschi, Lissoni, & Malerba, 2003). These two effects are described in the following paragraphs and represented by the two central reinforcing loops of Figure 3: "**economies of scope from activity**" and "**economies of scope from research.**"

The potential economies of scope (and thus the path of diversification) will be guided by the firm's existing knowledge base and oriented toward technological opportunities in the neighborhood of the firm's prior activity and research (Dosi & Teece, 1998; C. E. Helfat, 1994; Teece et al., 1997). Specifically, firms use the knowledge accumulated from previous diversifications as a basis for subsequent diversification (Penrose, 1996). Initially, firms are reluctant to move away from their current set of capabilities because of organization and R&D costs, and may prefer to follow a coherent pattern of transition into industries where they match a common or complementary asset or knowledge (Breschi et al., 2003; C. E.

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[8] This generates coherent synergies among a firm's technological resources and products, defined as the "level of interconnectedness" by Piscitello (Piscitello, 2004).

[9] Still, other authors have not found any direct causality between diversification and innovation. Rodriguez-Duharte et al., claims that, at least in the context of Spanish firms, the relation is the opposite: there is more evidence that innovation drives diversification (Rodríguez-Duarte et al., 2007).

Helfat, 1997; Neffke & Henning, 2013; Rodríguez-Duarte, Sandulli, Minguela-Rata, & López-Sánchez, 2007). Therefore, there is a path-dependence on the way firms diversify and also on their R&D activity (C. E. Helfat, 1994).

A firm undergoing a related diversification adapts and applies its internal resources in a related business field, especially thanks to "**seizing**" dynamic capabilities, which as explained in Table 2, will *"mobilize the firm's resources to capture value from new opportunities"*. Helfat and Peteraf introduced the concept of capability lifecycle to explain the evolution of a capability when it is transferred to a related market. Helfat and Peteraf suggest that the transfer of a capability into a related market implies an increase in the level of capability per unit of activity as a function of the cumulative amount of activity (C. E. Helfat & Peteraf, 2003)[10]. Therefore, and given that a firm decides to engage in a related diversification, the better its dynamic capabilities for "**seizing,**" the more it will incur in activities in a related market, and consequently the more it will strengthen its capabilities. This is represented in Figure 3 through the link between "**level of dynamic capability through seizing**", "**level of activity on related market**" and "**level of capability per unit of activity.**" Consequently, the more a firm leverages its capabilities to diversify into new markets, the further it will master these capabilities, and hence the more effective it will be at using these resources and preserving its economies of scope. This creates the reinforcing loop "**economies of scope from activity,**" which becomes incrementally more attractive for sustaining the firm's competitive advantage (Chiesa & Manzini, 1997), and is represented by the sequence linking "**decision to engage in related diversification**", "**level of activity in related market**", "**level of capability per unit of activity**", "**resource efficiency from learning**" and "**economies of scope**".

Similarly, the ability to develop and exploit internal scientific knowledge (internal R&D) is a relevant dynamic capability that will allow the firm to drive the diversification toward strengthening and expanding its current knowledge base. As pointed out by Alonso-Borrego and Forcadell (and confirmed by other empirical studies), *"the related diversification will tend to increase the expected return from R&D"* through the better capacity to use research

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[10] Helfat is an important contributor to this field of study, providing specific cases and empirical data from petroleum and gas firms.

outputs and the greater incentives to increase the expenditures of R&D (Alonso-Borrego & Forcadell, 2010; C. Helfat & Eisenhardt, 2004; Piscitello, 2004). This defines the first proposition of this thesis:

Proposition 1: The related-diversification of oil firms into geothermal technology development relies on developing and exploiting internal scientific capabilities.

The relationship stated by Alonso-Borrego and Forcadell is represented in Figure 3 by the linkage between the "**decision to engage in a related-diversification**" and "**R&D intensity**", and with the fundamental assistance of the firm's dynamic capability represented by the variable "**level of dynamic capabilities through seizing**". Thereafter, the more the firm increases its specificity of R&D — also referred to as "exploitative R&D" in (Mudambi & Swift, 2013) — the more it will increase the depth of its knowledge base. This causality creates the reinforcing loop "**economies of scope from research**"[11], which is built by the link between "**R&D intensity**", the "**level of capability per unit of activity**", "**resource efficiency from learning**" and "**economies of scope**", and represents the path dependence of learning inside the firm.

The reinforcing loop "**economies of scope from research**" illustrates the finding from Alonso-Borrego and Forcadell that *"an increase in related R&D may boost related diversification as long as it improves the capacity to exploit the available technological resources"* (Alonso-Borrego & Forcadell, 2010). This finding acknowledges a bidirectional relationship between related diversification and R&D expenditure. Helfat et al. also confirms the reasoning behind the reinforcing loop "**economies of scope from research**", by showing that oil and gas firms with larger complementary technological knowledge and complementary physical assets had larger expenditures on R&D for new energy technologies. In addition, Helfat also demonstrated that there is a relevant influence of path dependencies, by showing that oil firms that had higher annual R&D expenditures in diversified technological fields were likely the ones that had previously larger R&D

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[11] It is important to point out that several causalities within the system presented are not instantaneous; instead, their effects are distributed over time: "The effects of strategic decisions are not instantaneous" (Alonso-Borrego & Forcadell, 2010). These delays are represented as cuts over the arrows in the causal-loop diagram.

expenditures committed to that same field (C. E. Helfat, 1997). This confirms the view from Edith Penrose that firms use the knowledge accumulated from previous diversifications as a basis for subsequent diversification (Penrose, 1996).

Alternatively, if the firm spends more R&D on topics on the cutting edge — also referred to as "explorative R&D" (Mudambi & Swift, 2013) — it will be able to expand the breadth of its knowledge and therefore diversify its product scope (Døving & Gooderham, 2008). This is supported by the variable "**level of dynamic capabilities through sensing**" (helping the company create new R&D opportunities as defined in Table 2) and represented by the reinforcing loop "**economies of scope from expanding the knowledge base,**" which has the following the sequence: the more the firm invests in R&D, the more it will increase the breadth of its knowledge base, which therefore will increase the relatedness that the firm will experience with new business fields, which will consequently augment the economies of scope due to the diversity of possible diversification routes, stimulating further related diversification.

Figure 3 also shows that the intensity of R&D expenditures is constrained once the level of economies of scope achieved (and so of sales) surpasses a given threshold. This is the same as saying that the firm needs to allocate fewer resources (spend less on R&D) to maintain the same level of economies of scope, because it becomes more efficient at managing its knowledge and technological resources, which influences the decision to lower R&D expenditures (Alonso-Borrego & Forcadell, 2010). This is represented by the balancing loop "**marginal benefit from R&D expenditure on economies of scope**" that connects the following sequence of variables: the higher the "**economies of scope**", the lower the "**marginal impact from R&D on economies of scope**", which in turn reduces the "**R&D activity**", and lowers the "**level of capability per unit of activity**" and also lowers the "**resource efficiency from learning**", thus constraining the rate of growth of "**economies of scope**".

Helfat and Peteraf point out that leveraging an existing capability into a new market requires the additional adaptation of the capability in new directions and the combination with new capabilities (C. E. Helfat & Peteraf, 2003). This process is triggered by the influence of external sources of knowledge and also by the recombination of the firm's knowledge base through practices of knowledge transfer such as transfer of people within the organization. Both features can increase the firm's breadth of knowledge and therefore increase the economies of scope with the activation of two additional reinforcing loops: "**economies of scope from complementary knowledge**" and "**economies of scope from recombination of workforce**". These are represented at the lateral corners of the causal-loop diagram in Figure 3.

In particular, access to external sources of knowledge can be leveraged only if the firm has the absorptive capacity required to "*recognize the value of new, external information, assimilate it, and apply it to commercial ends*" (Cohen & Levinthal, 1990). Zahra and George have identified this absorptive capacity as a dynamic capability that influences the firm's ability to interact with the external knowledge and apply it. As seen in Figure 3 (the link between "**absorption of complementary knowledge from external sources**" to "**recombination of knowledge**" and to "**breadth of knowledge base**"), this source of knowledge can complement and expand the breadth of the firm's knowledge base (Zahra & George, 2002). This helps to frame the second proposition to answer the research question:

Proposition 2: The related-diversification of oil firms into geothermal technology development relies on the capability of shaping and capturing value from the industrial ecosystem.

Necessarily, the level of absorptive capacity (shaping and capture value from the industrial ecosystem) will depend on the firm's own research base. That means that an organization will not be able to interact properly with the external ecosystem and capture value from it unless there is a good stock of internal R&D capacity to absorb the value. This is represented by the link between "**R&D intensity**" and "**absorption of complementary knowledge**" in Figure 3.

Finally, it is important consider how the organizational processes used for knowledge specialization and development of diversified firms affect dynamic capabilities. Firm diversification will be the outcome of product discontinuities that happen because of a learning process under different types of organizational arrangements. Organizational learning has been identified as a source of dynamic capabilities that help the firm gain experience from prior projects and integrate external knowledge (Dosi & Teece, 1998; Zollo & Winter, 2002). Helfat and Eisenhardt studied the effect of different organizational arrangements on firm diversification and concluded that decentralized structures can provide the best conditions for related diversification (C. Helfat & Eisenhardt, 2004). This means that an M-form[12] can be a suitable arrangement for related-diversification since managers can quickly match organizational units with new business opportunities (and exercise the firm's dynamic capabilities more easily). This finding was also supported by Teece, who indicated that decentralized structures help a firm achieve reconfiguration and leverage capabilities through economies of scope (Teece, 2007b). Subsidiaries have greater autonomy to exercise their dynamic capabilities and thus adapt their organizational routines to spur collaboration with external organizations as a way to extend the firm's competencies (Døving & Gooderham, 2008). The third proposition then becomes:

Proposition 3: The related-diversification of oil firms into geothermal technology development relies on empowering a decentralized organizational structure.

This proposition is represented in the diagram in Figure 3 by the "**level of dynamic capability through transforming**" that is directly connected with the variable **level of autonomy of the subsidiary**. The higher the dynamic capability for transforming, the more autonomous the company will be to execute actions to reconfigure internal knowledge (by transferring workforce) and to engage in collaborative efforts with external parties[13].

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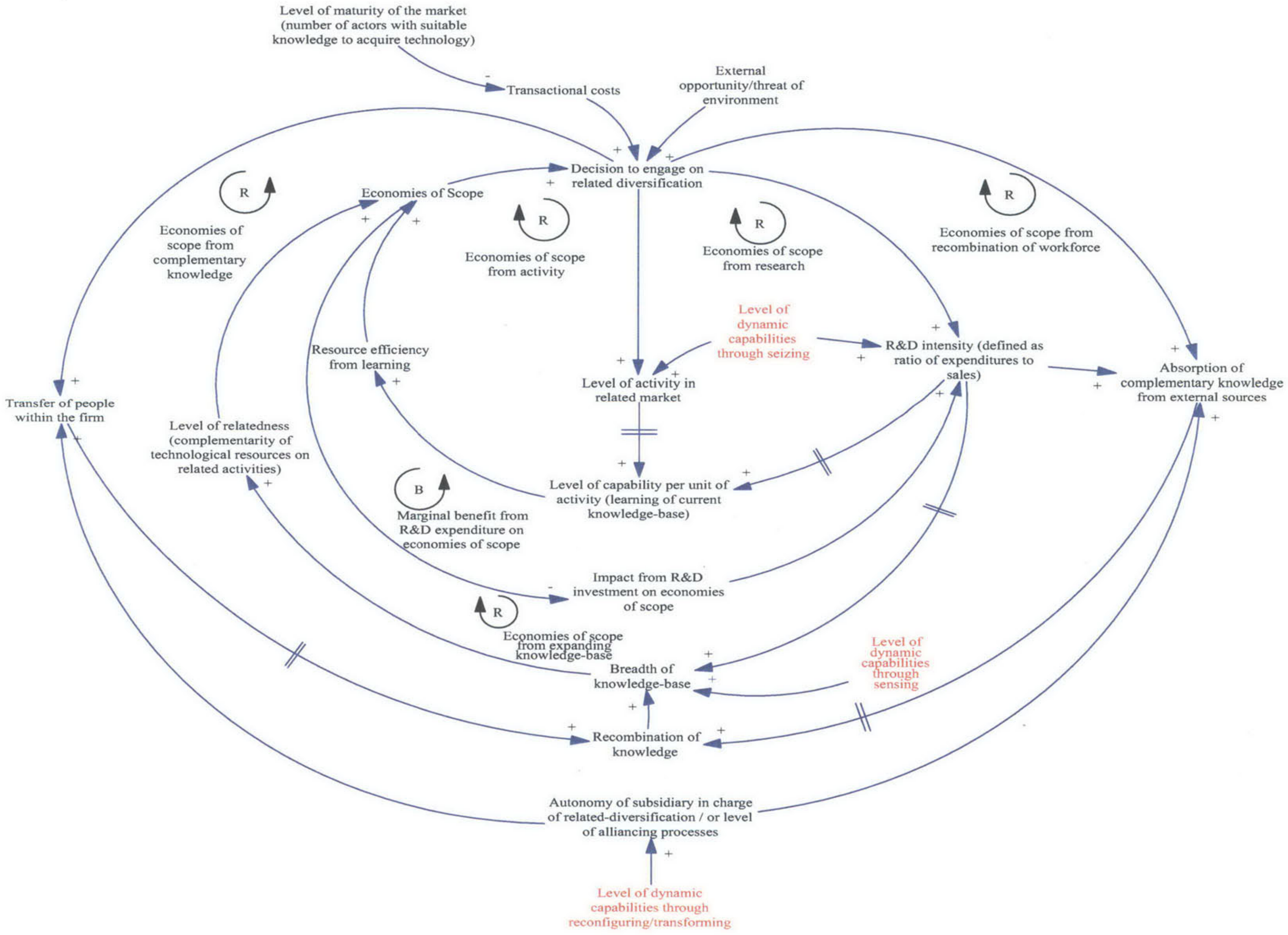
[12] The M-form is a Multidivisional structure that relievs top management of foreseeing the operational details and represents a shift from the functionally organization (U-Form) (Teece, 2010). The M-form organization is defined by a general control from central management, but its operational and even strategic decisions are in the hands of the divisions of the corporation.

[13] Previously, and conflicting with this vision, Hill et al. argued that a decentralized structure rewards individual performance of a division but it is not appropriate for economies of scope across divisions. Hill et al. propose four organizational characteristics that enable a proper related diversification: the coordination of divisions through integrating mechanisms, centralized control over strategic decisions of the divisions, non-financial criteria to evaluate divisional performance, and incentives tied to corporate profitability (Hill, Hitt, & Hoskisson, 1992).

Summarizing, the three dynamic capabilities acknowledged as enablers for a related diversification, and that will be tested throughout the case study analyses, are:

- Shaping and capturing value from the ecosystem (represented by "**absorption of complementary knowledge from external sources**")
- Developing and exploiting internal scientific capabilities (represented by "**R&D intensity**")
- Empowering decentralized units (represented by "**autonomy of subsidiary in charge of related diversification**")

Figure 3: System of interactions on the related diversification of a firm



III. Methodology

This chapter describes the methodology chosen to answer how did oil firms diversify into geothermal energy from the perspective of their capabilities.

Objectives of the research

The main research question proposed is to learn how do oil industries leverage their internal capabilities in order to enter the geothermal energy industry. This aspiration is broken into three specific objectives:

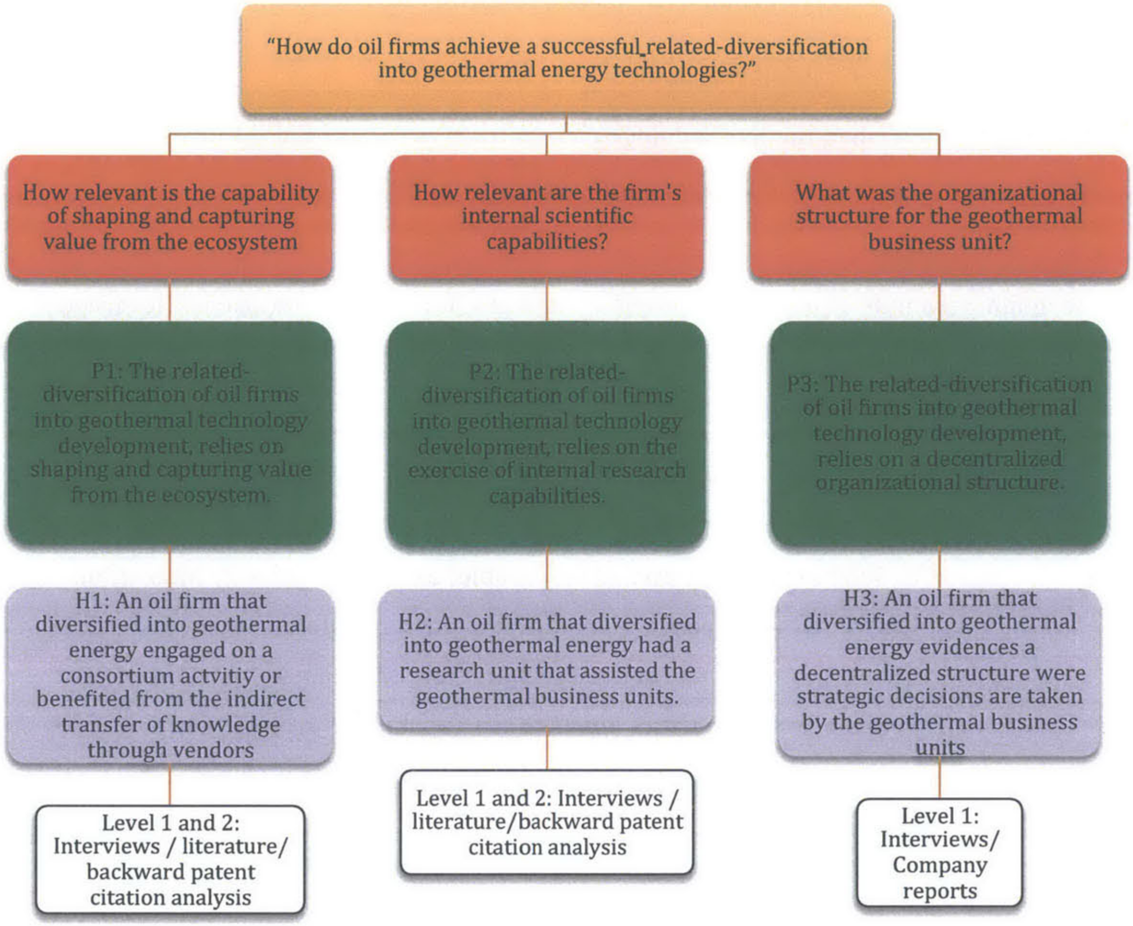
a. Unveil the knowledge relations between upstream oil operations and geothermal energy technologies, and provide insights about the capabilities of upstream oil that enable (or disable) low-carbon energy innovation.
b. Learn which main organizational arrangements make possible the diversification of extractive firms into low-carbon energy technologies.
c. Provide policy insights about those capabilities from extractive industries that can become an enabler or a barrier for low-carbon energy innovation.

Propositions and hypotheses

In Chapter II of this thesis I have explained what are the different drivers that nurture the diversification of a firm, emphasizing the role of three dynamic capabilities as enablers of this process. This thesis methodology benefits from the prior establishment of theoretical propositions to guide data collection. As represented by

Figure 4, each of the dynamic capabilities is tested through three sub-questions (in red) that frame the **propositions** (in green) and **hypotheses** (in purple) of this work. The boxes in white represent the source of **evidence** to test these hypotheses and validate the propositions. Two levels of analysis characterize the sources of evidence, which is explained below.

Figure 4: Research sub-questions, propositions, hypotheses and evidence.



Case study as research instrument

The hypotheses presented need a broad set of variables as evidence. Besides, the form of the research question asks for the "how" and is focused on factors that are relevant to contemporary strategies. Therefore, the case study methodology is recognized as the most suitable research instrument, using a deductive approach given that the hypotheses rely on a previous set of theoretical propositions (Yin, 2008).

This thesis employs a multiple-case design with embedded units of analysis of two different oil and gas firms that transitioned into geothermal development[14]. These are two well-matched cases, where the circumstantial similarities can help to highlight differences and test the replicability and reliability of the propositions (Yin, 2009). The cases chosen are those of Union Oil Company of California (Unocal) and Phillips Petroleum (Phillips), which share the following characteristics:

- Both firms started their geothermal business operations during the late 1960s to early 1970s (encompassing the period of the peak oil price crisis).
- Both had licenses to operate a geothermal field, drilled production geothermal wells, and invested on research and development in the area of geothermal energy technologies.
- Both were assigned with patents related with geothermal energy production.
- Both became suppliers of steam for power generation, and circumstantially both also became independent power producers (IPP) in charge of operating the power cycle and selling power to a local utility.
- The two firms had access to the same market characteristics, in terms of revenues and available knowledge from the ecosystem (in particular from government-sponsored research available to promote this technology). This stock of activity from the industry is described on Chapter IV.

Units of analysis

The study of the Unocal and Phillips cases relies on the following levels of analysis:

- Level 1: Each firm's history on geothermal development.
- Level 2: The sources of knowledge and transfer mechanisms required to overcome the technical challenges that each firm's geothermal business units confronted.

Both levels of analysis in each of the two companies provide a comparative basis to confirm the stated propositions and hypotheses (Yin, 2009).

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[14] Given the number of oil firms that engaged on the geothermal development during the peak oil price period, this type of case study is believed as appropriate to make comparisons among different contexts, in order to test propositions and hypotheses (Yin, 2009).

Level 1: Each firm's history on geothermal development.

This first level of analysis corresponds to a comprehensive description of Unocal and Phillips' geothermal activities, including:

1. The development of the firm's knowledge base between 1965 and 2000, built on each firm's transition through different path for business diversification.
2. The main milestones for each firm's geothermal business units and the fields it operated in terms of installed capacity.
3. The path dependency from the firm's diversification, which is explained by the interaction between exogenous factors (such as the price of oil and the government's R&D expenditures) and endogenous factors (like the number of geothermal wells[15], the R&D expenditures on geothermal energy, the number of patents related with geothermal technology[16] and the firm's revenues from geothermal operation)[17].
4. The organizational arrangements around the geothermal business units and the profile of its leadership (centralized or decentralized).
5. A general description of the internal research capabilities and its support for the geothermal business units.

This level of analysis will unveil if the diversification of these oil firms into geothermal depended on a decentralized organization or not (Proposition 3), and it will also provide additional information to study the drivers for diversification.

Level 2: Sources of knowledge and transfer mechanisms required to overcome technical challenges.

This second level aims to describe the sources of knowledge and the knowledge transfer mechanisms required to overcome the technical challenges involved in the diversification

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[15] The variable of geothermal wells represents the level of activity in the related business field (geothermal). The information on number and types of geothermal wells per company is not easily available for each State. This makes it harder to use the number of geothermal wells as a proxy for geothermal activity. For the Unocal case the information is readily available from the firm's annual reports, but for the Phillips case the information had poor quality and was not possible to consolidate it from the several States were the company had operations.

[16] The variable of number of geothermal-related patents represents the level of capability in the related business field (geothermal).

[17] The path dependency analysis is not core to the original propositions, yet this work includes the analysis of such interactions with the purpose of providing more information on the relevant capabilities and resources of each firm's diversification into geothermal energy technology.

from oil to geothermal development. This level encompasses as units of analysis a representative collection of technical challenges[18] from some of the geothermal fields that each firm operated.

Chapter V of this thesis describes the main technical challenges in the value chain of geothermal development, with an emphasis on those activities that go beyond those involved in upstream oil operations. Each of the technical hurdles identified by this chapter frame the units that populate this second level of analysis. Information is collected within this classification in order to construct a perspective of the dominant sources of knowledge and the transfer mechanisms. The purpose is not to document the knowledge transfer of each class of technical challenge (for which there is not enough evidence), but instead to let the available evidence highlight the trends in the diversification of the two companies studied.

Figure 5 provides a schematic representation of the knowledge sources and the transfer mechanisms for a generic technical challenge. The large squares in orange represent the boundaries of the different knowledge sources available: the geothermal division's internal capabilities, the assistance from the firm's in-house R&D group, and the support from the ecosystem beyond the firm's boundaries (including other operators, vendors or government-sponsored research projects that could be implemented by National Labs). If a technical challenge was solved through knowledge originated from the Geothermal Division, this means that it leveraged skills that are inherited from the upstream oil operations. The smaller white squares define the different transfer mechanisms to access the sources of knowledge. Such classification is derived from the correspondences between the geothermal business units studied.

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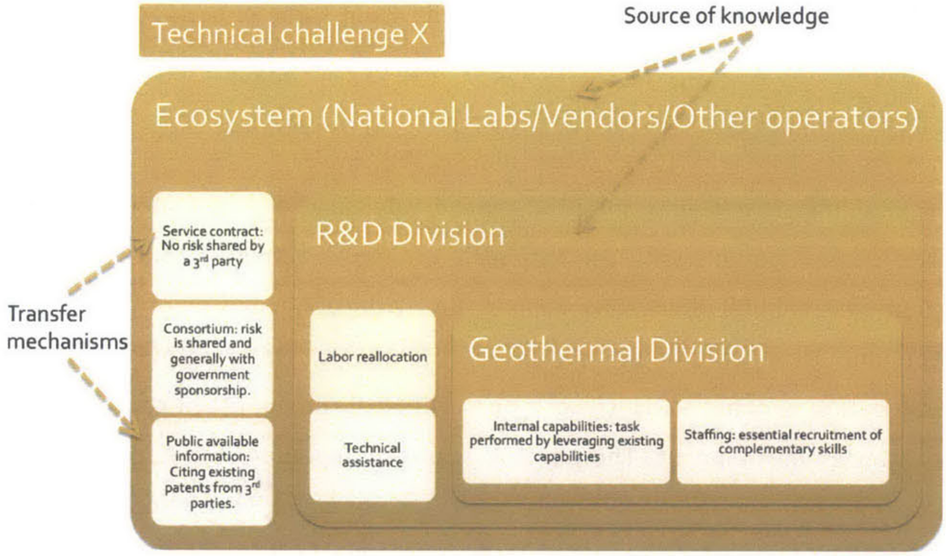
[18] The technical challenges classified as units of analysis for Level 2 are: Exploration, reservoir modeling & engineering (including reinjection), drilling and wellbore completion (including abrasive hard rock, loss of well control, lost circulation, corrosion, scaling and high temperatures), steam gathering system and steam cycle, and the business model.

Figure 5: Sources of knowledge and transfer mechanisms for each technical challenge



The source of knowledge and the transfer mechanism portray what are the necessary resources that go beyond the operational capabilities. Thus this becomes a suitable way to compare the relative importance of the dynamic capabilities of this research's propositions.

A total number of 28 units of analysis, with their respective sources of knowledge and transfer mechanisms, are collected for the Unocal and the Phillips case. Finally, all the information is consolidated under one graphical representation in Chapter VIII, so as to construct general statements about the dominant source of knowledge and the level of self-sufficiency that each business unit had[19]. For example, the more a geothermal division had to rely on sources of knowledge external to the firm, the more it would have exercised its dynamic capability of **shaping and capturing** value from the ecosystem (Proposition 1). The same applies to the knowledge transferred from the firm's R&D unit, which can denote the dynamic capability of **developing and exploiting internal scientific capabilities** (Proposition 2).

Reliability of this research is guaranteed by constructing the evidence based on a diverse group of interviewees (that provided a fair perspective of the knowledge transfer examples), a varied set of information sources (scientific reports, interviews, backward

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[19] Although there was no intention to build a representative statistical sample from such units of analysis, these still provide useful insights to answer the question of "how do oil firms diversify into geothermal energy".

patent citation analysis) and based on two distinct cases of diversification from oil to geothermal. Representativeness can only be claimed to cases of successful diversification from oil to geothermal, since none of the firm's studied failed in the operation of a geothermal field.

Sources of information

Data gathered to build these levels of analysis for the case studies include in-depth interviews, annual reports to shareholders, company history, public reports on geothermal R&D activities[20], number of geothermal wells, and records of patent applications (including their backward linkages).

Interviews

Each in-depth interview included a pre-determined list of questions structured as an interview protocol that served as a basis to interact with more specific inquiries, in line with the interviewee's background. Thus, the interview protocol was not a rigid questionnaire but a flexible guidance so as to understand the viewpoint of the interviewee. The list of the interviewees includes the managers, geologists and engineers that worked for the geothermal business units of these two companies, complemented by academic and industry authorities in geothermal development. The interview protocol and the list of interviewees are included under Appendix II. These interviews were recorded and analyzed, so the major statements could be ordered in consistency with the classification of technical challenges identified by Chapter V. The complete list of topics by which the statements from the interviews were ordered can be found in Appendix II.

Backward patent tracing

The patent citation analysis for each case is based on the backward linkages for the classification codes that represent each firm's geothermal-related patent applications. The main source of information comes from the National Bureau of Economic Research (NBER)

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[20] Some of these are publications from the Society of Petroleum Engineers, the DOE's Geothermal Technology Program, the Geothermal Resource Council, The U.S. Office of Scientific and Technical Information (including its portal "The Science Accelerator") and "One Petro" (database for the oil and gas industry).

U.S. Patent Citations Data File, prepared to consolidate all U.S. patents granted between 1963 and 1999 and including all the citations between 1975 and 1999 (Hall, Jaffe, & Trajtenberg, 2001).

None of the patent records provides a validated list of classification codes to identify geothermal energy (or any sort of technology use), mainly because geothermal technologies benefit from a diverse set of influences and disciplines. In order to represent each organization's patent track record on geothermal energy technologies, the following procedure has been done[21]:

a. Keyword search in Espacenet[22] using the name of the organization as the assignee and the keyword "geothermal" to find patents under the title or the abstract.
b. Export all the patents that result from this search and list all of their respective IPC (International Patent Classification) codes.
c. From this list of codes, identify the 15% most recurrent codes and collect them under group of families of IPC codes (2 letters-2numbers)[23].
d. Finally, from all of the organizations' patent stock for the period in analysis (1970-1990), narrow the search to only the IPC family codes under consideration. Appendix III sets the connection between the IPC codes and the classification of technical challenges identified by Chapter V.

Once we have the stock of patents related to geothermal energy for a firm, we can search for the main contributors based on the top 5% of linkages that can be counted through backward patent tracing (for each classification code selected by the above procedure). In addition, the backward patent citation analysis quantifies the number of direct linkages to

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[21] This procedure is different to the approach used in other reports (Kacham, Vemula, Uppala, Achanta, & Turaga, 2012; Ruegg & Thomas, 2011; World Intellectual Property Organization, 2014), in that it focuses on tracing the backward connections of geothermal related patents instead of imposing one predetermined classification of what is understood as geothermal.

[22] European patent office search engine, available at: http://worldwide.espacenet.com/advancedSearch?locale=en_EP

[23] Only two classification codes (G01N and G01V) where added to the particular patent selection for Unocal, just to represent the patents related to instrumentation and measurement technology

DOE-sponsored patents[24]. Yet it is important to note, that the government-sponsored patents could be influencing new patent applications through second-generation citations.

Some methodological considerations

Several studies have used patents as indicators of technology creation and used patent citation analysis as indicative of technology diffusion (Ruegg & Thomas, 2011). Some of these previous studies rely exclusively on the use of patents and the breadth of patent classifications as a measure to characterize the knowledge base of a firm (Breschi et al., 2003). Other studies have used patents and their classification codes as a guide to recognize the core competency of the firm (Lai & Wu, 2005; Wu, Chen, & Lee, 2010). Unfortunately, none of these approaches can neither effectively discern the nature of geothermal-related patents (since their outcome consists of aggregated results), nor consider the fact that some geothermal technology innovations are not patented or are unlikely to be patented at all. The latter occurs when the innovation is less tangible (the case of reservoir engineering, exploration procedures or business models for geothermal) or when there is a reluctance to seek patent protection (Mudambi & Swift, 2013; Piscitello, 2000). Patents could also be written to veil the involvement of the field operator in a geothermal innovation in order to avoid leakage. Even though the oil company can drive the development of a technology and test it, the patent can be held by a vendor contracted for this purpose or a research lab working as a consortium (Kitz, 2013). In addition, a backward citation analysis based on only a first generation of linkages (direct citing) cannot faithfully represent the real originators of an influential technical solution, unless second generation linkages are included. Finally, the patent citation analysis does not easily discern the share of knowledge that originated from the R&D groups, since the patent database would require a metadata with the names of the authors (which was not available from USPTO database) (Hall et al., 2001).

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[24] The total list of government-sponsored patents related with geothermal energy comes from the study "Linkages from DOE's Geothermal R&D to Commercial Power Generation" (Ruegg & Thomas, 2011).

Based on the considerations stated above, the present thesis uses backward patent citation analysis only to complement the information provided by interviews and the literature review.

IV. Historical context of the case studies and government support

The purpose of this chapter is to describe in very general terms the relevant conditions in period in which the two oil firms that we study (and others) diversified into the development of geothermal projects. This context is useful to first understand what incentives the oil firms had to engage into this new business arena, and second, to identify the conditions and resources were readily available to help these oil companies overcome some of the technical challenges they encountered in the geothermal business field.

The oil price crisis and the development of alternative energy technologies

In 1973, Arab oil producers (Organization of the Petroleum Exporting Countries - OPEC) imposed an embargo to oil imports as a response to the United States' support for Israel in the Yom Kippur war. U.S. Crude Oil prices jumped from 3.89 US$/barrel in 1973 to 6.87 US$/barrel in 1974, and the forecast of oil prices was for continued increases. This event is commonly referred to as the "oil price shock", and it stressed the need to reduce oil imports and add new generating capacity from alternative energy sources. The other important oil price shock happened in 1979, at the beginning of the Iranian revolution, when production from this country was curtailed and exports suspended. This raised the prices even more, from 12.64 US$/barrel in 1979, 21.59 US$/barrel in 1980 to a peak of 31.77 US$/barrel in 1981 (Energy Information Agency, 2013; Smil, 2003).

With high oil prices, alternative energy technologies become more cost competitive. This new scenario encouraged oil firms to increase their expenditures on applied research[25] and commercial alternative energy projects, thus expanding the business opportunities for oil companies through the creation of subsidiaries. Yet, these companies already possessed an extended breadth of knowledge as a result of their diversified set of operations in the

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[25] As documented by Helfat, the increase of R&D expenditures on alternative and conventional energy sources was focused during the period between the mid 1970s and the early 1980s. The classification of such energy technologies includes examples of related and unrelated diversification: oil and gas recovery, refinery, coal gasification/liquefaction, coal, nuclear, oil shale, tar sands, geothermal and solar (C. E. Helfat, 1994). The drop in the price of oil during the mid 1980s signaled the end of this period of technology rise.

upstream, middle and downstream activities. It is important to emphasize that the main incentive for an oil firm to invest in alternative energy technologies had more to do with exogenous factors such as the oil price than the potential economies of scope from the internal capabilities.

One of such areas of alternative energy investment was geothermal, where Unocal was the first mover with the positive experience of the Geysers field. This success inspired more oil companies to enter the geothermal industry and pursue the innovation efforts required to the cost reduction required to make geothermal energy competitive. By 1980 the geothermal industry was largely dominated by oil companies who were transferring tools and techniques (more-or-less adapted) from the upstream operations. Some of these oil firms were: SunOil, Sunbelt, Anadarko, Arco, Chevron, Unocal, Shell, Phillips Petroleum, Aminoil, McCulloch Oil Corporation of California, Occidental Petroleum and Sunoco (W. R. Benoit, 2014; Department of Energy, 2010a; Suter, 1980). During the 1980s, and especially after 1985, the price of oil collapsed (from 24.09 US$/barrel in 1985 to 12.51 US$/barrel in 1986), decreasing the attractiveness of technological alternatives to oil (Energy Information Agency, 2013). This caused several geothermal operators leave the industry, and consequently, decreased the activity of many service companies.

Worldwide Status of geothermal resource development in the early 1970s

Stanford Professor Paul Kruger acknowledges that although the birth of geothermal development started with the Larderello project in 1913, the era of commercial deployment and technological innovation in geothermal energy started during the early 1970s, and was only possible thanks to global economic conditions, a better understanding of the technology and an increasing energy demand (Kruger & Otte, 1973).

Before the first oil price crisis, the technology to explore and operate a geothermal field had not reached a level of technological maturity. The technology had not been deployed extensively and few fields were in active operation and providing steam for electricity purposes. Some of the few projects in operation were located in Japan (1966), USA (1960), Italy (1916), New Zealand (1958), the USSR (1966), and Mexico (1973). With the exception of Japan and Italy, they all had been developed by the local governments (Bertani, 2012; Kruger & Otte, 1973). Hence, there were not enough parties with general capabilities in the geothermal domain to acquire licenses and exercise proper drilling for geothermal energy development. Furthermore, any transaction to transfer these capabilities from an oil firm to an external buyer would have encountered relevant transactional costs that would hinder the development of geothermal technologies[26]. Therefore, some oil firms preferred taking this opportunity by their own rather entrusting it to a third party. This was under the assumption that they could effortlessly leverage their upstream capabilities to enter the geothermal business (Barnes, 2013; W. R. Benoit, 2014). The following thesis shows that these operational capabilities were not enough to diversify, but that firms needed to develop and exercise dynamic capabilities as well.

Figure 6 shows the historical growth of installed capacity from geothermal energy. By 1970 there were only 720 MW of worldwide installed capacity, but the rate of growth was duplicated every 5 years till 1985. Before 1980 the growth was driven mainly by projects in the U.S., whereas after 1990 no new projects seem to have emerged in the U.S (Bertani, 2012).

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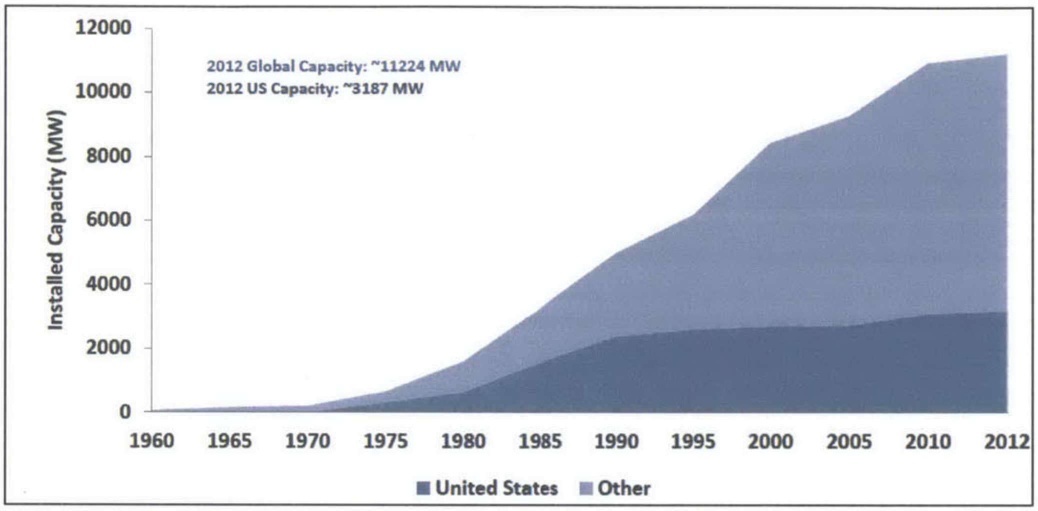
[26] That means, there would be large gaps of tacit knowledge required that few other actors would have, and also very few interested parties since the economic value of this business field was still unknown to many possible agents.

Figure 6: Global context of U.S. Geothermal Installed Capacity 1960-2012 (Geothermal Energy Association, 2012)



Early public investments in geothermal technology and regulation for private development

Another factor that drove the development of geothermal energy was the supporting role of the government, in particular the U.S. government, through a clear regulatory framework to license the geothermal resources and encourage the contribution of private companies, and through the active sponsorship of applied R&D and pilots. Such government effort enabled the development of an industrial ecosystem around geothermal energy, encompassing universities with new academic programs and research centers, vendors offering new technologies, the national labs providing critical expertise for this energy source and the operator companies that own the license to extract the heat.

The Geothermal Steam Act of 1970 and the California Geothermal Resources Act of 1967 enabled the licensing of geothermal resources on lands managed by Federal agencies, for the exploration and operation by private organizations. Some of these (like Unocal and Phillips Petroleum that are described in the case studies) provided active feedback for the U.S. Department of the Interior (DOI), in charge of enacting the rules and regulations for the leasing of geothermal resources. In 1980 President Carter signs the Energy Security Act, which consisted of several acts for the support of new energy technologies that could minimize the reliance on foreign imports of fossil fuels. This included the Geothermal

Energy Act, which allowed the provision of loans for geothermal development (Department of Energy, 2014).

DOE's activities on geothermal energy technologies were hosted under the Geothermal Technologies Program (GTP). In addition to the Geothermal Steam Act, the DOE enacted six categories of policies to support geothermal energy technologies (Doris, Kreycik, & Young, 2009; Lund & Bloomquist, 2012):

1. Investment in research, development and demonstration (RD&D) –described below.
2. Mandating utilities to purchase renewable power at avoided costs through the Public Utilities Regulatory Policies Act (PURPA) –described below.
3. Geothermal Loan Guarantee Program (GLGP): This was a policy instrument available between 1978 and 1982, which allocated $139.6 million in loan guarantees, so that banks would be more open to finance these new endeavors. In 1982, the program was concluded due to lack of evidence of its effectiveness relative to the influence of PURPA (Doris et al., 2009).
4. Investment tax credits (ITCs): This was a policy instrument available between 1978 and 1986, which gave a 10% investment tax credit available to geothermal developers. In general, the ITC has not been considered a major driver for geothermal energy development relative to other market pull instruments like the PURPA, or tech-push instruments like the RD&D programs (Doris et al., 2009).
5. The Program Opportunity Notice (PON) initiated in 1979, which provided incentives for exploration and resource definition of lower-temperature systems suitable for direct use (National Research Council, 1987).
6. The User Coupled Confirmation Drilling Program (UCDP) initiated in 1980, which absorbed a portion of the risk for the confirmation of hydrothermal resources, by sharing 20% of the cost for a successful well and 90% for an unsuccessful well. Thanks to this program, several exploratory wells throughout northern Nevada and southwestern Utah were drilled with partial government funding, and a data based of public information was made available that described the characteristics of these different reservoirs. Research institutions

could now use part of this information to develop new tools for geothermal assessment and exploration (W. Benoit & Butler, 1983; Doris et al., 2009; Fiore, 1980; National Research Council, 1987).

The first of these categories is meant to create new knowledge to solve some of the technical challenges of geothermal fields and reduce its costs in order to make geothermal a competitive technology (generally referred as a technology-push policy). The other five categories correspond to policies for market expansion and deployment (generally referred as market-pull policies). I will focus on the investment in RD&D and PURPA, since these are considered to be the most effective policy instruments for the development of geothermal energy technologies in the U.S.

Investment in research, development and demonstration (RD&D)

Economic regulation was not enough to enable the growth of this industry. Therefore, in 1971 the U.S. Congress approved a legislative mandate for the creation of the federal geothermal R&D program. After several institutional shifts[27], this program was hosted at the Department of Energy. From 1977 through 1981, DOE would use most of the geothermal budget for a commercialization program to promote the use of geothermal energy. After 1981, policy emphasis shifted away from commercialization back to research and development, and budgets were reduced greatly. The argument was that there was already a regulatory framework to support new energy technologies through the National Energy Act of 1978 (Department of Energy, 2014; National Research Council, 1987; U.S. Congress, 1974).

Figure 6 details the historical R&D budget of the GTP, including a measure of the installed capacity of geothermal projects and the timing of complementary market pull policies. It can be seen that the budget for the GTP reached a peak in 1979 and plunged after 1980. The public investment in geothermal R&D has empirically proved to enhance an increased

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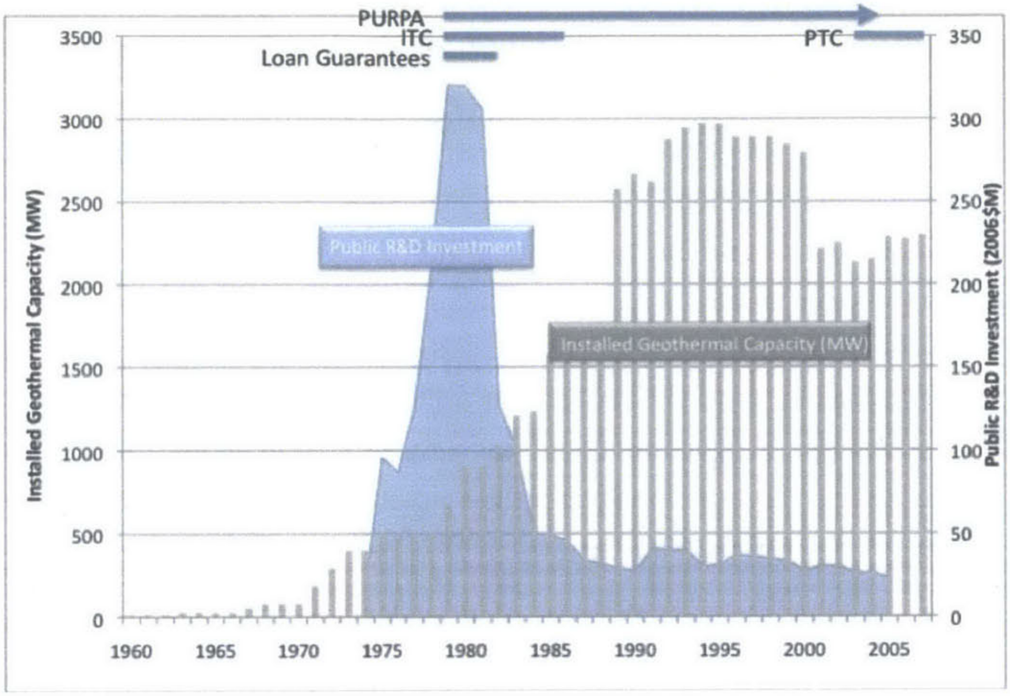
[27] The federal geothermal R&D program was initially implemented by conceding broad authority to the Atomic Energy Commission, so as to conduct research on all types of energy resources, and in close coordination with the National Science Foundation (NSF) that identified geothermal as a national priority. Later in 1974, Congress passed the Geothermal Research, Development and Demonstration Act, and so transferred most of the public funding for geothermal research to the Energy Research and Development Administration (ERDA), which in 1977 became the Department of Energy (DOE).

volume of geothermal-related patent applications, which is a proxy of private-sector investment in technology development (Doris et al., 2009).

Figure 7: Public R&D investments and installed capacity for geothermal energy technologies (Doris et al., 2009)



It is visible from Figure 6 that the combined effect of the public R&D investment plus the regulatory conditions of PURPA between the mid-1970s and the mid-1980s, created the suitable conditions for the escalated adoption of geothermal energy (in terms of installed capacity). This figure also shows the lack of a stable funding for geothermal research and development.

Some of the most successful R&D activities of the GTP to the development of the geothermal industry were:

- Test facilities at water dominated fields: In the early days of the GTP none of the commercial geothermal projects relied on a liquid-dominated field, since these had a higher degree of risk and a relative immaturity. To support the development of such class of geothermal field[28], DOE developed test facilities in California at the Salton

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[28] In 1975 the U.S. Geological Survey (USGS) confirmed that 90% of the geothermal resources of the United States are water dominated (McLarty & J. Reed, 1992).

Sea, East Mesa, Heber (involving Chevron and Unocal), in New Mexico at Baca (involving Unocal), in Idaho at Raft River; and later in Texas at Pleasant Bayou.

- The "Geothermal Logging Instrumentation Development (GLID)" program: created by the second half of the 1970s decade and conducted by Sandia Laboratories, with the purpose of upgrading and improving existing logging tools so they could perform under high temperatures (Veneruso, Polito, & Heckman, 1978).
- The "Geothermal Reservoir Well Stimulation Program (GRWSP)" program: Created in 1979, in recognition of the potential benefits of developing a successful geothermal well stimulation capability.
- The "Geothermal Drilling Organization" (GDO): Created in 1982s as a cost-sharing plan between the government and 23 industrial members geothermal operators and vendors. The GDO was managed by the Sandia National Lab with the purpose of improving and reducing the costs of drilling and exploration[29] (Atkinson, 2013; Henneberger, 2013; S. Pye, 2013; Sandia National Laboratories, 1989, 1998). This was a very meaningful program for the industry, as stated by Jerry Hamblin from Unocal's Geothermal Division:

  > *"There were no research projects that did not have direct application to reducing the cost of geothermal drilling"* (U.S. Department of Energy, 1992).

- The Geothermal-Loop Experimental Facility (GLEF): This is an example of a consortium that gathered the government and industry into a geothermal research facility, including as members the San Diego Gas and Electric Co. (SDG&E) and Magma Power Co. The deployment of geothermal technology in water-dominated reservoirs was delayed given the difficulty in handling high-salinity brines (which at the Salton Sea had over 20% salt by weight). The GLEF was built in 1976 to with the intention to manage the saline brine from the Salton Sea area and prevent scaling to occur. The outcome from the GLEF was a technology called the crystallizer-clarifier, which demonstrated to be a technically and economically feasible solution for power generation (McLarty & J. Reed, 1992; National Research Council, 1987; S. Pye, 2013; Ruegg & Thomas, 2011).
- Long-term R&D to develop technologies for using non-hydrothermal resources like the heat from Hot Dry Rock (HDR) resources.

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[29] One important outcome of this program was the development of the polycrystalline diamond compact (PDC) drill bits, which are widely used today in the oil and gas industry (and in some cases in geothermal fields) (Milliken & U.S. Department of Energy, 2011)

- Funding to improve the binary conversion cycle, resulting in a 15% increase in productivity over flash-steam technology, and funding to develop geothermal reservoir models to increase geothermal productivity by 10% (Milliken & U.S. Department of Energy, 2011).
- TOUGH[30] series of reservoir models: The support from DOE to research helped to identify the limitations of traditional exploration techniques, and confirmed the potentials for imaging and surface characterization tools (Gallaher, Link, & O'Connor, 2012).

Since the beginning of the public support on geothermal development, the National Laboratories[31] have been active in a variety of geothermal research areas. In addition to funding research at the national laboratories and universities, DOE contracted with the geothermal operators to conduct research at the test facilities.

Mandating utilities to purchase renewable power at avoided costs through the PURPA

In 1978 Congress enacted the Public Utility Regulatory Policy Act (PURPA), which had the objective of establishing a legal infrastructure for the existence of independent power producers (IPPs). This was done by requiring utilities to purchase power from qualifying facilities (QFs), which correspond to IPPs with a maximum net capacity of 80 MW, hence giving them a guaranteed source of income. The implementation of this Act by FERC included a requirement to utilities to pay fixed energy charge and a capacity charge for QFs at the utility's full-avoided cost, making sure that the utility's transmission infrastructure was available for the QFs. This last requirement was particularly significant to geothermal energy, given its capability to provide base-load generation and thus, receive sufficient compensation as a capacity payment. The effect has been a shift from a model relying on a regulated utility as the single buyer for a dry-steam field, to the promotion of several IPPs receiving the steam from water-dominated fields at multiple locations (Doris et al., 2009; McLarty & J. Reed, 1992; Sanyal & Enedy, 2011). This shift is present in the cases of Unocal and Phillips described in the following chapters.

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[30] TOUGH stands for Transport Of Unsaturated Groundwater and Heat, which is a suite of multi-dimensional numerical models for simulating geothermal reservoirs, developed by the Lawrence Berkeley National Laboratory (LBNL) in the early 1980s (Gallaher et al., 2012).

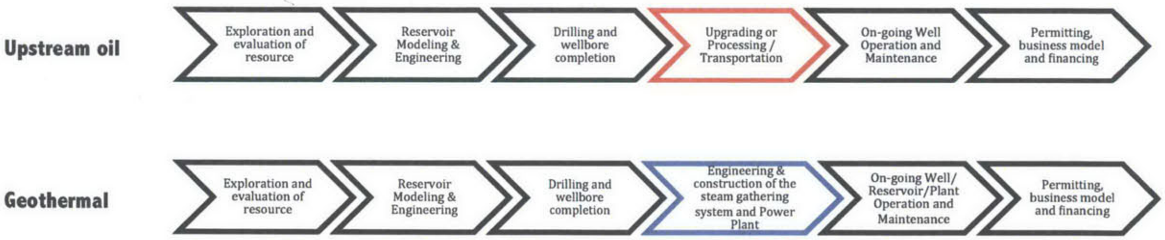
[31] In particular the Lawrence Berkeley National Lab, the Sandia National Lab, the Idaho National Lab, the Lawrence Livermore National Lab, the National Renewable Energy Lab, and other DOE laboratories.

V. Affinities and differences between upstream oil operations and geothermal energy development

The skills and knowledge required for succeeding in the oil industry, and specifically in the upstream oil operations, are not sufficient for being successful in the geothermal industry. Even though there is relatedness between these two industries (both are energy sources, both deal with the extraction of fluids from inside a field and both require drilling technologies to achieve this) there are a number relevant differences that should be explained in order to understand the technical hurdles that oil companies confronted during their diversification into geothermal. The purpose of this chapter is to provide an overview of the distinctive features between the upstream oil operations and geothermal operations.

The following chart summarizes the affinities and highlights the structural differences between the activities for upstream operations from oil extraction and production and the activities for geothermal energy development[32].

Figure 8: Common activities between upstream oil and geothermal development (Based on Ruegg & Thomas, 2011; Tordo, Tracy, & Arfaa, 2011)



The arrowed-blocks represent one specific activity for each of these two business fields. The figure is not meant to represent a definite interpretation of the value chain. Instead, it is shown to emphasize the affinities and differences from the two business areas. Black

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[32] The scope of cases described under this thesis is limited to the exploitation of natural hydrothermal systems, including vapor-dominated systems and liquid-dominated systems. Other type of geothermal fields and technologies like hot-dry rock (HDR), magma-enhanced system or geopressured fields, are not covered under the scope of this research, since these were not implemented by the oil firms diversifying into geothermal during the late 1960s and until the late nineties.

arrows represent closely related activities in the two value chains, whereas the colored arrowed-blocks highlight the evident singularities for each particular business field. For upstream oil, the colored arrow in red corresponds to the processing and subsequent transportation to downstream operations. For geothermal energy, the colored arrow in blue corresponds to the steam collection system and its use into a power cycle for electricity generation and subsequent interconnection to the grid. The rest of the arrowed-blocks illustrate an apparent close relation between these two energy industries. This level of relatedness could have been one of the initial drivers for oil firms to engage in the geothermal business and exercise their economies of scope (W. R. Benoit, 2014). These similarities have also enhanced the transfer of equipment, techniques, and terminology from the oil industry, to be adapted for geothermal development. Indeed, in principle a geothermal company and an oil company need a similar workforce profile to execute a similar set of jobs (MIT, 2006; Suter, 1980). Yet, if we take a closer look at these related activities we can find inherent differences that represent the challenges that the diversification from oil to geothermal confronted. These differences are translated into costs such as the values represented by Table 3:

Table 3: Comparison of U.K. geothermal and U.S. oil well costs (Mortimer & Harrison, 1989)[33]

Cost Category	Cleethorpes geothermal well (thousand dollars of 1984)	Oklahoma oil well - simulated cost (thousand dollars of 1984)
Drilling charges	219	73
Site preparation	131	9
Rig transportation	47	12
Fuel, mud, water, mud disposal, mud engineering /logging, and bits	270	29
Casing and accessories	176	112
Cement and cementing services	49	27
Wellhead	19	16
Logging and Surveying	168	27
Well testing	275	0
Miscellaneous	537	70
Total	**1892**	**374**

The rest of this chapter describes and explains each of the technical adaptations that are required to move from the upstream operations of an oil company to the development of a geothermal field and its related power generation facility.

Exploration

Generally speaking, geothermal fields are embedded in a system of fractured rock through which geothermal fluid can percolate. These **rock fractures** can be miles deep while also be very thin, and hence **hard to locate and drill** (MIT, 2006). The first geothermal operations done by oil firms had to **rely on the direct observation of geothermal surface manifestations** (hot springs). The other approach has been to use electronic sounding techniques to find low resistivity. However in most of the cases, exploration and project development has been limited to fields that have surface manifestations (S. Pye, 2013; Sanyal, 2003).

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[33] This table might not reflect the fact that the first cost of a geothermal unit will not be the same as the second project. That means, there is a cost reduction in the learning process from technology deployment.

On the early days of geothermal development, experts in the area (like geologist Carel Otte from Unocal and professor Paul Kruger from Stanford) were aware of the **limitations of petroleum exploration tools** (seismic imaging, gravity, well-to-well correlation of logs, electrical resistivity and magnetotellurics) for the identification of a geothermal reservoir. Indeed, some of the techniques not commonly used for upstream oil exploration, like geochemical assessments and heat flow surveys became much more relevant once applied for the definition of a geothermal reservoir. Furthermore, reservoir modeling and engineering became a much more integrated activity within the stage of geothermal exploration (Kruger & Otte, 1973; Sanyal, 2003).

Reservoir modeling & engineering

As with oil and gas fields, the behavior of a geothermal reservoir depends on very specific local conditions and can only be predicted once the production performance of its wells has been analyzed and compared to wells from similar fields that have been producing longer periods. During the late 1960s and the early 1970s (the period when oil companies started to engage in geothermal development) there were **not enough records on the operation of geothermal systems**, not even for the vapor-dominated project of Larderello[34] in Italy where operations began in 1904. Therefore there were no good references to characterize the performance of a geothermal field or to learn from the completion and operation of a geothermal well (Kruger & Otte, 1973; MIT, 2006). Since then, reservoir engineers have begun to learn what are the main differences in the behavior of oil/gas reservoirs and geothermal reservoirs. These are summarized as:

- Oil and gas reservoirs are generally in static equilibrium whereas geothermal reservoirs are **highly dynamic** and exposed to the flow of mass and heat within and without the reservoir. This required the development of new and more complex models to characterize the **active convection process of mass and heat transfer** to estimate its capacity (reserve) and productivity. The addition of energy considerations was not commonly taught in petroleum engineering schools during

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[34] Larderello is the first power generation project using geothermal steam, which started operation in 1904.

the 1960s, because the oil industry of that time did not need this knowledge at that time. So the knowledge also from engineers with other types of training, became a useful resource (physics, chemical engineering and mechanical engineering) (Atkinson, 2013; MIT, 2006; Sanyal, 2003).

- Oil reservoirs are embedded in sedimentary rocks with generally an unambiguous definition of its structural boundaries (determined by the contact of oil and water), whereas the geothermal reservoir occurs in **metamorphic or igneous rock** with a much more complex and **vaguely defined structure**, often described as a "plume" of hot water which is difficult to position (Sanyal, 2003).
- Finally, and not less important, the exploitation of geothermal reservoirs requires the **reinjection of all produced fluids**, which increases the costs of operating a geothermal field in comparison to an oil and gas field, where this factor is not a requirement.

Because of these differences, geothermal energy development requires an **integrated approach to analyze the field**, joining together reservoir engineering and geoscience for the development of the model. Instead, in the upstream oil operations, these two disciplines work independently from each other[35].

Unfortunately, there is still a poor empirical understanding of the behavior of different geothermal reservoirs, given the small number of records from geothermal operations relative to that of upstream oil operations. This is a critical difference between both industries. Further, even within a same field, geothermal wells are more different to each other than oil and gas wells, so more has to be studied about the local-specific conditions (J. Finger & Blankenship, 2010; Sanyal, 2003).

Drilling and wellbore completion

Drilling costs are a critical element of the capital costs for geothermal development. Drilling and completion costs can account up to **60% of the capital cost** of a geothermal energy facility (MIT, 2006; J. W. Tester, Drake, Driscoll, Golay, & Peters, 2012). Indeed, geothermal

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[35] For petroleum operations, the geologist defines the scope of the reservoir while the reservoir engineer studies the pore space and the fluids in it.

wells can be substantially more expensive than oil wells (in a factor of 2), for depths between 1 to 5 km. (J. W. Tester et al., 2012).

Another of the issues that makes geothermal wells more expensive than oil and gas wells is casing development. Because the flow of steam or hot water is less economically valuable relative to the same flow of petroleum, well design requires **casing with larger diameters** in comparison to the size used in oil and gas wells in order to increase the flow rate (considering the same depth). Other reasons to have larger diameters is to **reduce the pressure** drop if there is a two-phase flow in the wellbore (J. Finger & Blankenship, 2010)

Drilling includes not just the technologies required to perforate the soil and rock (rigs and bits), but also all the technologies required to monitor the characteristics of the field under high temperatures, protect the wellbore's structure and stability, deal with the differences of pressure between the drilling fluid and the geothermal fluid, and handle the high levels of scaling that can be produced inside or outside the wellbore.

Table 4 summarizes the influence on drilling and wellbore completion activities from the most relevant differences between the operation of a geothermal field and that of an oil field. Rows represent the problems confronted because of the geothermal environment, while columns represent the drilling and wellbore completion activities.

Table 4: Summary of the influence from geothermal conditions to the drilling and wellbore activities

Differences with oil	Casing	Cementing	Drilling fluids	Drilling tools	Logging equipment
Abrasive hard rock				Serious wear to the heal row	
Loss of well control	Kick can create large damage				
Lost circulation			Loss of fluid + clog the drill pipe		
Corrosion	Failure of the casing	Carbonation			
Scaling	Reduce the flow area				
High temperatures	Thermal expansion of casing	Carbonation	Change properties of drilling muds		Burn of tools or incoherent results

Each challenge, and the way it influences casing, cementing, drilling and logging, is described by the following paragraphs.

Abrasive hard rock

In contrast to oil fields, geothermal fields tend to rest on abrasive hard rock, specifically fractured quartz crystals or granitic formations, which increase the complexities from drilling. Conventional oil drilling bits do not have a suitable cutting structure to pass through the abrasive formations from geothermal reservoirs, which causes serious wear to the heel row[36]. To solve this situation, bits used for geothermal operations are selected from the class of **bits for oil drilling in hard rock**, which are mostly rotary cone bits that grind and crush rock. New developments on materials and design include **new bearings**, new heel row designs, more **wear-resistant tungsten carbide cutters**, and polycrystalline diamond compact (**PDC**) bits[37] (MIT, 2006; J. W. Tester et al., 2012).

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[36] "Heel row: the outer row of teeth on a cone of roller-cone bit (Schlumberger, 1998).

[37] Only recently, and after many years of research and test, PDC bits have been able to offer an acceptable performance and extended lifetime in their use on harder rocks (J. Finger & Blankenship,

Loss of well control

Well control is a critical topic in geothermal exploitation. If the wellbore reaches a fractured or permeable section where the pore pressure is higher than the static pressure of the drilling fluid, then the formation fluid[38] will enter the wellbore. This is usually named as a "**kick**". If the "kick" is not prevented and controlled, the well is exposed to a risk of **blowout** that entails the potential fro damage to equipment and danger to workers. This situation is more likely to happen in geothermal fields than in oil fields due to the high, shallow temperatures. Experience has proved that a string of **casing** is a good method to **prevent** this from happening (J. Finger & Blankenship, 2010).

Lost circulation

It is important to cautiously balance the appropriate amount of drilling mud in the wellbore to control any risk of kick with making sure not to overweight the drilling mud with risk of losing the fluid because of lost circulation (Baza, 2014). Lost circulation is not an unfamiliar topic to upstream oil drilling, yet it is a much more prevalent phenomenon for geothermal reservoirs given that these are under-pressured (its pressure is less than the drilling fluid's pressure head) and considering the abundance of rock fractures on the reservoir. Lost circulation happens when the drilling fluid[39] reaches sections with pressures below the hydrostatic equilibrium, and it permeates through the fractures and outside the wellbore, so it is not recoverable at the surface. Lost circulation can cause a **loss of fluid in the annulus**[40], which consequentially accumulates cuttings[41] that **clog the drill pipe**, and significantly reduces the penetration rate. In addition, lost circulation can make the wellbore more susceptible to loss of well control. Consequently, lost circulation is estimated

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2010). The DOE recognizes that 50% of the economic benefits from PDC bits are an effect from DOE's research sponsorship (Gallaher et al., 2012)

[38] Formation fluid: "Any fluid that occurs in the pores of a rock and is encountered in the process of drilling" (Schlumberger, 1998).

[39] Drilling fluid: Generally a mud (water-based, non-water based or pneumatic fluid) pumped down the borehole to clean, cool and lubricate drill bit and drill string. Air is also used as a drilling fluid to control lost circulation. (Sandia National Laboratories, 1989)

[40] "Annulus: The space between two concentric objects, such as between the wellbore and casing or between casing and tubing, where fluid can flow" (Schlumberger, 1998).

[41] "Rock pieces dislodged by the drill bit as it cuts rock in the hole" (Schlumberger, 1998).

to represent 10% or more of the costs of the well[42] (Kruger & Otte, 1973; MIT, 2006; Sandia National Laboratories, 1989).

Unfortunately, the substances designed to plug lost circulation zones for upstream oil operations cannot cope with the high temperatures characteristic of geothermal fields. This is because the permeability zones for oil and gas drilling have a smaller fracture aperture than those commonly found in geothermal reservoirs (MIT, 2006). One option to prevent loss circulation in geothermal fields has been to inject cement into the loss zone. However, this can significantly increase the material costs for drilling (Sandia National Laboratories, 1989).

A successful alternative approach to address loss of circulation, inherited from the upstream oil industry, has been to use **air drilling** instead of mud as circulating fluid. Once the well reaches the geothermal reservoir, the aerated fluid's pressure head will be less than that of the pore pressure, avoiding the leakage of drilling fluid. In addition to this, air drilling can help to cool-down the drill bit and sustain the cuttings out of the well[43]. Altogether, air drilling increases the drilling performance. Yet, this technique can only be applied in the segments were casing can protect the borehole from loss of well control (J. Finger & Blankenship, 2010; Kruger & Otte, 1973; Sandia National Laboratories, 1989).

Corrosion

One distinctive feature of geothermal fields is the coexistence of high temperatures, oxygen, water, hydrogen sulfide and carbon dioxide, which creates a very corrosive environment. This requires the use of sophisticated materials that are not commonly used for oil and gas wells for the casing and cementing to protect the well from this corrosive condition,

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[42] These additional costs are associated with drilling problems and the high expenditures on additional drilling fluid. These are also related to the fact that zones of lost circulation harm directly the productive potential of the well (J. Finger & Blankenship, 2010).

[43] Instead, the use of a drilling mud is exposed to chemical changes when mixed with the geothermal environment, which can hinder the effectiveness of carrying the cuttings out of the borehole (J. Finger & Blankenship, 2010).

Cements are meant to shelter the casing from corrosive environments. Yet, Portland cements (commonly used for oil wells) can fail in less than 5 years, because of their interaction with geothermal brines that contain acids and carbon dioxide, which increases the cement's permeability and reduces its resistivity. This deterioration is an effect called **carbonation** caused by the interaction of cement and carbon dioxide. One modification to deal with this problem has been the **addition of retardants and silica flour** to the standard class G cement, yet this does not avoid the carbonation problem (J. Finger & Blankenship, 2010; MIT, 2006; S. Pye, 2013; Vuataz & Goff, 1987b). This was finally solved through a research consortium led by Brookhaven National Laboratory, bringing together Unocal, CalEnergy and Halliburton. The outcome of this work was a high-temperature corrosion-resistant cement, which doesn't change with (or under?) exposure to carbon dioxide thanks to zeolite and calcium phosphate minerals that block this destructive chemical reaction[44], and is actually commercialized by Halliburton as ThermaLock™[45] (Brookhaven, 2000; S. Pye, 2013).

The exposure of conventional tubing used in oil and gas wells to corrosive fluids such as hydrogen sulfide, calcium carbonate and calcium bicarbonate[46] can lead to the **failure of the casing**. The control of corrosion of the casing from geothermal wells, depends on the type of **alloys** used for the piping[47] and the availability of oxygen (MIT, 2006; S. Pye, 2013).

Scaling

Scaling is an undesirable effect unusual to oil and gas drilling. Silicate scaling occurs when the silica dissolved in the geothermal brine precipitates as a solid in production equipment or pipes (because of a drop of temperature). Calcite scaling occurs in response to the pH change. Both types of scaling **limit the well's production and restrict the re-injection** of

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[44] The first large-scale field testing of this product was done at Unocal's geothermal operations in Indonesia

[45] ThermaLock™ is a non Portland cement system. A complete description of this product is available at http://www.halliburton.com/en-US/ps/cementing/materials-chemicals-additives/cement-blends/thermalock-cement.page#

[46] These last two are a by-product from cement's exposure to carbon dioxide and acid conditions.

[47] Field experience proved the successful use of Beta-C titanium on casing of the production wells, which unlike carbon steel, didn't deteriorate under corrosive environments and also reduced the scaling in the wells (J. Finger & Blankenship, 2010; Holligan et al., 1989; D. S. Pye et al., 1989).

the brine. Such effect can reduce the flow area of casing by 50% in a period of few months. One simplistic alternative to handle this problem is to keep the pressure of the brine and temperature to a suitable range so that the silica does not precipitate, and brine can still be re-injected. The problem is that this approach limits the power productivity of the field[48]. Two alternative approaches that are described in detail under the case of Unocal in Chapter VI are the pH-modification treatment[49] and the crystallizer-clarifier technology[50] (J. Finger & Blankenship, 2010; Hoyer & Whitescarver, 1990; S. Pye, 2013).

High temperatures

Temperatures in a hydrothermal system can reach ranges between 200°C and 350°C, whereas in an oil field it is more likely to find a maximum of 150°C. This condition of the geothermal environment, causes a set of problems with equipment and materials transferred from the oil and gas industry that. Some of these limitations on equipment and materials are the following:

- **Drilling muds**: High temperatures can adversely affect the properties of drilling fluids (such as Bentonite base fluids) and make them loose their stability because of an increased flocculation. High temperatures can also make the drilling fluid boil or "flash" (Suter, 1980; Zilch, Otto, & Pye, 1991). As it is explained in Chapter VI, this was solved through the development of **third generation drilling fluids** that can resist high temperatures.
- Casing: The well's **casing can suffer thermal expansion** with the consequential collapse of the casing. On a similar way, the casing from injection wells can suffer thermal contraction due to cooling, and eventually suffer failure. The proper solution is to use casings with a **larger diameter** than that of oil and gas wells, to allow the high volume and elevated enthalpy of the geothermal fluids being extracted. In addition, it is important to provide a complete **cover of cement**

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[48] For each subsequent stage of flash, the pressure and temperature would drop, reaching the phase when the silica started to form as a solid and precipitate, thus creating scaling which prevented the reinjection (S. Pye, 2013).

[49] The purpose is to alter the acidity of the brine by adding chemicals, which can prevent heavy scaling from coming out of the brine.

[50] This technology controls the precipitation, by allowing it to solidify in crystallizer and subsequently treat the outflow in a clarifier, were remaining solids precipitate, so that the remaining brine can be re-injected making sure it would not plug up the system.

throughout the well's length, so as to provide mechanical strength to the casing during thermal expansion (avoid the casing from reaching its compressive yield stress[51]), and simultaneously protect against corrosion of the casing (J. Finger & Blankenship, 2010; MIT, 2006; S. Pye, 2013; Teodoriu & Falcone, 2009).

- Cements: High temperature emphasizes cement **carbonation**. One approach to solve this is to add silica flour to the cement so it can resist higher temperatures, yet this is not effective for highly corrosive environments (B. Barker, 2013; Gallus, Waters, & Pyle, 1979). As described above, a special high temperature corrosion-resistant cement was developed thanks to a joint project and is currently commercialized by Halliburton (Brookhaven, 2000; S. Pye, 2013).
- Instrumentation and seals: The electronic tools directly transferred from oil operations to survey the well's trajectory are not suitable at temperatures above 150°C. During geothermal operations these tools would **burn or give incoherent results** on the measurements[52]. The solution has been to implement **heat-shielded instruments**. The same temperature restrictions apply to seals, drill pipe protective rubbers and downhole packers which are damaged by temperatures over 190°C[53] (J. Finger & Blankenship, 2010; Isselhardt, 2013; Suter, 1980).

Steam gathering system and steam cycle.

The geothermal development becomes a useful asset once it can be recovered from the field and sold for direct use (in case of a low enthalpy resource) or for power generation (in case of a high enthalpy resource). This stage is essentially distinct from any of the upstream oil activities, since the gathering system of the geothermal brine is very sensitive to any loss of pressure, and also because the geothermal brine cannot be transported for its commercialization in the market and there are technological limitations that impede the commoditization of the geothermal brine to be sold as a fuel. Therefore geothermal requires the installation of a steam turbine next to the field (in the case of a high enthalpy resource).

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[51] "Yield stress: The stress that must be applied to a material to make it begin to flow (or to yield)" (Schlumberger, 1998).

[52] The same applies to positive displacement motors, steering tools and measurement while drilling surveying technology (J. Finger & Blankenship, 2010).

[53] For example the matrix where the diamond bit was set would melt and the diamond would fall (Isselhardt, 2013).

The development and improvement of the steam gathering system and the development of the steam cycle will imply a set of new capabilities which are not present in the upstream oil operations.

If the firm decides to design and operate its own power cycle, then it will more in control of its revenue stream, since it is easier to measure the electricity sold than to measure the flow and quality of the steam supply. Still, it will confront a very different risk profile and it will have to develop new skills for delivering the power supply service.

Business Model

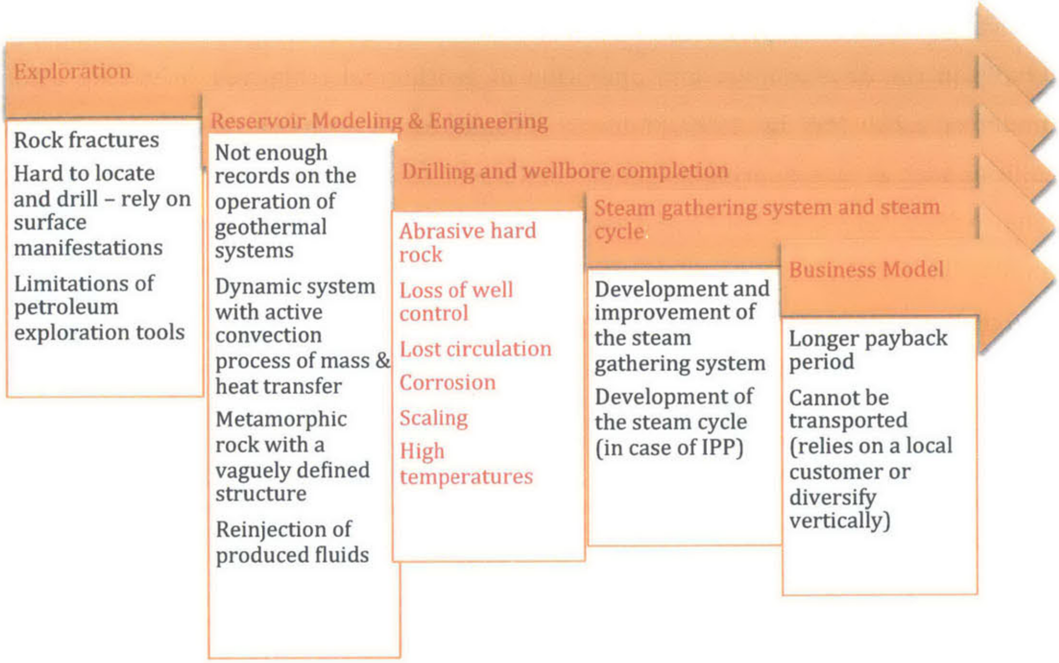
The extraction of oil and gas can lead to a **shorter payback period** than the operation of geothermal field, considering all the relevant differences explained above which increase the drilling costs for geothermal by a factor of 2 or even 5, at comparable depths. This slows down geothermal development (J. Finger & Blankenship, 2010).

The other important difference is that the heat obtained from the geothermal brine **cannot be transported** or even directly traded as a commodity, as it is the case with oil and gas. This constrains the market opportunities for the technology by forcing the operator to **rely on a local customer** (utility company or independent power producer) or **to diversify vertically** by entering the power generation business. Geothermal becomes then a mix of a utility business (selling electricity at a low margin and low risk with a long term cash flow) with an upstream resource business (selling fuel, equivalent to oil or gas, at a high margin and high risk with a short term cash flow perspective) (S. Pye, 2013).

Summary

Figure 9 summarizes the main challenges in the operation of a geothermal field in comparison to an oil field.

Figure 9: Main operational challenges for a geothermal field in contrast to an oil field (J. Finger & Blankenship, 2010; MIT, 2006; S. Pye, 2013; Teodoriu & Falcone, 2009).



Each of the technical hurdles included as headlines for Figure 9 are selected as the classification groups for the units of analysis that populate the second level of each case study (see Chapter III). For the particular case of the stage "drilling and wellbore completion" (the most demanding stage in terms of costs and adaptations), each of its specific technical hurdles are also included as independent units for the second level of analysis. This selection is highlighted in red on Figure 9.

VI. Union Oil Company of California (Unocal)

The case of the Union Oil Company of California (from now on Unocal) and its business diversification into geothermal energy is the paradigmatic example of a related diversification from oil into geothermal. For years, the company maintained worldwide leadership in the development and operation of geothermal resources, achieving a total maximum of 2,260 MW by 1999 (Table 5). Thanks to the exercise of valuable dynamic capabilities such as empowering its geothermal business units, exploiting internal scientific knowledge from Unocal's Science and Technology Division and absorbing knowledge from the industrial ecosystem fostered by the government through its National Labs, Unocal became the birthplace of several technological innovations. These innovations were critical to the deployment of geothermal energy technologies given the uncertain and varied behavior of hydrothermal reservoirs. The combination of all of these factors enabled an accelerated maturation of the industry, which today has large worldwide investment opportunities.

The purpose of this case study is to describe the factors that made Unocal successful in the development of geothermal energy technologies and the supply of steam, in order to provide evidence for testing the hypotheses presented in Chapter III.

Unocal's diversified activities (1965-2000)[54]

Diversification was an explicit objective of Unocal's strategy, with the greatest interest focused on diversification into new energy markets. This is confirmed by Unocal's Annual report of 1973 where the CEO at that time, Fred Hartley[55] stated: "*We must develop more and different sources of energy*". This is later emphasized by Hartley in the Annual Report of 1979: "*Concurrently there must be an expansion and refinement of conservation practices and an acceleration of the development of alternative forms of energy*" (Unocal, 1973, 1979).

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[54] This period includes the years of the peak oil price crisis.

[55] Fred Hartley originally joined Unocal as a research engineer to become later the man behind this vision of an integrated and diversified energy resource company (B. Barker, 2013).

As early as the mid 1960s, Unocal had already been exploring related and unrelated business fields, which in some instances became strong foundations for the growth of the company. The company became well known for its involvement in the oil and gas upstream business, the refinery operations, geothermal and the marketing of gasoline. Yet the firm also engaged on a broad range of industries such as mining explorations, the manufacturing of chemical fertilizers, manufacture of paving materials for streets, real estate and the production of byproducts such as petrochemicals and solvents, and commercializing these all around the world. As shown in Figure 10 below, all of these different businesses provided an extended knowledge base for diversification into new areas.

Figure 10: Transition in business diversification of Unocal (Moody's Investors Service, 1965b, 1970b, 1975b, 1980b, 1985b, 1990b, 1995a, 2000b)[56]

	1965	1970	1975	1980	1985	1990	1995	2000
Exploration and production of Oil & Gas (upstream)	▨	▨	▨	▨	▨	▨	▨	▨
Compression and transportation of Oil and Gas	▨	▨	▨	▨	▨	▨	▨	▨
Downstream Oil & Gas (refinery)	▨	▨	▨	▨	▨	▨	▨	
Retail and marketing of Petroleum and gas products	▨	▨	▨	▨	▨	▨	▨	
Manufacture and sale of chemicals derived from petroleum and gas	▨	▨	▨	▨	▨	▨		
Agricultural products	▨	▨	▨	▨	▨	▨	▨	
Mining exploration and production of copper concentrates	▨	▨	▨	▨				
Real Estate		▨	▨	▨	▨	▨	▨	▨
Market and manufacture graphite		▨	▨	▨	▨	▨	▨	
Manufacture of paving material and road construction		▨	▨					
Geothermal resource production		▨	▨	▨	▨	▨	▨	▨
Power generation				▨		▨	▨	▨
Exploration, Production and Marketing of molybdenum, columbium, lanthanides and other rare earths				▨	▨	▨	▨	▨
Exploration and development of oil shale[57], coal and uranium				▨	▨	▨	▨	
Research Group (Science and Technology Division)	▨	▨	▨	▨	▨	▨		

It is interesting to note that by 1980 Unocal had an explosion of diversified activities, which declined during the last decade of this period (1990-2000) with the resultant contraction of the business activities of the company[58]. It is relevant to emphasize that the firm was able to vertically diversify from the operation of the geothermal field into the power generation

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[56] This table has included the years of operation of the Science and Technology Division as a reference to show its permanence during this period of analysis, even though it is not a product development unit.

[57] Shale oil was included as part of the Synthetic Fuels business unit, located in Colorado.

[58] During the mid 1990s the firm decided to sell assets that were "marginally related to its core activities or that were not a strategic fit for Unocal", alluding to the need of "keeping with the challenging environment for the company" (Moody's Investors Service, 1997). One of the most emblematic abandonments corresponds to most of the sale of the refinery operations and retail network to TOSCO (which virtually removed Unocal from the downstream sector) (New York Times, 1996).

market, at the Salton Sea units and for operations in Indonesia[59]. Finally, it is interesting to note that the geothermal business units (at least those outside the U.S.) were kept until the sale of Unocal to Chevron in 2005.

Unocal's diversification into geothermal energy

History

Unocal's diversification into geothermal technology starts in 1965, with the merger of Unocal and Pure Oil Co[60]. Pure had a network of gas stations in the mid-west of the United States that Unocal sought to expand its retail network (Barnes, 2013). Pure Oil had already been exploring opportunities to diversify into related natural resource areas. During the early 1960's, thanks to the leadership of the independent geological consultant Dr. Carel Otte and a partnership with Magma Power Company, Pure engaged in the exploration and exploitation of geothermal resources at the Geysers field in California[61]. There was an evident match between a small company with the determination to undertake this new field of energy development (Magma) and this larger oil firm that had capital, engineering capabilities and geological experience (Pure Oil). Unocal arrived in this setting to provide further capital, drilling expertise and a greater knowledge base, which made this diversification opportunity more feasible and certainly successful (Berger, 1998).

Figure 11 illustrates the relation between the price of oil and a selection of key milestones in Unocal's geothermal development. The figure shows how Unocal took the opportunity to leverage its capabilities into the development of different geothermal fields and quickly became the largest geothermal field operator in the world. Still, it is important to emphasize

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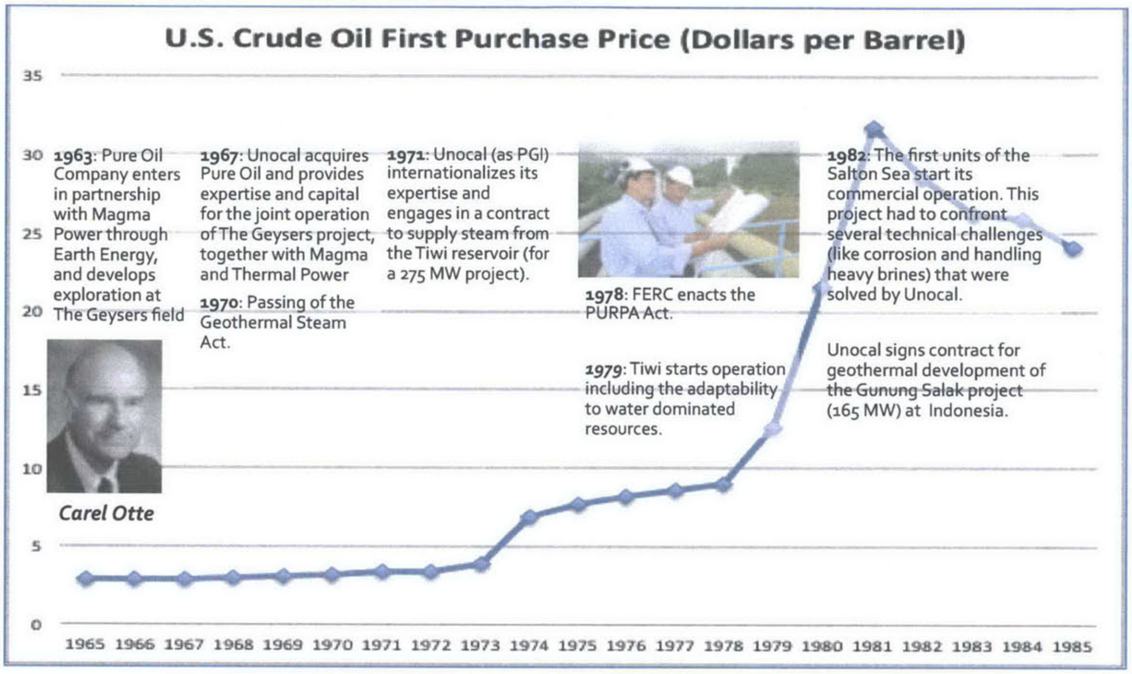
[59] Unocal had a first experience by sharing 50% of the ownership of a 325 MW fuel oil project in the Republic of Korea between 1969 and 1983 (Posco Energy, 2012; Unocal, 1971). Years after, the company retook this business through the vertical integration of the geothermal operations (at the Salton Sea in 1989 and later in Indonesia) and also by sharing 15% of the investment of two natural gas cogeneration units (165 and 112 MW) in Thailand (Asia Times, 2005).

[60] Given the relative small size of Pure Oil in comparison to the assets of Unocal, the merge resembled more to an acquisition in practical terms.

[61] Magma was the first company that arrived to explore this field commercially. Thanks to the collaboration with the Thermal Power Company of San Francisco, they were able to provide high-pressure steam to the Pacific Gas & Electric Co. (local utility company) for power generation, with a first unit connected in 1960 and a second one in 1963 (Finney, Miller, & Mills, 1972). Still, the first unit can be considered as a R&D project, given the level of experimentation that it carried (Kruger & Otte, 1973).

that the incentive for the related diversification was the financial soundness more than the usefulness of the technical expertise inside the company (Barnes, 2013). Although the geothermal business units were initially seen as cost centers and not as profit centers, they would soon become a stable source of revenue during a period of high oil price volatility.

Figure 11: Key milestones in the development of the Geothermal Division of Unocal



By 1990, Unocal had active operations of exploration and production of oil and gas in 15 countries (Moody's Investors Service, 1990b). The company used this international presence to extend the geographic scope of its geothermal activities, so as to reach countries like the Philippines and Indonesia, where it could leverage its expertise from being an international operating company that knew how to drill in odd places with poor local infrastructure and that knew how to work with the local authorities (Barnes, 2013; K. Williamson, 2013). Some of the fields proved to be unfruitful, such as the case of operations in Japan[62] or also in New Mexico[63], where the wells drilled evidenced poor results that didn't justified investment.

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[62] The firm developed a completely new subsidiary called the Union Geothermal of Japan, to develop fields on the areas of the island of Hokkaido (as co-venture with other partners).

[63] This corresponds to the Valles Caldera project, which was originally planned together with DOE as a pilot facility through a cost-sharing contract. It was supposed to be completed by 1982 with 50 MW.

Table 5 provides the complete list of fields that were successfully operated by Unocal since its engagement in the geothermal development business, and the representative installed capacity for each year.

After the cooperative agreement was signed, only 2 of 13 wells drilled by Unocal were successful (Goff, 2002).

Table 5: Installed capacity throughout time of Unocal's geothermal business units (Asia Times, 2005; Unocal, 1969, 1971, 1973, 1977, 1978, 1979, 1989)[64]

Year	USA	Philippines		USA					Indonesia	Accumulated Installed Capacity (MW)
	Geysers (MW)	Tiwi (MW)	Mak-ban (MW)	Imperial Valley 1-Brawley (MW)	Imperial Valley 2 - Heber (MW)	Salton Sea Unit 1-Niland (MW)	Salton Sea Unit 2 (MW)	Salton Sea Unit 3 (MW)	Gununk-Salak (MW)	
1965	26									26
1966										26
1967	27									53
1968	27									80
1969										80
1970										80
1971	110									190
1972	110									300
1973	110									410
1974										410
1975	110									520
1976										520
1977										520
1978										520
1979	110	110	126.4							866.4
1980	110	110	126.4	10						1222.8
1981		55								1277.8
1982	110	55				10				1452.8
1983	110									1562.8
1984										1562.8
1985	110		110	-10[65]	52					1834.8
1986										1834.8
1987					-52[66]					1782.8
1988										1782.8
1989								47.5		1830.3
1990							20			1850.3
1991										1850.3

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[64] Cells in yellow illustrate the closure of two pilot projects in the Imperial Valley whose primary purpose had been to demonstrate technical feasibility. Cells in pink represent the sale of projects.

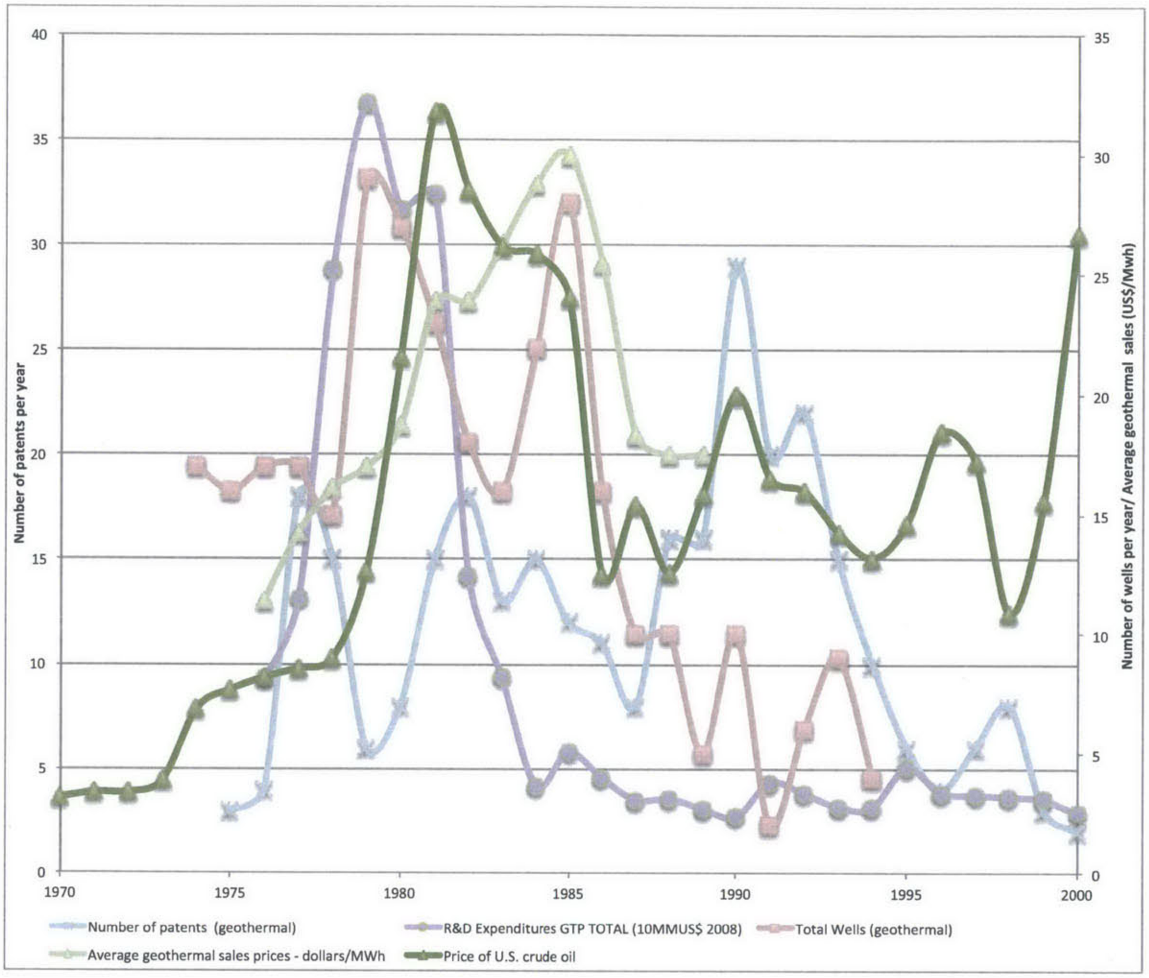
[65] This corresponds to a pilot at Brawley (CA), which was dismantled in 1985,given that it served its initial purpose of testing the field.

[66] This project also corresponds to a pilot, which was initially developed together with Chevron but it was closed in 1987, because it "became apparent that operating costs would exceed the budget previously approved by the state Public Utilities Commission" (Los Angeles Times, 1988).

1992										1850.3
1993				SALE	SALE	SALE	SALE	SALE		1850.3
1994									110	1960.3
1995			40							2000.3
1996			40							2040.3
1997									220	2260.3
1998										2260.3
1999	SALE									2260.3
2000										2260.3
TOTAL	1070	330	442.8	10	0	10	20	47.5	330	

A complete timeline shown in Figure 12 describes the evolution of the firm's geothermal activities in terms of patents, number of geothermal wells, average sale price from geothermal operations, its response to the change in the public R&D expenditures from the Geothermal Technology Program (GTP) and the price of oil.

Figure 12: Trend of geothermal-related patents, number of geothermal wells, price of crude oil (US$/barrel), average price for geothermal sales (US$/MWh) and public-funded R&D expenditures for geothermal energy (Energy Information Agency, 2013; Gallaher et al., 2012; Hall et al., 2001; Unocal, 1975, 1979, 1985, 1990, 1995)[67]



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[67] This graphs starts in 1975 given that there is no information consolidated in a manageable database for patents before this period.

Some interesting relationships can be inferred from Figure 12:

- An apparent direct relationship between the price of oil (exogenous) and the average geothermal sale price with a lag of 3-5 years, for the period of 1975-1990: This relationship seems to be consistent with the pricing strategy of that period, leveraging the effect of the oil price crisis into the return of geothermal projects.
- A correspondence between the geothermal sale price and the number of geothermal wells for the 1982-1988 period.
- A correspondence between the price of oil and the number of geothermal patents between 1977-1993. The price of crude oil reaches an historical maximum of 32 US$/barrel in 1981, and its later drop explains the fall in the patenting rate (becoming evident after the closure of the S&T Division in 1997).
- A positive relationship between the GTP's R&D expenditures and the number of wells for the 1983-1985 period.
- A correspondence between the number of geothermal patents and the number of geothermal wells with a delay of 5 years, for the period of 1975-1985.

Although the evidence provided cannot confirm a systemic relationship among these variables, at least it shows that for the 1975-1990 period, the diversification of Unocal into geothermal behaved similarly to the path dependence illustrated in Figure 3. The exogenous effect from the price of oil drove the revenues from this diversification, which in turn led the company's patenting activity in the geothermal field, and consequentially influenced the number of wells drilled. Likewise, the GTP's R&D expenditures reveal a better match with the annual Unocal-geothermal patents than the annual geothermal wells. This seems to suggest that the loop "economies of scope from activity" from Figure 3, might have to be adjusted to start with the number of patents (capability) and then connect with the wells (activity).

In the early 1990s the price of oil dropped relative to the prices of the early 1980s. At the same time, Unocal's geothermal operations in the U.S. ended up being less competitive than those in the Philippines and Indonesia. Also, there was already a larger market of companies who could operate geothermal fields (hence there were lower transaction costs). These factors led the company to sell its U.S. geothermal assets (first its Salton Sea Units sold to Magma Power Co. in 1993 and then the Geysers project sold to Calpine in 1999) (Barnes, 2013).

Throughout the rest of this chapter, the emphasis will be first to describe the crosscutting factors that drove the diversification into geothermal energy, and second, to explain the technical features that were the essential drivers for the success of each of Unocal's geothermal business units.

Leadership

Dr. Carel Otte (President of Unocal's Geothermal Division) was skilled and determined enough to persuade Unocal's top management to continue Pure's efforts on geothermal development, even though this business field was not part of Unocal's initial strategy and there was no regulatory framework to guide geothermal development[68]. Dr. Otte himself recognizes that his technical credibility was essential to approve a persistent budget support for the geothermal operations (Otte, 2013), and almost all of the interviewees (who used to work with him as Unocal employees) unambiguously distinguish him as the main driver for the geothermal operations of the company for more than 20 years (DiPippo, 2013; Newell, 2013; S. Pye, 2013; K. Williamson, 2013). As pointed out by Ken Williamson (reservoir engineer for Unocal's Geothermal Division):

> *"If they would have constantly been switching up presidents I don't think you would had seen the developments that we did. Carel Otte was the one that really had a passion for it and made sure that it stayed as a coherent group, and manages its own budget and make its own development decisions. Without him it wouldn't had worked"* (K. Williamson, 2013).

Dr. Otte also played a fundamental role in the development of geothermal energy for the U.S., not only because of his drive for project development and solving the particular

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[68] The reason why this venture made sense to Unocal's presidency had also to do with Fred Hartley's strategic approach to growth based on engaging in new endeavors to leverage the firm's skills, as opposed to grow as a pure financial investment vehicle.

technical challenges of Unocal, but also because he was strongly involved in creating the framework that this industry required. He actively participated in federal strategic planning to identify R&D needs and opportunities (National Research Council, 1987) and also had an active role in promoting suitable regulation for California's geothermal resources (Berger, 1998). Indeed, Dr. Otte, on behalf of Unocal, testified before the U.S. Congress - so that the company could have the right to lease government land - and advocated for the approval of a general Geothermal Steam Act (Berger, 1998). This regulatory framework was instrumental in enabling new geothermal project development on state lands, not only for Unocal but also for the whole industry.

Organizational structure and self-sufficiency of Unocal's Geothermal Division

In 1970 the directors of Unocal decided to create a Geothermal Division and empower Dr. Otte to lead this division as VP, with the funding and workforce resources to boost the development of the Geysers geothermal field. The mission of the Geothermal Division was that it "explores for and produces geothermal energy in the United States and overseas". Clear evidence of Unocal's commitment to this new business field is shown by the resources available to the geothermal division: the team started with only Dr. Otte as the main responsible together with the former workers from Pure Oil's geothermal operations, and it reached a peak of more than 1,000 employees for the Geothermal Division (Berger, 1998). It took some years until in 1978 Dr. Otte became the president of the Division in charge of three VPs within his group (Unocal, 1978).

The organizational structure of the geothermal operations under Unocal's Geothermal Division is sketched under Figure 13[69]. The president of the Geothermal Division reported directly to the senior VP of operations for Unocal and then to the chairman of the company. The Geothermal Division had its own business units where each represented a geothermal project. This included as well the Division's office at Santa Rosa, where subsurface scientists provided technical assistance for the geothermal operations and explorations (K. Williamson, 2013). Every business unit was an operating profit center with its own budget.

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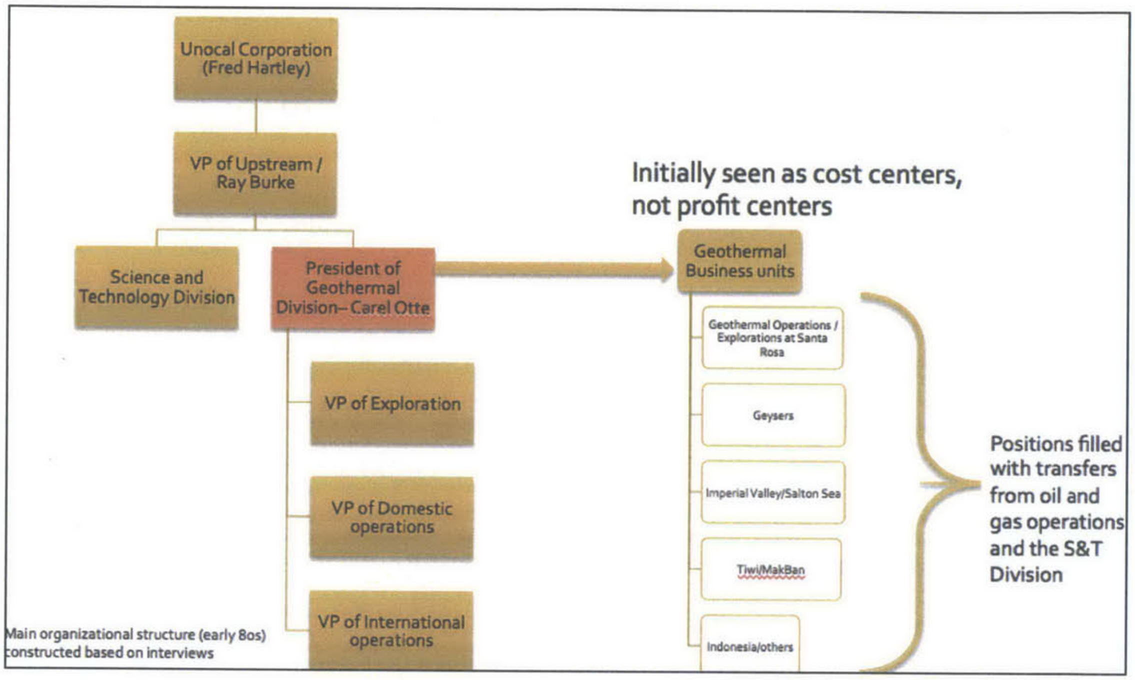
[69] The chart on Figure 13 is based on interviews to professionals that worked at the Geothermal Division, given that there are no publicly available organizational charts that could provide such specific information.

The general manager of that office reported to the Vice-president of operations for the Geothermal Division, who reported to Carel Otte, the president of the Geothermal Division (Newell, 2013).

Figure 13 Sketched representation of the organizational structure of the geothermal activities at Unocal during the early 80s (Newell, 2013; Otte, 2013; S. Pye, 2013; K. Williamson, 2013)



Main organizational structure (early 80s) constructed based on interviews

The Geothermal Division was a self-reliant subsidiary with its own HR department, land department and legal department. Once a year, the budget was approved for the Division, where the Division leadership would validate their own strategic decisions with Unocal's top management, and after that the Division operated as a separate business sending monthly financial updates to Unocal headquarters (Barnes, 2013; Kitz, 2013; Otte, 2013; K. Williamson, 2013)[70]. As pointed out by Dr. Otte:

> *"I had a capital budget that had to approved, and that was the level of control that was exercised - once we had the budget approved we were operating independently"* (Otte, 2013).

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[70] This self-autonomy was limited when the firm confronted high-risk projects with an unexpected growth in their budget, such as the operations at the Imperial Valley (which is described below in further detail) (Kitz, 2013).

Different interviewees highlight that the autonomy granted was a critical factor for the success of this diversification (Newell, 2013; K. Williamson, 2013). Ken Williamson, for example, states that:

> *"If geothermal isn't an independent entity within the company, it is going to have a hard time getting projects initiated"* (K. Williamson, 2013).

Even though the oversight of the headquarters was mostly on the financial side, there was a permanent and informal follow-up from the Geothermal Division to the top management at Unocal to explain the technical challenges that they had to confront (Amend, 2013; Atkinson, 2013; B. Barker, 2013; Otte, 2013).

Through the merger with Pure Oil, Unocal inherited Pure's geothermal assets at the Geysers and the Imperial Valley, including a small team of at least 50 people with operational experience on these fields. Nevertheless, to cope with the technical burdens that this new venture required, such a small team had to join a larger group with complementary drilling expertise, specially people from Unocal with an oil and gas background (Barnes, 2013; Isselhardt, 2013; Kitz, 2013). Mike Barnes, former manager and VP for Unocal, points out that *"there where no strong drilling expertise in Pure, and that was what Unocal had (particularly under new conditions)".* There was a transfer of people, especially young professionals, from various positions in the oil and gas operations and from Unocal's Science and Technology Division, acknowledging the inexistence of a specialized workforce in geothermal energy (Atkinson, 2013; B. Barker, 2013; Isselhardt, 2013; S. Pye, 2013).

By the year 2000, once Unocal had already sold its geothermal assets in the U.S., the organizational structure was reconfigured by making the international geothermal business units directly dependent on their respective regional vice-presidents who where also in charge of oil and gas, so there was no longer a need of a president of the Geothermal Division (K. Williamson, 2013). This made the geothermal operations more embedded into the rest of Unocal's businesses, reducing their autonomy.

The support from Unocal's Science and Technology Division

Unocal's Science and Technology Division was a key knowledge hub to support the company's involvement into an extended breadth of diversification opportunities. Unocal's Science and Technology Division located in Brea, Southern California was able to grow up to 830 company research scientists, engineers and supporting personnel (Moody's Investors Service, 1990b)[71]. A measure of its productivity is the fact that by 1969 the Science and Tech Division had registered almost 4,000 U.S. and foreign patents[72] (Unocal, 1969). The Science and Technology Division was a driving force to solve complex scientific and engineering problems confronted by the geothermal business units, like the pH-modification treatment to handle the brine's high levels of salinity (described below) (Gallup, 2013).

During the birth of the Geothermal Division scientists and technicians were recruited from the Science and Technology Division to join this new business unit at Santa Rosa. This allowed a high level of technical proficiency to be close to the field decisions (Atkinson, 2013; B. Barker, 2013). Still, additional support from the Science and Technology Division would show up as a genuine interest to collaborate in solving the technical challenges for the deployment of geothermal energy.

On the early years of Unocal's geothermal business development, the Science and Technology Division was a fundamental sponsor to the firm's geothermal-related knowledge base, necessary to sort technical challenges on the field. The Geothermal Division piloted innovative solutions created at Unocal's research lab in close coordination with the Science and Technology staff. The latter had a broad-based background from assisting other business areas of the firm, so they were able to integrate knowledge from various outside sources (Amend, 2013; B. Barker, 2013).

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[71] Unfortunately, and because of the important financial hurdles that Unocal was confronting throughout the whole corporation, the assets of the Science and Technology Division were sold to UOP in 1995.

[72] Some examples of the products that came from this division and that were relevant to the core operations of the upstream and downstream oil and gas industry are: improved catalysts for the refining operations, technologies to remove sulfur from the waste gases of the primary sulfur recovery units, new fuel additives, improve the ability to find petroleum that have not been used before, development of enhanced oil recovery technologies and technologies for a better recovery of oil and gas.

There was a fair amount of informal interaction between the Geothermal Division and the Science and Technology Division, which enabled the transfer of knowledge and the trial of new technical solutions. Staff from the Science and Technology Division had the incentive to provide direct assistance to the engineers of the Geothermal Division, given that a positive recognition of an inter-division assistance would had a significant benefit on the scientist's performance evaluation. Indeed, these interactions didn't require the interface of managers and, at least initially, there was no economical charge for such assistance. The good interpersonal relationships between both Divisions helped to nurture such collaboration, specially considering that some of the employees of the Geothermal Division started their careers at the Science and Technology Division and conserved a network of contacts (and thus of skill profiles) (Amend, 2013; B. Barker, 2013). As Benjamin Barker (Geothermal and Petroleum engineer for Unocal for 30 years) points out:

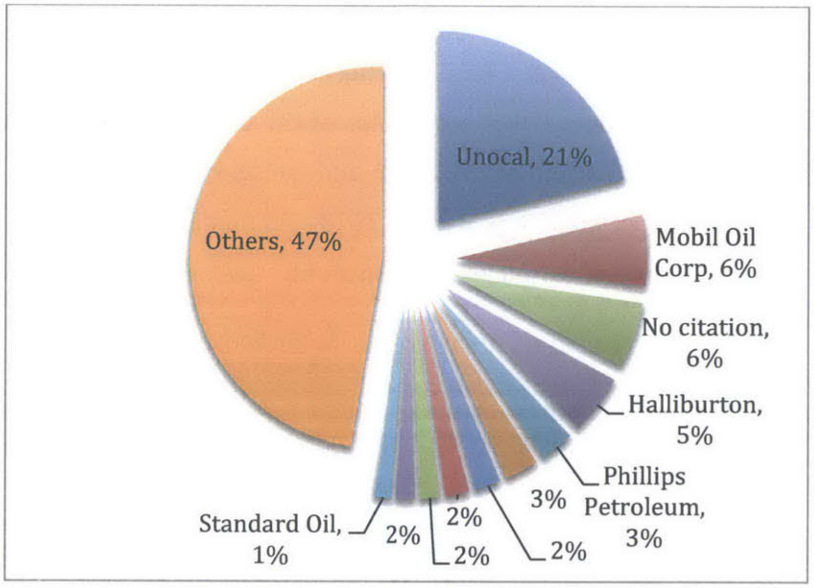
> *"We had a capability that other companies didn't had, and it was to motivate the guys at the research laboratory to get out of the lab and solve real world problems. We had a very good relationship with the Science and Technology people. The foundations of that where the personal links formed by having people stolen from Science and Tech and moved into geothermal"* (B. Barker, 2013).

Patenting activity

During the 1975-2000 period, Unocal was particularly productive in patenting geothermal-related technologies, as can be seen from Figure 12. Indeed, Unocal ranks after the DOE as the largest assignee of geothermal-related patents, and has the largest number of links with subsequent geothermal patents (Ruegg & Thomas, 2011). Most of the patents assigned to Unocal where not licensed to others, so patenting did not became a relevant source of revenue. Instead, they where mostly protective patents, to prevent competitors from using these innovations or to prevent competitors from patenting them before Unocal could have used them (Gallup, 2013; Kitz, 2013; S. Pye, 2013). The protective approach to patenting was transferred also to the company's policy on publication. Publication was rarely allowed outside the company (Amend, 2013) given that Unocal had a very secretive attitude towards the technical knowledge.

A large share of the stock of Unocal's geothermal-related patents are self-cited. This is confirmed by Figure 14 that details the sources of citation for all of 2,745 Unocal's geothermal related patents. From all of the citations, 21% are linked with Unocal, which is an evidence of the influence of the firm's knowledge base into its diversification. The second and third most influential sources for patenting comes from Mobil and Halliburton with only 6% and 5% respectively.

Figure 14: Direct sources of Unocal's geothermal knowledge (Hall et al., 2001)



As seen in Figure 15, there is an important rise of Unocal patent applications between 1988 and 1995, which is driven by the "Earth or rock drilling " (E21B) classification, representing 38% of the total Unocal geothermal-related patents (the largest share in the classification of patents)[73].

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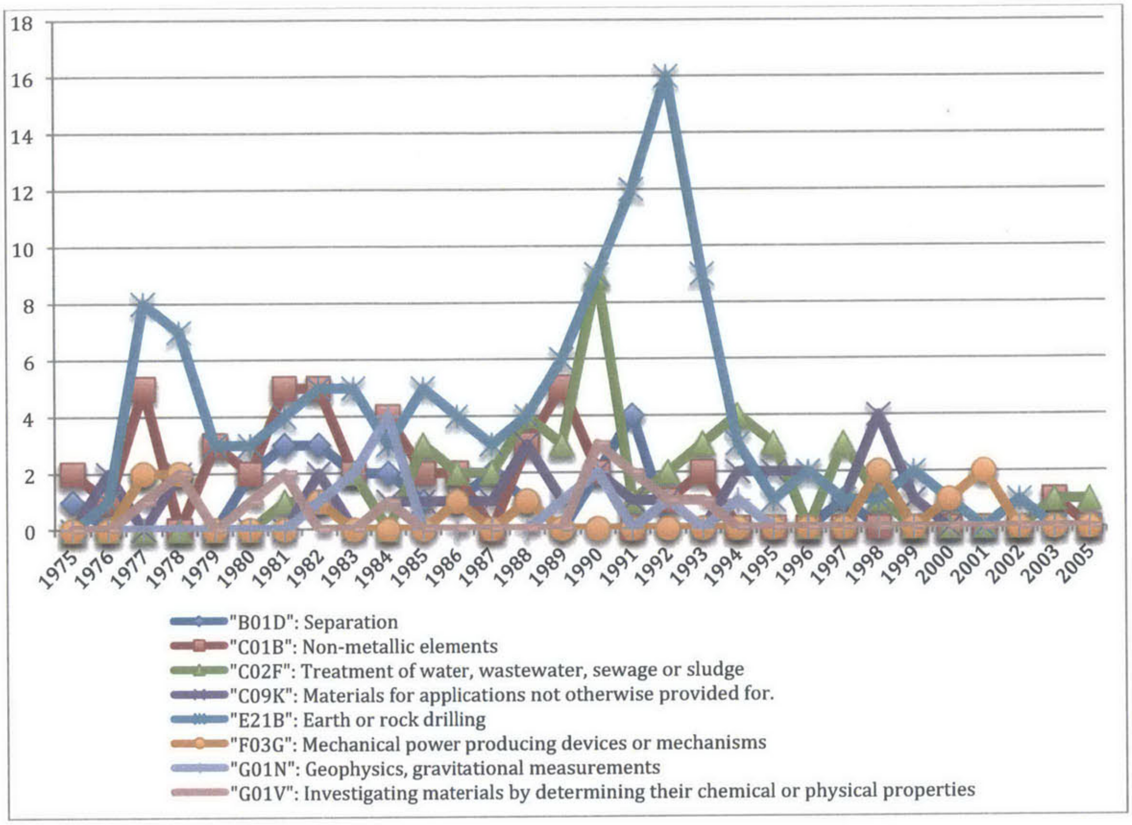
[73] The classification of geothermal-related patents is described under Appendix III.

Figure 15: Trend in patent applications per year and per classification code (Hall et al., 2001)



By analyzing Unocal's self-cited patents that are linked with Unocal geothermal-related patents we find out mostly all of the classification codes rely heavily on self-citation, with largest exception of E21B and C09K[74]. This is consistent with what is presented by Table 6, where the proportion of other sources of knowledge (other organizations) is much more relevant for the E21B & C09K classification codes, including influences like Mobil, Halliburton and Phillips Petroleum.

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[74] All classification codes are identified under Appendix III. G01N and G01V also do not rely on self-citations, yet these are a minority of the geothermal-related patents.

Table 6: Top 5% of cited organizations by Unocal's geothermal related patents (for each type of classification code) (Hall et al., 2001)

Patent classification	Fraction of patents without citations in total number of Unocal's geothermal-related patents	Number of citations from Unocal's geothermal-related patent stock	Name of organization
"B01D": Separation	10/160	27	Unocal
		11	ASAHI KASEI
		7	Dow Chem.
"C01B": Non-metallic elements	7/309	99	Unocal
		31	Mobil Oil Corp
"C02F": Treatment of water, wastewater, sewage or sludge	26/498	189	Unocal
		15	SOUTHERN PACIFIC LAND CO
		14	NALCO CEHMICAL CO
		11	ENVIROTECH
		9	MAGMA POWER CO
		7	Exxon Research & Eng.
		7	CALGON CORP
"C09K": Materials for applications not otherwise provided for.	15/424	60	Unocal
		49	Halliburton
		48	Exxon Research & Eng.
"E21B": Earth or rock drilling	71/1103	168	Unocal
		102	Mobil Oil Corp
		88	Halliburton
		70	Phillips Petroleum
		37	Marathon Oil
		35	Texaco Inc.
		27	Chevron Res

		24	Standard Oil
		22	Dow Chem.
		22	BAKER INT CORP
"F03G": Mechanical power producing devices or mechanisms	12/108	33	Unocal
"G01N": Geophysics, gravitational measurements	4/56	3	INST FR DU PETROLE
		3	Mobil Oil Corp
"G01V": Investigating materials by determining their chemical or physical properties	7/87	9	SCHLUMBERGER

Influence of government-funded research

Since the early beginnings of Unocal's geothermal activities, the firm was an active participant on industry panels to guide the R&D priorities of government-funded research institutions such as the Sandia National Laboratory. Some of the technical needs that were presented were issues like loss of circulation, high-temperature logging tools and other drilling-related topics (Sandia National Laboratories, 1989).

During the 1980s Unocal joined another DOE-industry consortium, again also implemented by the Sandia National Lab, called "The Geothermal Drilling Organization" (GDO), with the purpose of improving the drilling technology by reducing well costs and exploration costs (since the drill bit is the ultimate exploration tool).

Unocal engagement on the GDO, enabled a research agenda to help with field experiments primarily on (Knudsen, S. D., Sattler, A. R., Staller, 1999; S. Pye, 1989):

- High temperature elastomers,
- High temperature logging instrumentation (in particular the televiewer logging which became commercialized by Unocal),
- Percussive drilling,
- Foam for controlling loss of circulation and

- Deformed casing remediation.

Another relevant government-funded initiative was the Geothermal Loop Experimental Facility (GLEF), a consortia funded in 1976 including as members the San Diego Gas and Electric Co. (SDG&E) and Magma Power Co., which had the intention to manage the saline brine from the Salton Sea area and prevent scaling to occur[75]. Although Unocal was not part of this consortium, it greatly benefited its patenting activity as it can be seen from the backward patent citation analysis.

Although Unocal was the second largest assignee of geothermal patents (after the DOE), none of its patents were directly sponsored by DOE. Yet, public-sponsored research had a large influence on Unocal's technological solutions for the geothermal industry. Indeed, according to the DOE report "Linkages from DOE's Geothermal R&D to Commercial Power Generation", over 40% of Chevron's patents (which are almost only patent applications originally assigned to Unocal) are linked[76] with DOE-attributed geothermal-related patents, making it the organization with the highest share of its geothermal patents linked to earlier DOE-sponsored technological developments. The main families of geothermal related patents linked with DOE-funded patents are in the area of geothermal brine treatment through pH modification and for controlling salt precipitation and scale deposition (Ruegg & Thomas, 2011). This is confirmed by Table 7, which summarizes the first generation linkages between the stock of Unocal's geothermal-related patents and government-funded patents, highlighting the influence from government sponsorship on patents for silica control (C02F)[77].

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[75] Further description of this transfer is provided at the end of this chapter.

[76] This refers to first and second-generation backward linkages (Ruegg & Thomas, 2011).

[77] Indeed, patent 4429535 represents the achievements to handle the brine at the Geothermal Loop Experimental Facility, which became the main driver to help Unocal master the Salton Sea field, as it is explained at the end of this case.

Table 7: Number of citations to government-funded patents by Unocal's stock of geothermal-related patents (per classification code) (Google - USPTO, 2014; Hall et al., 2001)[78]

Name of Organization	"B01D"	"C02F"	"C22B"	"E21B"	"F03G"	Most influential patent
Government of the United States Department of Energy		6		1		4328106: Method for inhibiting silica precipitation and scaling in geothermal flow systems (6 citations by Unocal's geothermal)
Magma Power Co	1	9	3	1	2	4429535: Geothermal plant silica control system (13 citations by Unocal's geothermal)

In summary, Unocal indicated to the National Labs[79] which technologies were needed to master geothermal development, so it could later test new innovations funded by the government, and based on this publicly available information, extend their applicability to a commercial scale (DiPippo, 2013). This was the way the company "grabbed value" from the innovation ecosystem. Yet, the research base from government-funded work was not a requisite for Unocal's initial engagement on geothermal development, neither an incentive to disclosure its own scientific capital (B. Barker, 2013).

Learning by doing at the field

Unocal's achievements on the geothermal industry are the outcome of the ability and willingness from its team to learn, experiment and adapt. Originally, Unocal did not foresee the technical difficulties and risks from each field profile, and they did not possess all the capabilities required to commit to such operations. In fact, the people that initially joined the Geothermal Division were not experts in the exact topic, but had a good background on science and engineering and the ability to adapt what they have been doing in one place to the challenges of another place, by integrating different sources of knowledge (vendors, Science and Technology Division, government-sponsored research) and testing them at the

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[78] Description of each classification code is available under Table 13.

[79] Sandia National Lab became a big driver in high temperature tools and the Brookhaven National became strong on cements and coatings (Atkinson, 2013; S. Pye, 2013).

geothermal field[80] (Atkinson, 2013; Barnes, 2013; Gallup, 2013; Henneberger, 2013; Newell, 2013; S. Pye, 2013). If the knowledge was not available at the Geothermal Division or the Science and Technology Division, Unocal could always reach out to other sources like external consultants, National Labs, or – less probably - vendors. If it was more sophisticated than that, they could always advocated for the government to support the development of such technology. Nevertheless, no matter how complex the tasks would be, the Geothermal Division was always the final responsible to implement and adapt the solution to the field's reality (B. Barker, 2013; S. Pye, 2013).

Unocal's approach to risk management in the field was to empower its team to test new ideas and cope with high-risk endeavors. Taking risks was the common practice by oil and gas companies at the time, and Unocal's geothermal operations was not an exception (B. Barker, 2013; Kitz, 2013; S. Pye, 2013). This is confirmed by Steven Pye (engineer and general manager for Unocal's geothermal operations at the Philippines) by stating that

> *"Drilling wells in the Geysers, Tiwi or the Salton Sea isn't much more different than drilling wells anyplace else. So there are a few additional challenges, but there are always a few additional challenges"*.

The company's culture was to promote experimentation with technical proficiency and a problem-solving mindset (Isselhardt, 2013; Maione, 2013; S. Pye, 2013). As Pye corroborates,

> *"You hire good quality people and provide them good training and then you left them go out and make mistakes and reward them for their ingenuity"* and *"the company cuts its teeth with whatever new problem was required to be solved"* (S. Pye, 2013).

This approach to learning in the field would also be carried over to the relation with vendors: if there was a failure on the adaptation of a technology to uncertain conditions,

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[80] A good example of Unocal's intrepid approach to field-experimentation comes from the article "Performance of Oil well Cementing Compositions in Geothermal Wells" by (Gallus et al., 1979): "Normally, the necessary advances in hydrothermal cement chemistry would precede field experimentation. However, we needed immediate information about cement durability in geothermal wells, and the necessary research would require almost a decade to complete. Therefore, we decided that the urgently needed data could be developed best in the shortest period of time by empirical field testing in actual geothermal wells with cementing compositions exposed to geothermal fluids and temperatures".

Unocal would take all the financial risk (Barnes, 2013; Kitz, 2013; Otte, 2013). Kevin Kitz (engineer and manager for Unocal) recalls,

> *"Unocal didn't went back to the vendor and said, "this didn't work. You owe us a refund", instead they said "well, that still doesn't work, let's try upgrading it again", and then they would pay for the next evolution"* (Kitz, 2013).

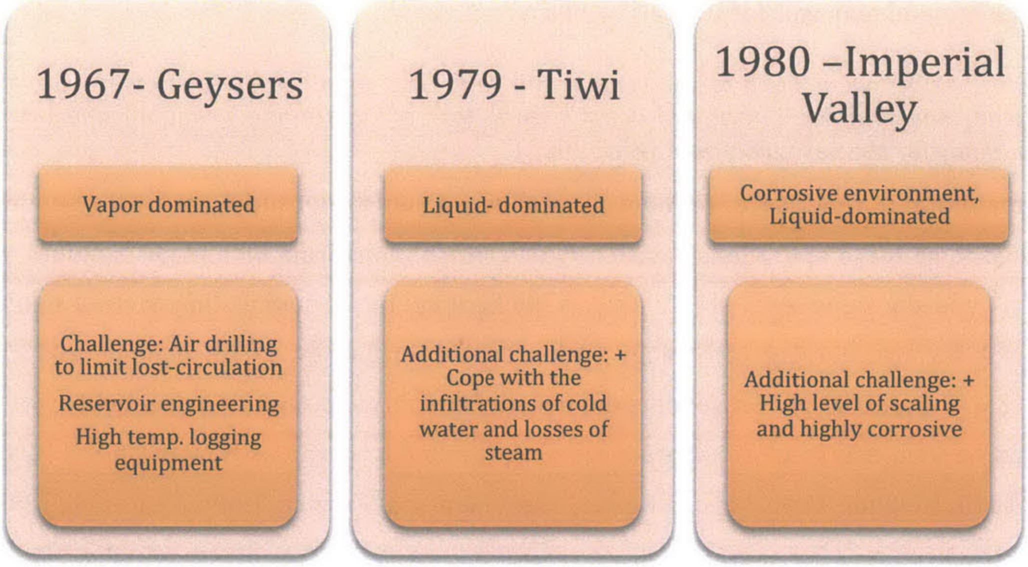
At that point in time there was no well-established industry of suppliers for the geothermal industry, so these operations had to rely on contributions from oil and gas vendors, which didn't had the same level of initiative as the field operator, neither they were a significant source for transferring technology (Atkinson, 2013; Barnes, 2013; Maione, 2013; Otte, 2013; J. Tester, 2013). Yet vendors did benefit from this exposure to a new field of work, as it can be seen that some collaborate research resulted from the work with Unocal (Gallus et al., 1979; Holligan, Cron, Love, & Buster, 1989; Maney & Strozier, 1989; Zilch et al., 1991)

Incremental level of technical sophistication for the Geothermal Division's business units

Each of Unocal's geothermal business units called for a set of unique technological solutions that required the flexibility and adaptability of its geothermal subsidiaries and the Science and Technology Division. The more Unocal got involved in geothermal energy, the more sophisticated were the technical challenges it confronted, and so they had to create new capabilities and new technologies to overcome those technical challenges which were not necessarily related to their previous core competences (Amend, 2013; Barnes, 2013; Kitz, 2013).

Figure 16 summarizes Unocal's learning path in managing the field's operation in a selection of three business units from the Geothermal Division. These units are the Geysers project (which incorporated air drilling and confronted issues with high temperature logging equipment), the Tiwi project (which confronted the challenges of a liquid dominated resource) and the different projects at the Imperial Valley, California (which had to deal with a very corrosive brine). Each of these three units or fields represents an incremental level of technological sophistication, and thus a learning path on Unocal's geothermal activities.

Figure 16: Main technical challenges from Unocal's development into geothermal energy



The rest of this chapter explains the most significant technical developments necessary to meet the challenges confronted by these three geothermal business units in order to meet Unocal's operational responsibilities and keep geothermal cost competitive. These technical challenges are the units of analysis for the Unocal case, with data consolidated from the various interviewees. For each challenge, we identify the source of the knowledge required overcome technical difficulties and the transfer mechanisms. It is important to emphasize that these technical challenges are not exclusive to one geothermal field. Instead they are linked with the characteristic hurdles confronted by the firm in that specific project. That is, while the Geysers project had to solve critical issues on air drilling, reservoir engineering and high temperature logging equipment, the Tiwi project had to build on the Geyser experience and move beyond it in order to, overcome new challenges like the infiltration of cold water. The same applies with the fields at the Imperial Valley, where the firm had to address scaling and corrosion in addition to the technical hurdles encountered in the previous fields.

The Geysers - California

The Geysers Geothermal field is the first privately developed geothermal power project and the largest geothermal field in the world (in terms of its area – at least 100 km^2). This project is located 100 km north of San Francisco, at the Sonoma County of California (Khan, 2010). The Geysers field is a vapor-dominated field, given that it produces saturated steam instead of water or a mix of steam and water. In addition, there are no relevant infiltrations of cold or hot water from outside the reservoir that influence the quality of the field. Therefore, this field corresponds to a closed system[81] (Kruger & Otte, 1973; Sanyal & Enedy, 2011). Thanks to Unocal's contribution to the operation of the Geyser's field, the rate of growth of the installed power capacity increased importantly from 26 MW in 1965 to 520 MW in 1975 (Table 5).

By the second half of the 1970s, Unocal undertook **exploration** campaigns based on 53 thermal gradient boreholes (as deep as 500 meters) and 4 deep exploration wells (as deep as 2,358 meters). Later, Unocal made the exploration data publicly available, in exchange of DOE's share of the exploration expenses (Department of Energy, 2010a). Still, these initial explorations were based on tools and techniques directly transferred from oil exploration, which didn't fit with the behavior of geothermal fields. Besides, since the Geysers was the only geothermal field Unocal knew and had successfully developed during the early 1970s, they were not prepared to identify fields without surface manifestations (S. Pye, 2013).

Generally speaking and during the first years of operations of this field, most of the technology to solve these drilling challenges was initially carried over from the oil and gas industry with some variations. Further, this development faced drilling problems not encountered in drilling oil and gas wells, like hard rock drilling, loss of circulation and the lack of proper instrumentation for high temperature conditions (Kruger & Otte, 1973). Still, with the need to reduce drilling costs, Unocal and the industry in general, had to search for technological alternatives that could alleviate some of the challenges described in Chapter V. An important part of this need was solved through the GDO plus other public-sponsored research projects.

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[81] Both conditions, steam field and a closed system, make this field quite uncommon, since only half a dozen of similar vapor-dominated fields are commercially exploited in the world including the Larderello field and the Matsukawa field in Japan (Kruger & Otte, 1973).

The Geysers reservoir consists of a highly fractured, slightly metamorphosed sedimentary and igneous rock referred to as greywacke sandstone. Under these conditions, **drilling penetration** rates become too slow and raised the risk of failure of the joints on the drill pipes, even when using bits specifically designed for hard rock drilling (Isselhardt, 2013; Kruger & Otte, 1973). Still, the first developments relied on existing drill bits designed for hard rock drilling for upstream oil operations (S. Pye, 2013). By the late 1980s, there was an important effort by the Sandia National Laboratory to increase the rate of penetration and the longevity of the polycrystalline diamond compact (PDC) bits[82] in their use at geothermal operations. This was field tested in continuous cooperation with Unocal's Geothermal Division and several bit manufacturers, so it could become a commercial application for geothermal (DiPippo, 2013; J. T. Finger & Glowka, 1989; Hoover & Pope, 1981).

The Geysers reservoir is a dry steam system, which has a lower pressure (550 psi) relative to a hydrostatic geothermal reservoir. Therefore if it is drilled with mud and water (which is a circulating fluid heavier than the pressure from the fluids in the formation), there can be massive **losses of the circulation fluid** and thus no recovery of the steam. The solution to address this problem was to drill with air at depths exceeding four kilometers in order to have a pressure balance with the air column, relying on integrating existing technology from Unocal's upstream oil operations. As stated by Stephen Pye:

> "*So you would pick this piece from the Rocky Mountains where they drilled a lot with air*" (B. Barker, 2013; Isselhardt, 2013; S. Pye, 2013; Sanyal & Enedy, 2011; Williamson, 2013).

Later, in 1987, through Unocal's involvement in the GDO, lost circulation was addressed through the collaboration with several industry actors (including Halliburton) and research institutions (including Sandia National Labs) (Department of Energy, 1995; J. T. Finger & Glowka, 1989)[83].

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[82] PDC bits were already an innovation in place for the oil and gas operations. The temperature and the hardness resulted initially in a poor performance in geothermal. The efforts to improve PDC bits have been able to overcome these problems, but still in most of the cases drilling is still done with tri-cone bits (S. Pye, 2013)

[83] This type of projects did not isolate the lost circulation issue from other technical challenges. Instead, they integrated as well the development of instrumentation to characterize loss circulation

As it has been explained under Chapter V, normal **logging equipment** used for upstream oil operations was not transferable to the environmental conditions of geothermal reservoirs, given the very **high temperatures.** Early operations had to rely on a set of approaches to measure the borehole's characteristics (to mitigate the risk of burning the equipment): wait until the boreholes could cool down, do single shot surveys, do regressions based on measurements up on the shallow part of the well (which is cooler), or manage the directional part of the well. Vendors were unwilling to develop a heat logging technology that could withstand these conditions unless the field operators would agree to take all the financial risks for such technology ventures. High temperatures would also melt seals such as the matrix where the diamond drill bit would be set, making the bit collapse (Barnes, 2013; Isselhardt, 2013; S. Pye, 2013). During the mid 1970s the Sandia National Laboratory led influential research for adapting existing logging instrumentation to high temperatures through the Geothermal Logging Instrumentation Development Program (with the short term goal to reach 275°C, and 350°C as a long term goal)[84]. Unocal's Geothermal Division was a key partner to test these new technologies. Further work on this field would be later continued by Sandia through the GDO (DiPippo, 2013; Veneruso et al., 1978).

From the early beginning of Unocal's involvement in the Geysers project, there was evidence of a declining productivity on the wells' performance, which was studied since 1967. Additional wells had to be continuously drilled to keep a same level of steam supply for the generation units. In addition, substantial internal efforts were devoted to optimize well spacing through mathematical simulation (Kruger & Otte, 1973). In the case of the Geysers field there was initially no incentive to manage the reservoir, because the steam was not a valuable commodity and because there was no external cheap source of water to be re-injected (DiPippo, 2013). As the field got more populated by several other operators and as Unocal started to develop liquid dominated fields in other areas, they started to realize the importance of reinjection and managing the **balance of the reservoir.** During

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zones, the development of downhole tools to assist the placement of control material, and the development of improved treatment materials (Department of Energy, 1995).

[84] Some of the tools included to be upgrade are those that measure temperature, flow rate, downhole pressure, caliper, and fracture mapping sondes.

the early 1980s, Unocal's Geothermal Division explored the feasibility of injecting the winter runoff from the Big Sulphur Creek. Initially this approach was discarded given that energy prices didn't justify the development of new water sources for injection, but later it was implemented[85] (B. J. Barker, Maney, Camille, & Williamson, 1990; Crecraft & Koenig, 1989). In the early-nineties Unocal joined an ambitious collaborative project with other operators of the Geysers field (Calpine and the Northern California Power Agency), with the purpose of investigating the decline in the Geysers' field generation capacity and implement the reinjection of treated municipal effluents to maintain the balance of the Geysers reservoir (Department of Energy, 1995; Sanyal & Enedy, 2011).

Unocal's participation in the Geysers project ended in 1999, with the sale of the field's operations to Calpine.

Tiwi - The Philippines

The Tiwi field is located on the northeastern flank of Mount Malinao (volcano), on the southeastern side of Luzon Island (the Philippines). As early as 1971 Unocal received an invitation from the Philippine Government to explore and develop geothermal resources on this area. An agreement was achieved in 1971 through a service contract with the state-owned National Power Corporation (NPC), where Philippine Geothermal Inc. (PGI – Unocal's subsidiary in charge of this geothermal business unit at the Philippines) would be in charge of funding and executing the exploration and the development of the Tiwi field, while NPC would be responsible of building and operating the power units (Alcaraz, Barker, Powell, & Datuin, 1989).

Most of the challenges encountered in the Geysers project (high temperature logging equipment, reservoir engineer, balance of the reservoir and hard rock drilling), were also present in this field. Beyond this, Tiwi was like a greenfield development in terms of capabilities. No prepared workforce was available at the Philippines that could replicate the

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[85] This project became later economically feasible thanks to the gradual increase in information from collaborating with other operators of the field, and also thanks to the merge of assets (from a series of acquisitions) which allowed economies of scale and the integration of field management, hence reducing the operating costs (Sanyal & Enedy, 2011).

successful experience from the Geyser let alone improve on it. Therefore a lot of technology had to be transferred by expatriating Unocal employees from other operations to the Philippines, where they would become the trainers and managers of this new development. After this they hired a large staff of 400 people from Philippines to learn and populate the local subsidiary (Barnes, 2013; Gallup, 2013).

One of the most challenging issues in the operation of the Tiwi project was to manage the field under a new environment (water dominated), with a totally different behavior to the Geysers field (dry-steam reservoir). The extraction of water for electricity generation caused the formation of steam zones in the reservoir and the unpredictable **infiltration of cold water** into the reservoir. This last effect decreased the productivity of the wells during 1983-1987. Consequently PGI had to implement different innovations to mitigate this productivity loss: move drilling west to largely unaffected areas, undertake recompletion and stimulation programs (Barnes, 2013; Hoagland & Bodell, 1990; S. Pye, 2013). Such solutions where the result of PGI's ability to integrate different knowledge sources including their own expertise and that of the Science and Technology Division, so as to experiment on the field new solutions or adapt existing ones. Still, as Benjamin Barker acknowledges

> *"The most successful achievements were thanks to the folks in the field looking at the data everyday and making observations on what seem to be going on and then going out and testing solutions"* (B. Barker, 2013).

In particular, one of the ideas was to inject chemicals to reduce the permeability of a large area and slow the infiltration of cold water. This idea was put forward by the PGI people in the field, designed by the Science and Technology Division, and finally tested and implemented by the PGI in the field (B. Barker, 2013).

The **contracting model** between PGI and NPC was drafted as a "cost recovery and operating fee contract", similar to Unocal's contract with PG&E for the Geysers project. Such arrangement allowed the recovery of PGI's operating costs, a profit and the interest on the investment they made. If the field was unproductive, the operator received a partial reimbursement of the initial costs, to guarantee a certain return on the investment. PGI supplied steam and received a share on the revenues from electricity sales, which was the common contracting practice in the oil industry (and that of Unocal's other geothermal activities at that point in time)[86]. This original contracting arrangement had the consequential effect of an inefficient operation of the power plants, since the generation company (NPC) didn't have the incentive to make an efficient use of the steam[87]. In addition, Tiwi suffered a sharp decline in production capacity from 280 MW to 190 MW between 1983 and 1987.

Correspondingly, PGI decided to first, **improve the management of the steam gathering system**. Five different approaches to improve the steam gathering system had to be implemented, which are detailed under Table 8, with the respective outcome in terms of power capacity increase (Gambill & Beraquit, 1993). There is no evidence of external support to overcome these technical challenges during the early nineties.

Table 8: Different approaches to improve the steam gathering system (Gambill & Beraquit, 1993)

Steam gathering system efficiency	Increase in production (MW)
1. Improvements to the steam-gathering system flexibility (1990)	10 (one line to 4 power units)
2. Decreased scrubber flooding (1987-1990)	1
3. Introduction of steam washing (1991-1992)	3.5 (one unit)
4. Maintenance of pipeline insulation (1990-1991)	25
5. Increase effectiveness of wellbore scale-removal (1991-1992)	5 (7 wells)

The second reaction to the decline in production capacity, was to **improve the efficiency of NPC's power cycle** (Kitz, 2013). PGI's assisted NPC with the rehabilitation of the power cycle, during the early nineties. To provide this service, PGI partnered the Japanese consultant company West Jec, to design the improvements incorporated into the

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[86] After the first price oil crises beginning in 1973, the contract was revised: the original steam pricing formula indexed to oil prices was replaced so as to not overrate the steam value and also NPC's risk in the steam field development was increased from 25% to 55% of the investment. As recognized by Philippine volcanologist and geothermal expert Arturo Alcaraz "*Both parties have shown their adaptability to changing circumstances. They worked together to evolve a contract beneficial to both*" (Alcaraz et al., 1989; Barnes, 2013; Dolor, 2006).

[87] If the operator of the power cycle pays the field operator a share from the total revenues, then it will not have the incentive to make an efficient use of the steam it receives. Instead, if the contracting agreement is based on a fixed rate per unit of steam, then the power cycle operator will be incentivized to make an efficient use of the resources it acquires.

rehabilitation, and with the engineering firm Sinclair-Knight-Mertz (New Zealand) to implement a brine separator technology that they had developed, along with other techniques from previous Unocal experience (DiPippo, 2013; Kitz, 2013; S. Pye, 2013).

After a long negotiation, compromise was reached around 2003 to renew PGI's contract with NPC, by which PGI would have to sell 60% of its ownership to a Filipino company and the pricing mechanism was changed from a fee contract to a steam sales contract based on a fixed rate per unit of steam ($/lb or $/BTU basis) (which significantly reduced the income from this project) (S. Pye, 2013).

Imperial Valley – California.

The Imperial Valley lies in the Imperial County at the south of California. The Valley is crossed by the San Andreas fault and bordered by the Colorado River to the east and includes the Salton Sea. The Salton Sea geothermal reservoir is the largest of several geothermal resources within the Imperial Valley (Unocal, 1989).

Since the early days of Pure Oil's engagement into the geothermal business, the development of the Imperial Valley area (among the other resources owned by Pure) had been an ambitious objective of Dr. Carel Otte. He was well aware of the large potential of this area[88] but also of its difficulties, given that the first tests had revealed a very corrosive brine that obstructed the wells and had even forced the shutdown of the first pilot at the Salton Sea after only 1,000 hours of operation [89] (Berger, 1998; Featherstone, Co, Powell, & Co, 1981). As explained by Chapter V, another important difficulty was the siliceous scaling in the steam production line and the heat exchangers.

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[88] Each well in this field produces over 1.5 million kg/h of brine, which is equivalent to the generation of 30 MW of electricity (McLarty & J. Reed, 1992), whereas in normal wells you would only have 5 MW. This level of productivity was the main reason to persist in solving the corrosion problems at the Imperial Valley. Instead, in most of the fields, if the produced fields look as if it is going to be corrosive, they would not be economically viable (S. Pye, 2013).

[89] The brine is characterized as an extremely high salinity liquid with a total dissolved solids (TDS) concentration greater than 200,000 ppm and is supersaturated with silica and heavy metals (Featherstone et al., 1981). Over 20% salt by weight (McLarty & J. Reed, 1992). The major risk is to control the brine during steam separation and brine injection, and avoid its solidification.

All of the previous geothermal business units (Geysers, Tiwi, Mak-Ban) had proved to be an incremental evolution on the transfer of capabilities from the oil industry. However once the company arrived at the Imperial Valley, it had

> *"virtually no corporate applicable intellectual property or know-how. Is a grass-root development project which is supported by the fact that at that time in the world oil companies had actually a research and development division",*

as recalled by Kevin Kitz (Kitz, 2013). The fields at the Imperial Valley area had to confront not only most of the challenges described above for the Geysers and Tiwi fields, but also handle unusual levels of corrosion and salinity.

The development of the Imperial Valley fields was one of the greatest accomplishments of geothermal energy development because it was the first enterprise to demonstrate the commercial viability of power generation from highly saline geothermal fluids (DiPippo, 2013). The company was able to master the very corrosive environment of the Imperial Valley's highly saline brines and develop, as seen on Table 5, a first flash pilot plant of 10 MW at North Brawley[90] in 1980, a second flash pilot plant of 10 MW at the Salton Sea in 1982[91], a double flash generating plant of 52 MW at Heber in 1985 (together with Chevron)[92], a 47.5 MW unit (which later became of 53.9 MW) at the Salton Sea in 1989 and a 19 MW unit also at the Salton Sea in 1990 (Moody's Investors Service, 1985b; Unocal, 1989). These operations where an incremental transition of experimentation and learning that evolved from pilot units to prepare the capabilities for larger commercial power projects. Every project built the knowledge base to develop the next one.

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[90] This project lasted for five years as a pilot, because of reservoir uncertainties.

[91] Salton Sea Unit 1, which incorporated design and engineering drawn from the Brawley project. It was also intended to test and evaluate new methods for controlling scaling and corrosion related with high levels of solids from the Imperial Valley's fluids.

[92] The Heber project was the first commercial plant using a double flash system, suitable for moderate temperature projects and with less consumption of brine than a normal flash plant. This has helped to reduce corrosion and scaling in turbines and heat exchangers. The operation of the field was in charge of Chevron although Unocal acted as a partner (Department of Energy, 2010; Moody's Investors Service, 1985).

Reservoir engineering was initially transferred from Unocal's oil and gas expertise, even though the results of models where not representative. In distinction to oil reservoirs, a geothermal reservoir by definition must be in motion, so you have to model an active convection process of mass and heat transfer. Therefore, specialized reservoir engineering was required to first size the power unit because of the uncertainty regarding the reservoir's capacity, and second to identify where to re-inject the condensate fluid into the reservoir without causing cooling in the production zone. Initially the main modeling tool was an adapted version of the standard modeling reservoir-engineering tool from oil and gas, developed by Professor Henry Ramey of Stanford[93]. However, it was not until 1980 and thanks to a workshop set by DOE to test available geothermal reservoir simulators, that numerical models for reservoir management of geothermal projects (like dual porosity models) were generally accepted (Atkinson, 2013; B. Barker, 2013; DiPippo, 2013; Henneberger, 2013; Kitz, 2013; S. Pye, 2013; Ramey, 1975; Stanford University, 1980; J. Tester, 2013; K. Williamson, 2013).

The very-hot fluid characteristics at the Imperial Valley and Salton Sea, makes it difficult to model phase-behavior through numerical simulations. The assistance on **reservoir engineering** arrived from Unocal's Science and Technology Division who was in charge of developing a suitable software that could represent the behavior of the field (B. Barker, 2013). Later, some engineers of this team were transferred to the Geothermal Division, since their knowldge was perceived as specifically valuable for geothermal. In summary, although there was an active role from the experts of the Geothermal Division, the supporting knowledge to model the reservoir came ultimately from outside the Geothermal Division (S. Pye, 2013; K. H. Williamson, 1990).

There was no prior experience from oil and gas that could be directly transferred to handle the highly **corrosive** and saline environment that affected the **casing** of wells at the Imperial Valley. Initial guidance to address this problem was publicly available from DOE-sponsored research. While this guidance was not specific to the particular challenges

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[93] Professor Ramey was the chairman of the Department of Petroleum Engineering at Stanford. He and some of his fellow professors were hired by PG&E as chief consultants at the Geysers project, with the purpose of validating the adequacy of the resource before the California utility commission. Ramey conducted the first well tests at the Geysers field (B. Barker, 2013; Stanford University, 1993).

confronted at the Imperial Valley fields, yet it gave to the Science and Technology Division referential information about the performance of materials under different chemical compositions of the corrosive medium[94] (Amend, 2013; S. Pye, 2013). As Bill Amend recalls (who used to work for the Science and Technology Division):

"The DOE reports gave us a better idea of what the next steps in the program should be" (Amend, 2013).

The Science and Technology Division was actively connecting with the experts on this area, by joining the National Association of Corrosion Engineers (NACE), networking with corrosion resistance alloy manufacturers and interacting with the staff from DOE's geothermal program (Amend, 2013). At the field, the problem of corrosion on the casing was addressed using a test bed at the Salton Sea that allowed a collaborative working environment between the Geothermal Division, the Science and Technology Division and specialized vendors, so as to design and manufacture new alloys of metals for casing and threaded couplings. Field experience proved the successful use of Beta-C titanium for the casing of the production wells, which unlike carbon steel, didn't deteriorate under corrosive environments and also reduced the scaling in the wells (Holligan et al., 1989; D. S. Pye, Holligan, Cron, & Love, 1989).

By the late 1970s, the common practice to deal with casing stress in the oil and gas industry was to fully cement the wells with Portland cement plus additives. However, there was little applicable information about high-temperature hydrothermal cement chemistry and oil-well cements were perceived as unsuitable for geothermal development. Not even the Science and Technology Division had a good way of testing **high temperature cements**, (given that not much oil and gas wells were drilled to more than 10,000 feet). So by the late 1970s, Unocal requested the support from Halliburton and supplied a laboratory on-site (all under Unocal's expense) for developing a new testing procedure for geothermal cement mixes. One solution was to add silica flour to the cement so it could resist higher temperatures, and although this has common use today, it would only protect the casing from corrosion for a pH above 5.5 which did not represent the conditions of the Imperial Valley (B. Barker, 2013; Gallus et al., 1979). Under the highly corrosive environment of the Imperial Valley, cement would rapidly deteriorate by carbon dioxide, so this mix would last

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[94] The main guidance document is available in (DeBerry, Ellis, & Thomas, 1978).

for only months and wells would have to be re-drilled and re-cemented. Given that Unocal was actively advising the government on the key research priorities to promote geothermal development and considering that problems where occurring with this issue during the mid-1980s, they emphasized the need of developing **corrosion resistance cements** (Shen & Pye, 1989). As a response, a research consortium was brought in the mid-nineties, including Unocal (Geothermal and Science and Tech Division), Halliburton and the Brookhaven National Laboratories. The outcome of this work was a corrosion-resistant cement, which doesn't change with exposure to carbon dioxide thanks to zeolite and calcium phosphate minerals that block this destructive chemical reaction[95], and is currently commercialized by Halliburton as ThermaLock™[96] (Brookhaven, 2000; S. Pye, 2013).

Another relevant innovation that was encouraged by the environmental conditions of the Imperial Valley (high salinity and temperature, and high levels of carbon dioxide) was the development of **new drilling fluids**. A conventional drilling fluid would flocculate under high temperatures, had poor loss control and was sensitive to contamination by brine. Instead a so-called "third-generation geothermal drilling fluid" would perform properly under these extreme conditions[97]. This product was also the result of a collaborative and cohesive effort joining Unocal's Geothermal Division, the Science and Technology Division and vendors[98] (Zilch et al., 1991)

Dissolved silica in the produced brine created **scaling** (precipitation of the silica outside of the wellbore), which didn't allow the brine to be re-injected. One initial solution for this was to limit the drop of pressure of the brine and keep it at a necessary minimum temperature and pressure so it could still be re-injected. Yet, this limited the power productivity of the

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[95] The first large-scale field testing of this product was done at Unocal's geothermal operations in Indonesia

[96] ThermaLock™ is a non Portland cement system. A complete description of this product is available at http://www.halliburton.com/en-US/ps/cementing/materials-chemicals-additives/cement-blends/thermalock-cement.page#

[97] Its principal ingredients are Bentonite (as a viscosifying agent), a low molecular weight copolymer (for high temperature deflocculation and rheological stability), a sulfonated lignite and a modified vinyl copolymer (for high temperature filtration control) (Zilch et al., 1991).

[98] The vendor was Milpark Drilling Fluids who later became a stand-alone division within Baker-Hughes (Zilch et al., 1991).

field[99] (S. Pye, 2013). Two alternative approaches were developed by Unocal to handle the brine and reduce the scaling[100]: The first approach was the pH modification treatment, developed originally by Darrell Gallup (chemist of Unocal's Science and Technology Division), which addressed the scaling problem by injecting acid to retard the precipitation of the silica[101]. pH modification was successful to handle the brine in fields like Tiwi or Mak-Ban but it was harder to control scale deposition at the pilots of the Salton Sea and Brawley, although it became commercially operational by 1982 (L. Gallup & W. Jost, 1985; S. Pye, 2013).

Separately, the underlying science for a second approach was being developed thanks to a government-industry sponsored research initiative called the Geothermal-Loop Experimental Facility (GLEF)[102], which was built by 1976 with the purpose of solving the silicate **scaling** problem of the Salton Sea brine (DiPippo, 2013; McLarty & J. Reed, 1992; Newell, 2013). The idea was to allow as much of the brine to discharge into the crystallizer and solidify as salt. The outflow fluid was treated in a clarifier, where the remaining silica precipitated (Berger, 1998; S. Pye, 2013). The support from the GLEF was critical to prove this idea in a lab setting. Yet it needed further development to scale-up as a commercial application. Unocal was not part of this consortium, but saw an opportunity to benefit from this research initiative. So it lured John Featherstone (who was the main leader behind the GLEF project) away from Magma Power Co. to Unocal's Geothermal Division, and empowered him to develop a commercial application of the GLEF knowledge, which became the crystallizer-clarifier technology. Magma Power Co. was simultaneously also trying to

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[99] For each subsequent stage of flash, the pressure and temperature would drop, reaching the phase when the silica started to form as a solid and precipitate, thus creating scaling which prevented the reinjection (S. Pye, 2013).

[100] Other options to handle the silica explored during this time (but which were discarded because of their environmental impacts) were to precipitate all the silica in a pond or pump it in the sea (S. Pye, 2013).

[101] The most relevant and influential patents from Unocal related to this technical innovation (according on how frequently they have been cited by subsequent patents) are US 4537684 (Control of metal-containing scale deposition from high temperature brine) and US 4830766 (Use of reducing agents to control scale deposition from high temperature brine).

[102] Members of the GLEF where the San Diego Gas and Electric Co. (SDG&E) (acting through its subsidiary, New Albion Resources Co.) and Magma Power Co. The facility located in Niland (Imperial Valley) had an initial size of 10 MW. Costs where shared 50-50 by SDG&E and ERDA. The main purpose of the GLEF was to determine the technical and economic feasibility of the flash-binary cycle under the environmental conditions of the Salton Sea and also to establish the geothermal capacity and characteristics of the Salton Sea geothermal resource (Featherstone et al., 1981; Lombard & Nugent, 1975).

test the commercial applicability of what they had learnt with the GLEF project, and although Unocal and Magma Power were competitors, "*there was an awful [lot of] side by side sharing and looking over the fence and talking with each other*", as recalled by David Newell, former Senior Director for Unocal's geothermal business development (Newell, 2013).

Both of Unocal's competing alternatives to prevent scaling, the pH modification treatment and the crystallizer-clarifier technology, were the outcome of integrating several sources of knowledge that could be persistently tested on the field (24-hour a day pilot tests), with the collaboration of the Geothermal Division, vendors and the Science and Technology Division (Newell, 2013).

Thanks to the PURPA regulations described under Chapter IV, Unocal took the decision to diversify into the power generation business and created a subsidiary called Desert Power Company to acquire and operate the 47.5 MW Salton Sea Unit 3 from Southern California Edison (SCE), and in 1989 act as an independent power producer (IPP) contracted to SCE. In order to enter into the power generation business and acquire these capabilities, the company had included in its agreement with the SCE the transfer of the operation and maintenance team. In addition to this, and outside the scope of the agreement, Unocal recruited some of SCE's management and technical experts. Later, this capability was leveraged at Indonesia, where the company did not only operated the geothermal field but also but also operated the power plant for the second unit (S. Pye, 2013; Unocal, 1989).

By 1993 the firm had sold its Imperial Valley projects to Magma Power Co. putting end to an important era of corporate innovation.

Discussion of the case

The Unocal case depicts a progression in technology development from relatively low innovation and a high leverage of the firm's existing core competency towards a high level of innovation, leveraging corporate resources in the R&D department, but not relying on the technology from the core business. Figure 17, Figure 18 and Figure 19 show graphically the structure proposed from Chapter III to synthetically represent the units of analysis. These figures are used repeatedly to summarize the main sources of knowledge and the transfer mechanisms for each of the technical challenges studied. Each chart provides a schematic representation of the knowledge sources and the transfer mechanisms for a generic technical challenge. The large rectangles represent the boundaries of the different knowledge sources available whereas the smaller squares represent the different transfer mechanisms to access the sources of knowledge. From the inside out, the large rectangles and its respective small squares are: on a first level, the geothermal division's internal capabilities (including capabilities inherited from upstream oil and recruitment); on a second level, the assistance from the firm's in-house R&D group (including direct assistance and labor reallocation); and on a third level the support from the ecosystem beyond the firm's boundaries[103] (including service contract, a consortium and public available information)[104]. If a rectangle or square is white or grey, means that it was not a relevant source of know-how or was not used as a transfer mechanism. It is important to remember that the technical challenges represented as units of analysis, do not necessarily apply to the whole geothermal field, instead they are hurdles confronted by the firm within a specific project.

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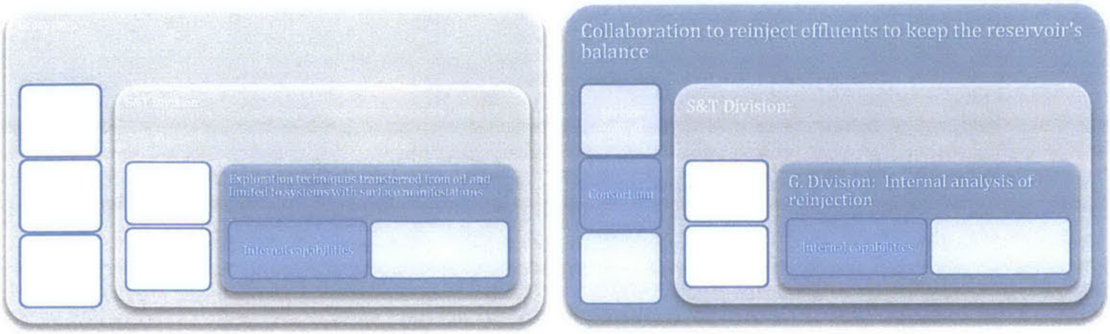
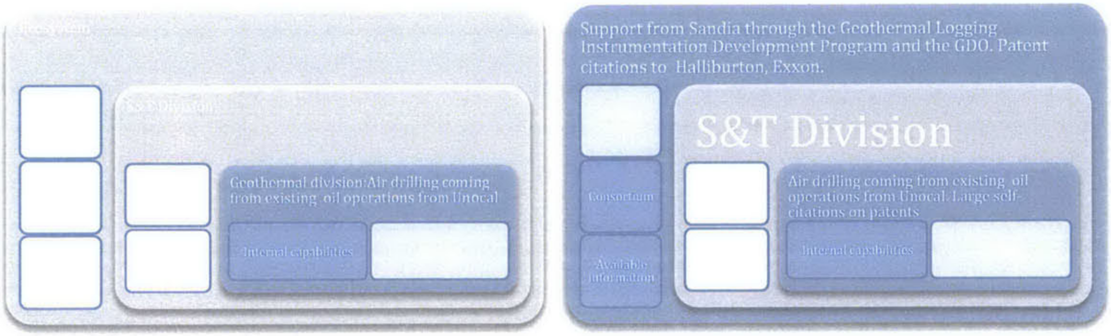
[103] Including other operators, vendors or government-sponsored research projects that could be implemented by National Labs.

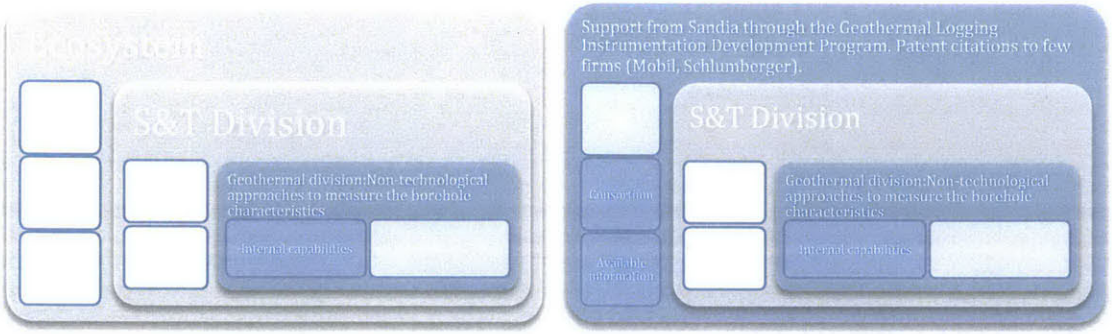
[104] Consortium is defined when the risk is shared and there is government sponsorship and service contract when there is no shared risk with the vendor.

Figure 17: Source of knowledge and transfer mechanisms for the technological developments of the Geysers project: dry steam system


Exploration (pre-1980)
Reservoir modeling & engineering (post-1980)


Abrasive hard rock (pre-1980)
Abrasive hard rock (post-1980)


Lost circulation (pre-1980)
Lost circulation (post-1980)

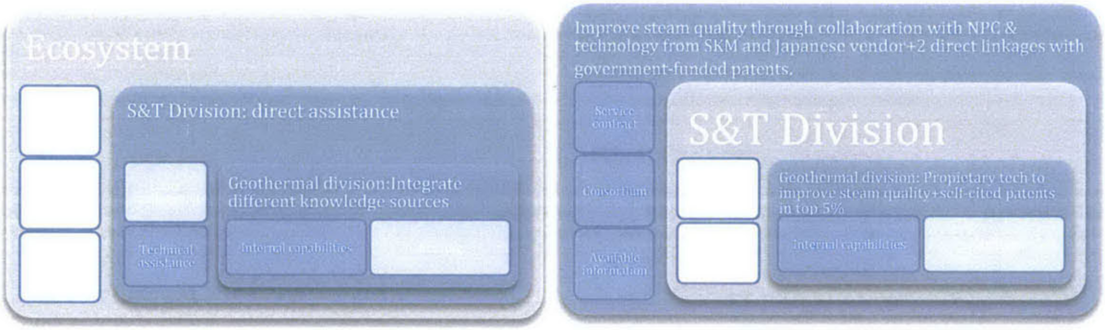

High-temperature logging equipment (pre-1980)

High-temperature logging equipment (post-1980)

Support from Sandia through the Geothermal Logging Instrumentation Development Program. Patent citations to few firms (Mobil, Schlumberger).

Geothermal division:Non-technological approaches to measure the borehole characteristics

Figure 18: Source of knowledge and transfer mechanisms for the technological developments of the Tiwi project: water dominated field with infiltrations


Loss of well control/Infiltration of cold water

Improve the steam gathering system and efficiency of the power cycle.

Geothermal division:Integrate different knowledge sources

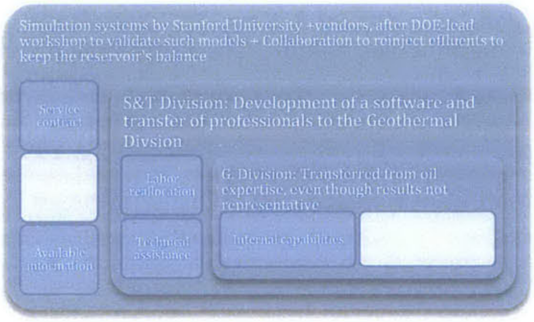
Improve steam quality through collaboration with NPC & technology from SKM and Japanese vendor+2 direct linkages with government-funded patents.

Geothermal division: Propietary tech to improve steam quality+self-cited patents in top 5%

Figure 19: Source of knowledge and transfer mechanisms for the technological development of the Imperial Valley/Salton Sea projects: Liquid dominated field, with corrosive and saline brines

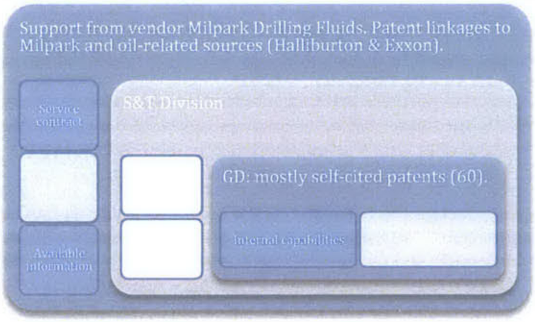
Corrosion on the casing

Reservoir engineering

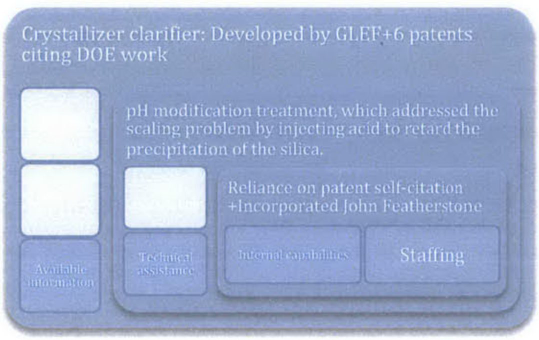


High temperature & corrosion-resistant cements

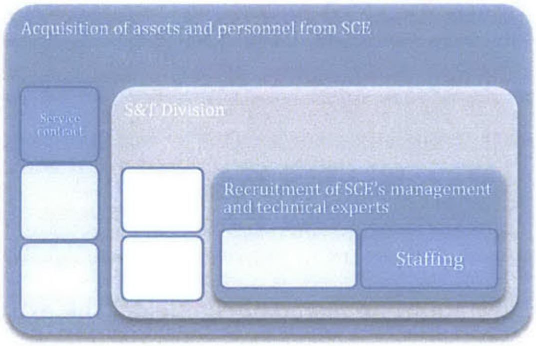
Drilling fluid (High temperature & corrosion-resistant)



Silicate and calcite scaling

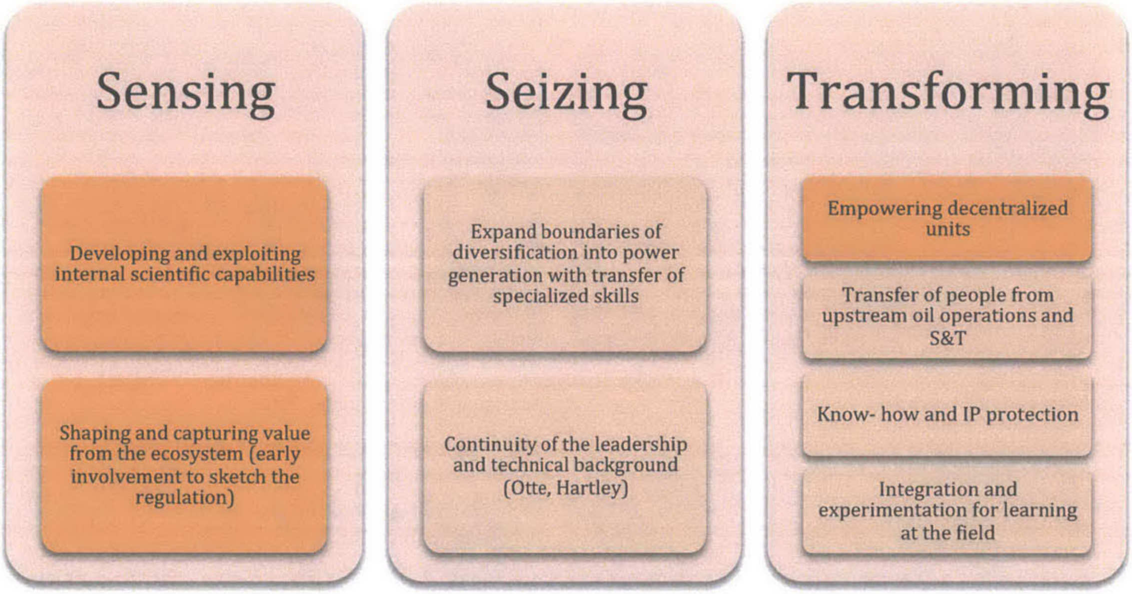


Operation of power unit as IPP



During the late 1960s and most of the decade of the 1970s, Unocal relied on their internal capabilities to address almost all of the technical challenges described. Before the late 1970s there is no evidence of a relevant transfer from knowledge sources outside of the Geothermal Division (not even from the Science and Technology Division). However, after the oil price peak of 1981 (see Figure 12), geothermal technology was quickly forced to become more cost competitive, even under very challenging fields (like the corrosions and scaling problems encountered at the Imperial Valley). This drove the company to develop and exercise **dynamic capabilities** (a concept introduced in Chapter II), such as for example the action of capturing sources of knowledge from the ecosystem, as it can be seen in Figure 17, Figure 18 and Figure 19. All of the relevant dynamic capabilities described throughout this chapter are summarized in Figure 20 shows the key dynamic capabilities ordered under the three main classes of capabilities, sensing, seizing and transforming[105], as proposed by David Teece (Teece et al., 1997). In color orange are emphasized the dynamic capabilities that are part of the hypotheses for this thesis.

Figure 20: Main dynamic capabilities of Unocal's related diverisfication into geothermal energy technologies[106]



Corporations need to have the capability of to reaching out and declare their technology needs so then they can afterwards absorb the complementary knowledge from the ecosystem to be tested at the field. The existence of an innovation ecosystem nurtured by the Department of Energy and triggered through the National Laboratories (like Sandia or

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[105] These three classes of capabilities are introduced in Chapter II. Sensing means to explore, anticipate and create opportunities outside the boundaries of the firm. Seizing is to mobilize the firm's resources to capture value from those opportunities through new products and business models. And transforming means an adaptive and continuous renewal to respond to environmental changes and overcome constraints such as cognitive limitations and rigidities (Teece et al., 1997).

[106] The classification of these dynamic capabilities into "sensing, seizing and transforming" is merely exploratory. Obviously, for example the act of "shaping and capturing value" does not have only a role in identifying external sources of knowledge and opportunity (sensing), but also of helping to transform the boundaries of the firm (transforming).

Brookhaven), was an enabling factor for Unocal's success into geothermal technology development. Evidence from backward patent citation analysis shows that government-funded research was influential to Unocal's patent applications, especially in the challenge of controlling scaling (classification code C02F). Nevertheless, the driving force that pushed Unocal's related diversification came from Unocal itself, in the form of the dynamic capability "**shaping and capturing value from the ecosystem**". This is exemplified by Unocal's active role in the sketch of a suitable regulation for geothermal energy (Geothermal Steam Act), as well as its participation in technology consortiums to extend the breadth of its technical knowledge.

Having an **in-house R&D capability** through the support of the Science and Technology Division was a critical asset, that provided Unocal with highly specialized scientific skills to be leveraged on the diversification into related markets and that helped to expand the breadth of its engineering solutions. In addition to this, the existence of such capability increased Unocal's absorptive capacity[107], and thus its ability to be a technically respected participant of the innovation ecosystem.

The third dynamic capability highlighted in this case corresponds to the **decentralized approach** to the organization of the geothermal business units. This capability was required to support the self-sufficiency in risk-taking for the development of this industry and to create a good environment for informal collaboration between the Geothermal Division and the Science and Technology Division.

Asides the three dynamic capabilities highlighted in orange cells, which confirm the validity of the hypotheses of this research, there other interesting dynamic capabilities that became relevant drivers for Unocal's related diversification into geothermal (and which is worth describing). One of these is the capability of **integrating different sources** of knowledge

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[107] Absorptive capacity is a term introduced by David Popp and generally applied to the ability of a country to "do research to understand, implement and adapt the technology locally, which influences the speed of diffusion - which is as well a function of technology literacy and skills of the workforce, governing institutions and financial markets" (Popp, 2011). From my perspective, this term can be applied also to organizations.

and testing them by **experimenting** in the field. Unocal didn't face capital constraints for piloting ideas to solve their needs. They were nimble to switch from the pH modification treatment into the crystallizer-clarifier technology. Indeed, this capability was embedded into the company's culture, which was to promote experimentation under technical proficiency with a problem-solving mindset.

Finally, it is also interesting to note that Unocal had a very strategic approach to diversification that allowed them to leverage their privileged position in the geothermal business, and **expand the boundaries of diversification** by vertical integration into the power generation business. By this, the firm was able to hedge the value of their steam operations directly into the market (and not through a secondary market with an intermediary acting as a buyer).

VII. Phillips Petroleum

Phillips Petroleum (from now on Phillips) was an oil company that, similar to other companies of its time, was able to expand into a broad range of business areas, thanks to a diverse knowledge base. Phillips' activity in geothermal technology development was short-lived but effective in the identification of new geothermal fields. The company explored and operated several assets, reaching a total accumulated installed capacity of 274 MW, of which 245 MW was the result of a takeover of Aminoil's assets at the Geysers field (see Table 9). In terms of achievement and the learning process, the Phillips story is similar to that of Unocal but more condensed in time (Johnson, 2014).

Phillips was the first company to develop a commercial-scale geothermal project outside of California and the first oil firm to move beyond the operation of the geothermal field into running the power cycle and selling the electricity as an independent power producer (IPP). The company possessed the ability to leverage its internal scientific capabilities to solve unfamiliar engineering challenges, and also the ability to empower a special purpose organization for geothermal deployment. These characteristics were critical to driving the diversification into geothermal at the speed at which it occurred, and helping its geothermal business unit learn to overcome some of the technical challenges of this new business field.

The purpose of this case study is to describe what characteristics of Phillips helped the company engage in the development of geothermal energy technologies and the supply of steam. This analysis will serve as a basis of evidence on which to evaluate the hypotheses presented in Chapter III.

Phillips' diversified activities (1965-2000)[108].

As early as the mid-1960s, Phillips was already a diversified organization, thanks not only to several products that came out of the petrochemical process and other downstream operations of the oil business (such as plastic, rubber and fibers), but also to the extraction of non-renewable commodities like uranium and carbon black.

The evolution of all of these different business units is summarized under Figure 10. Some of these units represent a related diversification based on the common assets of the oil and gas industry (upstream extraction and downstream processing), whereas others correspond to unrelated diversifications that were the outcome of leveraging the byproducts from the petrochemical industry. All of them, though, provided an extended knowledge base for learning.

It is important to mention that the company had many other spinoffs, which were driven specially by its R&D group, but that are not described in the Moody's reports. Hence these have not been included under Figure 10. Some of these are unrelated to the core business of the firm, such as a company dealing with automation and measurement (Applied Automation Inc., which was sold in 1988) (Associated Press, 1988), the manufacturing of photovoltaic modules through a partnership with Acurex Corp. (News OK, 1982), and the development of a fermentation plant to produce yeast as a flavoring and nutrition additive (News OK, 1983, 1987; Phillips Petroleum, 1973). Some of these unrelated ventures were short-lived and were cut off from the company's interest during the late 1980s and early 1990s, when the firm was strategically focusing more on its core oil and gas operations.

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[108] This period includes the years of the peak oil price crisis.

Figure 21: Transition in business diversification of Phillips (Moody's Investors Service, 1965a, 1970a, 1975a, 1980a, 1985a, 1990a, 1995b, 2000a)[109]

	1965	1970	1975	1980	1985	1990	1995	2000
Exploration and production of Oil & Gas (upstream)	▨	▨	▨	▨	▨	▨	▨	▨
Compression and transportation of Oil and Gas	▨	▨	▨	▨	▨	▨	▨	▨
Downstream Oil & Gas (refinery)	▨	▨	▨	▨	▨	▨	▨	▨
Retail and marketing of Petroleum and gas products	▨	▨	▨	▨	▨	▨	▨	▨
Manufacture and sale of chemicals derived from petroleum/gas (polyethylene, plastic molded products, helium, butadiene, solvents)	▨	▨	▨	▨	▨	▨	▨	▨
Agricultural products (anhydrous ammonia, nitrogenous fertilizers)	▨	▨	▨	▨	▨			
Synthetic rubber	▨	▨	▨	▨				
Synthetic fibers	▨	▨	▨	▨	▨	▨		
Oil Shale					▨	▨	▨	▨
Geothermal energy			▨	▨	▨			
Uranium Mining	▨	▨	▨	▨				
Coal			▨	▨	▨	▨	▨	▨
Carbon Black	▨	▨	▨	▨	▨			
R&D group (Corporate Technology Organization)	▨	▨	▨	▨	▨	▨	▨	▨

Phillips' diversification into geothermal energy

History

The concept of diversifying into geothermal energy was originally shaped and raised by Phillips' R&D group. The R&D group recognized the Unocal's potential for success in this new business field and as well as the potential for and availability of geothermal energy sources across the western U.S. Another relevant factor that encouraged Phillips to engage in geothermal was the passing of the Geothermal Steam Act of 1970, which allowed

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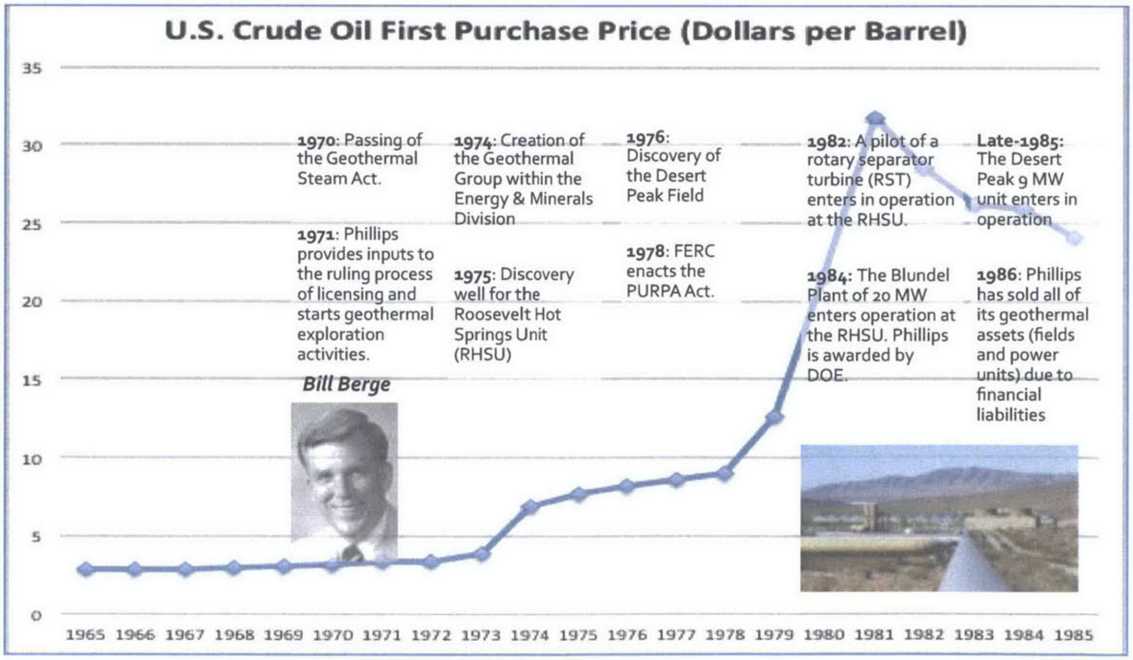
[109] This table has included the years of operation of the R&D group as a reference to show its permanence during this period of analysis, even though it is not a product development unit.

companies to obtain leases from federal lands, and the availability of federal tax credits (Baza, 2014; W. R. Benoit, 2014; Johnson, 2014).

The first evidence of activity in the geothermal business dates from 1971, when the firm actively provided input to the regulatory process in elaboration by the Department of the Interior, after the enactment of the Geothermal Steam Act of 1970 (Department of Energy, 1995). At that time there were already employees working on geothermal energy opportunities at the Phillips R&D office in Del Mar California (Johnson, 2014). However, this new business field was not formally mentioned as an institutional group within the organization until 1974 (Phillips Petroleum, 1974), and the first steam supply for power generation became a reality in 1982, thanks to a pilot project at the Roosevelt Hot Springs.

Figure 11 illustrates the relation between the price of oil and key milestones in Phillips' development of its geothermal business. It is important to emphasize as milestones the importance of new regulations that encouraged Phillips' engagement in this new business, such as the Geothermal Steam Act of 1970 and the PURPA regulation of 1978.

Figure 22: Key milestones in the development of the Geothermal Business units of Phillips Petroleum



1970: Passing of the Geothermal Steam Act.

1971: Phillips provides inputs to the ruling process of licensing and starts geothermal exploration activities.

1974: Creation of the Geothermal Group within the Energy & Minerals Division

1975: Discovery well for the Roosevelt Hot Springs Unit (RHSU)

1976: Discovery of the Desert Peak Field

1978: FERC enacts the PURPA Act.

1982: A pilot of a rotary separator turbine (RST) enters in operation at the RHSU.

1984: The Blundel Plant of 20 MW enters operation at the RHSU. Phillips is awarded by DOE.

Late-1985: The Desert Peak 9 MW unit enters in operation

1986: Phillips has sold all of its geothermal assets (fields and power units) due to financial liabilities

In terms of resources, Phillips was well endowed with leaseholds and options on geothermal prospects; by 1974 the company had covered more than 50 million acres all around the western U.S. (Phillips Petroleum, 1974). The firm owned assets in fields where it was actively pursuing exploration such as Audrey, Brawley, Carson Lake and Round Mt. (in California), and Rye Patch and Steamboat Hills[110] (in Nevada)[111]. Other developments were happening abroad in Italy and East Africa, but none of these became active geothermal operations for Phillips before the demise of its geothermal business units (Department of Energy, 2010b; Johnson, 2014).

The main business units that drove Phillips' success in the geothermal field were the Roosevelt Hot Spring Unit (from now on RHSU) and the Desert Peak Unit. 1984 was a year full of achievements in geothermal energy for Phillips. The firm started providing steam from the Roosevelt Hot Springs field in Milford, Utah, for the operation of a 20 MW unit. In addition, the company was also starting the construction of a 9 MW unit at the Desert Peak Field near Reno (Phillips Petroleum, 1984).

By 1984 Phillips executed the takeover of Aminoil Inc. and the Geysers Geothermal Company, both from R.J. Industries, Inc.. With this takeover, Phillips was immediately in charge of the operation of 4,000 acres of productive geothermal properties at the Geysers (Phillips Petroleum, 1984) field to supply steam for a 187 MW power plant from Southern California Edison, which was to have increased by100 MW by late 1985. Unfortunately, little more than one year later, due to corporate financial issues[112], Phillips sold the RHSU and its assets at the Geysers (Reuters, 1985)[113].

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[110] Streamboat Hills was developed together as a joint venture with Gulf Oil Company.

[111] Phillips' first years of geothermal exploration and leasing (the early 1970s) were focused on The Great Basin region of the western U.S., in a collaborative effort with Chevron Geothermal. Both companies evaluated more than 75 geothermal prospects during this period, but none of these developments became a field operated by Phillips, and most were later purchased by CalEnergy Inc. (Sass, 2005).

[112] The ultimate reason that Phillips left the geothermal business was because Carl Icahn had a controlling position over the company, and the only way to prevent him from exercising the takeover was to sell a large amount of the firm's assets, including the geothermal business units (Johnson, 2014).

[113] By 1987, with the purpose of exploring new types of geothermal fields, Phillips cooperated with the Los Alamos National Lab to study the shallow aquifer of the Milford Valley (to the west of the

Table 5 provides a complete list of fields that were successfully operated by Phillips since its first engagement in the geothermal development business, and the representative installed capacity for each year.

Table 9: Installed capacity througout time of Phillips' geothermal business units (W. R. Benoit, Hiner, & Forest, 1980; Chiasson, 2004; Phillips Petroleum, 1984; Reuters, 1985)[114]

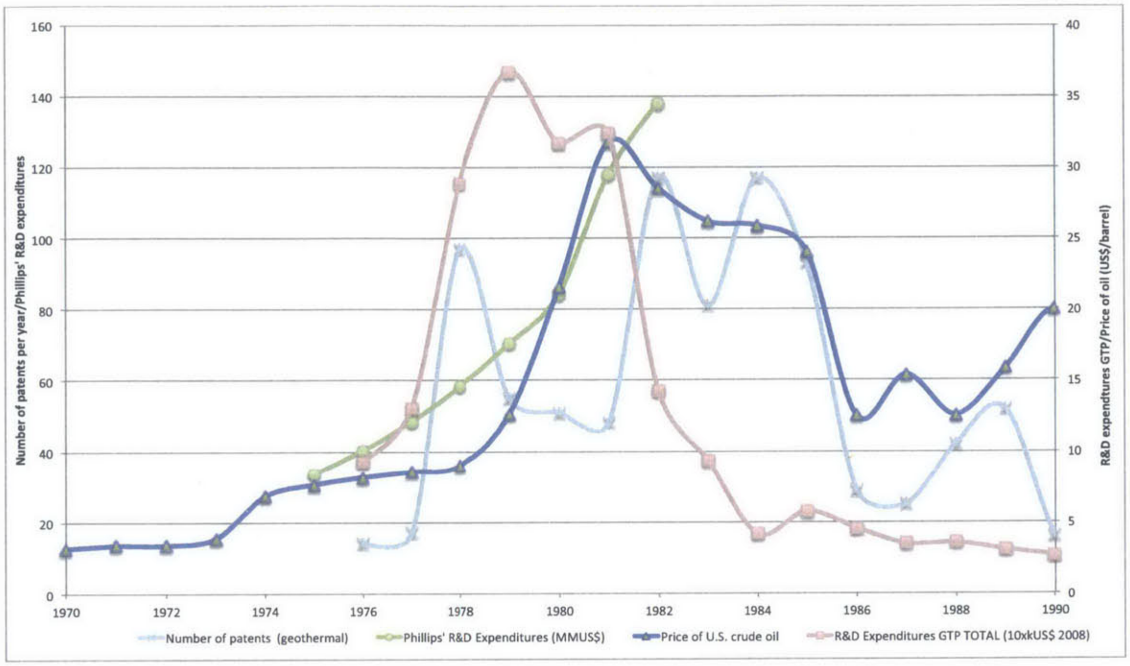
	1982	1983	1984	1985	1986
Roosevelt Hot Springs (MW)	1.6	-1.6	20		
Desert Peak (MW)					9
Geysers (MW)			187	100	
Total Installed Capacity (MW)	**1.6**	**-1.6**	**207**	**100**	**9**
Accumulated installed capacity (MW)	**1.6**	**0**	**207**	**307**	**316**

The complete timeline shown in Figure 23 depicts the evolution of the firm's capabilities in terms of patents and R&D expenditures, as a function of exogenous factors like the price of oil and the R&D expenditures from the GTP.

RHSU area) and determine the feasibility of a hot-dry rock system (Vuataz & Goff, 1987a). Unfortunately, Phillips had already sold most of its assets and this project did not flourish.

[114] Cell in yellow illustrates the closure of a pilot project at the Roosevelt Hot Spring, whose primary purpose was to demonstrate the feasibility of the rotary separator turbine.

Figure 23: Trend of geothermal-related patents, price of crude oil (US$/barrel), R&D expenditures for Phillips (MMUS$/year) and R&D expenditures for the GTP (10kUS$/year) (Energy Information Agency, 2013; Gallaher et al., 2012; Hall et al., 2001; Phillips Petroleum, 1978, 1980, 1984)[115]



Some interesting relationships can be inferred from Figure 12:

- An apparent correspondence between the price of oil and the number of geothermal patents between 1976 and 1986, with a lag of almost 3 years. The price of crude oil reached an historical maximum of 32 US$/barrel in 1981, and its later drop explains the fall in the patenting rate (becoming evident after the closure of the S&T Division in 1997).
- A positive relationship between the price of oil and the firm's R&D expenditure for the 1974-1982 period, which is also present between the GTP's R&D expenditures and the firm's R&D expenditure for the 1976-1981 period.
- An apparent correspondence between the price of oil and the number of geothermal-related patents, for the period of 1976-1982.

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[115] This graphs starts in 1970 and ends in 1990, which is the period of interest for the Phillips' case. This is because the geothermal assets from Phillips were sold by the mid-1980s.

Although the evidence provided is not sufficient to confirm a systemic relationship among these variables, at least it shows that for the 1976-1982 period, the diversification of Phillips into geothermal behaved similar to the path dependence represented in Figure 3. The exogenous effect from the price of oil drove the firm's R&D expenditures, which in turn led to the company's patenting activity in the geothermal field. This seems to confirm the existence of the "economies of scope from research" loop. Unfortunately, it is not possible to confirm a positive relationship between the GTP's R&D expenditures and the annual-geothermal patents. This might suggest that other factors could be influencing this systemic relation.

Throughout the rest of this chapter, emphasis will be given first to describing the crosscutting facts that drove the diversification into geothermal energy, and second, to explaining the technical features that were the essential drivers of the success of each of Phillips' geothermal business units.

Leadership

Phillips' development of geothermal energy was spurred and guided by Bill Berge, long-time Phillips geologist, who started his career with the Research & Development group performing basic geothermal research. As recognized by the interviewees, it was Berge who persuaded Phillips to engage in geothermal energy, by forming a group to evaluate geothermal resources as an emerging energy source (W. R. Benoit, 2014; Johnson, 2005, 2014).

Between 1973 and 1976 Berge served as the manager of the Phillips Geothermal Exploration and Development Program in San Diego, CA; Salt Lake City, UT; and Reno, NV. Since then and until 1984, Berge was Phillips Manager of Geothermal Development. Interestingly, Berge's activities in geothermal energy were not limited to his work with Phillips. He taught geology and performed geothermal research at Utah State University, and served as one of the founders and the president of the Geothermal Resource Council (GRC)[116] between 1980 and 1988 (Johnson, 2005).

Berge was instrumental in assembling a proficient and multidisciplinary team that was willing to stay for the long-term operations of Phillips' geothermal undertakings. He also exercised wise leadership by establishing best practices and allowing the team enough freedom to experiment and learn (W. R. Benoit, 2014; Johnson, 2005). As Stuart Johnson recalls:

> *Bill's strength in solving problems was to simply bring the right people together to share ideas and concepts. This ethic led to success for geothermal development at Phillips. (Geothermal Resources Council, 2005)*

It is mostly interesting how Johnson recalls Berge with respect to his commitment to sharing and transferring knowledge, inside and outside of the company.

> *Bill talked to people outside of the company—to people at research labs, at other companies, and to people in other countries—about developing new exploration techniques and growing geothermal into a real industry. At the time, we thought it a little odd to give away ideas and technology that were bringing us success, but Bill was already helping to found the GRC. In essence, he was creating the reason that we are all here this week—to share our ideas and technologies, and to broaden the success of the geothermal industry. (Geothermal Resources Council, 2005)*

Organizational structure and self-sufficiency of Phillips' Geothermal Operations

During the early 1970s, Berge established an office in Del Mar (CA) in charge of geothermal evaluations for all western states, including business units in San Diego (CA), Salt Lake City (UT) and Reno (NV) (Johnson, 2005). Del Mar office became the office of the Geothermal Division, and by 1978 was moved to Salt Lake City so the team could be closer to fields Phillips was managing at the time (Baza, 2014). Berge was empowered by the management to drive this new business field, and he had to report directly to the Head of the Energy

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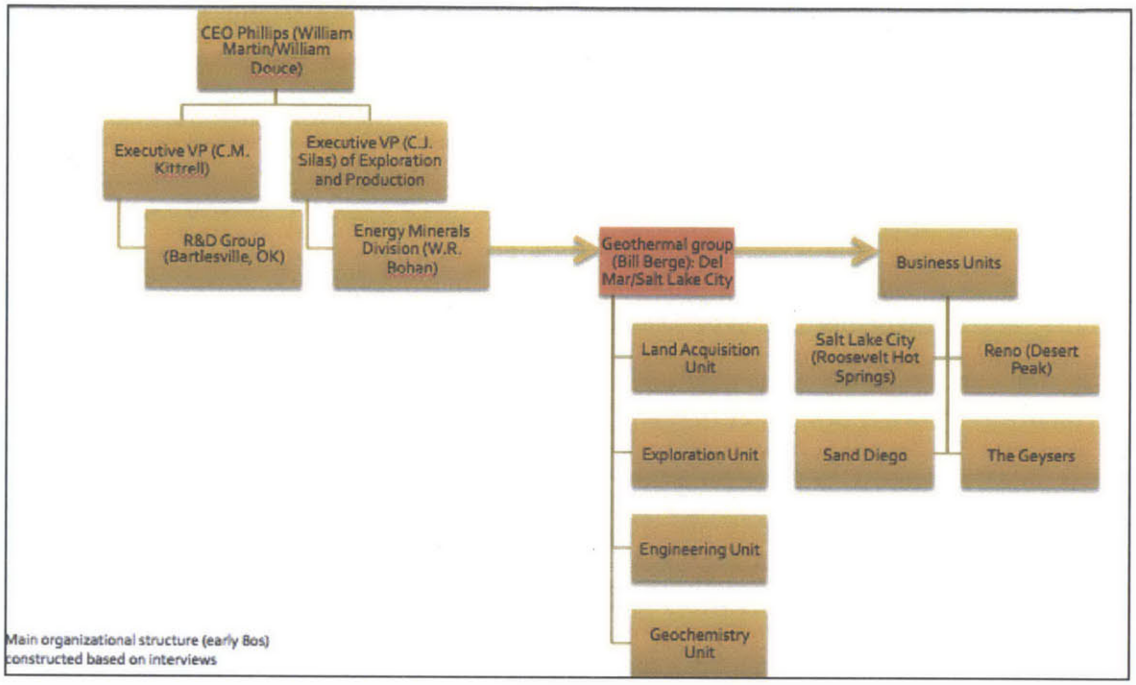
[116] The GRC is the main guild or group of collaboration for geothermal energy development in the United States.

Minerals Division, who was under the supervision of the V.P. on Exploration and Production, as shown in Figure 13[117].

Figure 24 Sketched representation of the organizational structure of the geothermal activities at Unocal during the early 80s (Johnson, 2014; Phillips Petroleum, 1980)



Besides geothermal energy, the Energy and Minerals Division was in charge of managing uranium and coal reserves and assets. The Geothermal Division within this division was a self-reliant unit with its own HR department and land department. The Geothermal Division had enough autonomy to grow and strategically acquire new licenses, explore or interact with the ecosystem (W. R. Benoit, 2014; Johnson, 2014). As recalled by Stuart Johnson (who was the head of the Geothermal geochemistry unit):

> *We had substantial budgets and large discretionary ability to spend those budgets in an efficient manner to discover resources. We were tied real closely with Research and Development.* (Johnson, 2014)

Management was very supportive of new endeavors by the Geothermal Division (such as Desert Peak, Steamboat), given the rapid success in exploration that the company had at the Roosevelt Hot Spring field. The central headquarters would scrutinize budgets only if

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[117] The chart in Figure 13 is based on interviews with professionals who worked in the Geothermal Division and a chart available from Phillips Annual Report for 1980.

expenses from the geothermal operations surpassed the levels authorized by a large amount (Johnson, 2014). Indeed, at least during the 1970s and the early 1980s, centralized control was not a restriction on Phillips' engagement in geothermal, as stated by Walter 'Dick' Benoit (geologist for 12 years at Phillips Geothermal):

> *"The Geothermal Division was totally autonomous. They just got everything they asked for. In the first 10 or so years, Phillips had lots of money*[118] *so anything we wanted to spend, we did".* (W. R. Benoit, 2014)

Phillips' Geothermal Division was significantly skilled in acquiring new lands and exercising leases, so as to gain strategic positions for the exploration of geothermal resources, even in a period when the Federal Leasing Act was not in place yet. The employees in charge of these duties came from Phillips' Petroleum group, and it can be regarded as the most transferable activity from oil to geothermal. Indeed, the firm had a very favorable position in terms of land, since it owned an option on 5 million hectares of land along the railroads in Nevada and Utah (W. R. Benoit, 2014; Johnson, 2014).

Recruitment for the geothermal drilling operations was an internal transfer of people mostly from the Petroleum group at Phillips' headquarters in Bartlesville, Oklahoma. Yet a lot of young people were also hired for the Geothermal Division (at least two-thirds) who did not have previous work experience in the oil and gas industry (W. R. Benoit, 2014; Johnson, 2014). From the perspective of Dick Benoit:

> *"It was ok* (using non-petroleum people for geothermal). *Petroleum people did not know how to look for geothermal. They would have got it wrong anyway, by starting off with people that didn't know anything".* (W. R. Benoit, 2014).

As Benoit sees it, relying too much on oil-related knowledge while diversifying into geothermal could become a detriment to the firm's geothermal operations:

> *"Oil skills do not readily transfer to geothermal. The drilling looks similar but it is really not. And it was very important because we saw companies like Chevron wasting a lot of money doing stupid things in drilling, because that was the way they did it on*

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[118] This large availability of cash was thanks to Phillips' successful operations in the North Sea during the 1970s (W. R. Benoit, 2014).

> *the oil field. And Phillips fortunately did not bring that (oil capabilities) with them* (W. R. Benoit, 2014)".

Such a statement opens a very interesting door for analysis in terms of the relative importance of core capabilities versus dynamic capabilities in related diversification. This issue will be discussed further in Chapter VIII.

Former employees of the Geothermal Division recognize that one of the main drivers for Phillips' successful diversification into geothermal came from the generous availability of financial and time resources, which allowed the Geothermal Division to hire the right people and localize them near the fields so they could directly experiment and learn without depending on external assistance (Baza, 2014; W. R. Benoit, 2014; Johnson, 2014):

> *"We didn't pay some vendor to go out and do the thinking for us"* (W. R. Benoit, 2014).

Learning was happening in the field. There were no specific industry training classes on developing a geothermal resource, although there was a limited amount of knowledge from the upstream oil operations that could be used in a geothermal setting. Yet learning had to rely on the ability of the team to go out and seek information on the geothermal ecosystem that was being nurtured mostly through the DOE's efforts (Baza, 2014).

Another factor mentioned during the interviews was the pride and attractiveness that Phillips' professionals and management felt in working in such a pioneering field, which only a few firms addressed (Baza, 2014).

By 1986, due to financial liabilities, Phillips had sold all of its interest in the Roosevelt Geothermal Field and the Desert Peak Field (along with the power generation unit) to Chevron and its assets at the Geysers field to Freeport-McMoran Inc.[119] (U.S. Department of Energy, 2009; Wright, Blackett, & Ross, 1990).

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[119] Which was later bought by Calpine.

The support from Phillips' Research and Development Group

Phillips' R&D group had its offices in Bartlesville (OK). Some of the developments of by the R&D group for the oil and gas industry were a technique for increasing oil recovery by thermal fracturing, additives specially adaptable for extensive engine use, and technology to upgrade the lowest grade crude oils for refining (Phillips Petroleum, 1973, 1984). Special mention is deserved for the work on new improvements to meet the automobile emission standards imposed by the Clean Air Act of 1970 (Phillips Petroleum, 1970), and the develpment of a design to solve vibration problems in large heat exchangers used in cooling proccesses (Phillips Petroleum, 1974). In addition the R&D group also engaged in research unrelated to the oil industry, such as work on nuclear safety with the Atomic Energy Comission or the development of new nuclear fusion processes, activities related to automation, PV module manufacturing and the production of feeding supplements (Phillips Petroleum, 1968).

The R&D group was the birthplace of Phillips' geothermal business unit and it closely accompanied geothermal development by providing technical assistance to address issues like calcite scaling, reservoir engineering and new geochemical analyses (to assess whether the water from a well had been in contact with hot rock). Even though the R&D group was an available resource and seemed to be very innovative (based, for example, on its cooperation with the USGS on helium gas to describe the geology of a reservoir), they did not provide anything that was considered of critical operational value to the geothermal business unit (W. R. Benoit, 2014; Johnson, 2014; Phillips Petroleum, 1973). As recalled by Stuart Johnson and Dick Benoit, respectively:

> *"They would come out and try new exploration techniques in areas were we already had a good understanding"* (Johnson, 2014).
>
> *"It worked like if they had more money than they knew what to do with and they just wanted to do something fun and interesting". "The Science group didn't knew much about geothermal either (asides from not being very effective)". "They were not "living geothermal", they were sitting back in Oklahoma"* (W. R. Benoit, 2014).

Patenting activity

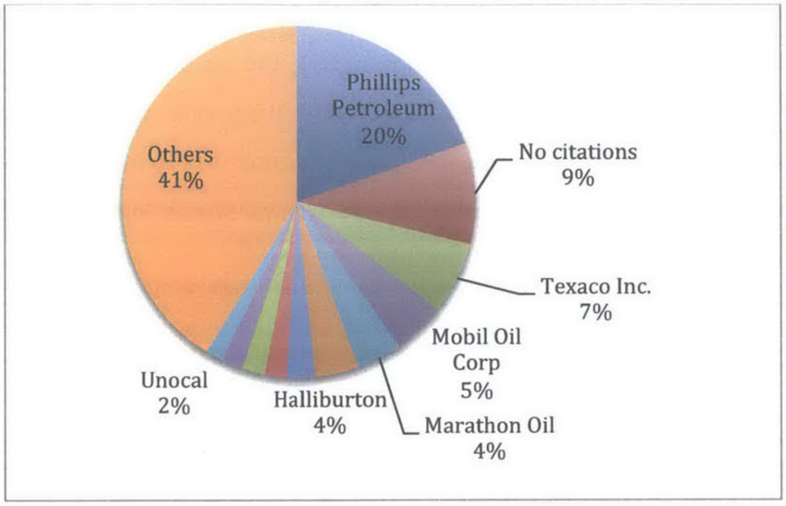
Due to the efforts of Phillips' R&D group, the company was able to rank first among oil companies in terms of the number of U.S. patents. Between 1973 and 1985 Phillips accumulated a total of 7,385 patents (Hall et al., 2001). Such active research effort gave Phillips a diverse breadth of knowledge to engage in new business fields and acquire new capabilities. Phillips was counted as the 13th largest assignee of geothermal-related patents, and the 7th most influential organization in terms of its links with downstream geothermal patents (Ruegg & Thomas, 2011).

In the early days of geothermal development, Phillips was concerned about protecting some of its internal knowledge from the competition, especially in fields in which simultaneously hosted several operator companies were looking for a business advantage (like in the Roosevelt Hot Springs field). Instead, at the Desert Peak field, Phillips' geothermal professionals were allowed to publish research papers, mainly because there was no competition established in this field that could have their own leases (Baza, 2014; W. R. Benoit, 2014).

Neverhteless, an important set of capabilities required for geothermal development did not rely on patents and instead were the result of a combination of tacit knowledge to address reservoir engineering and interpreting the data from exploration activities.

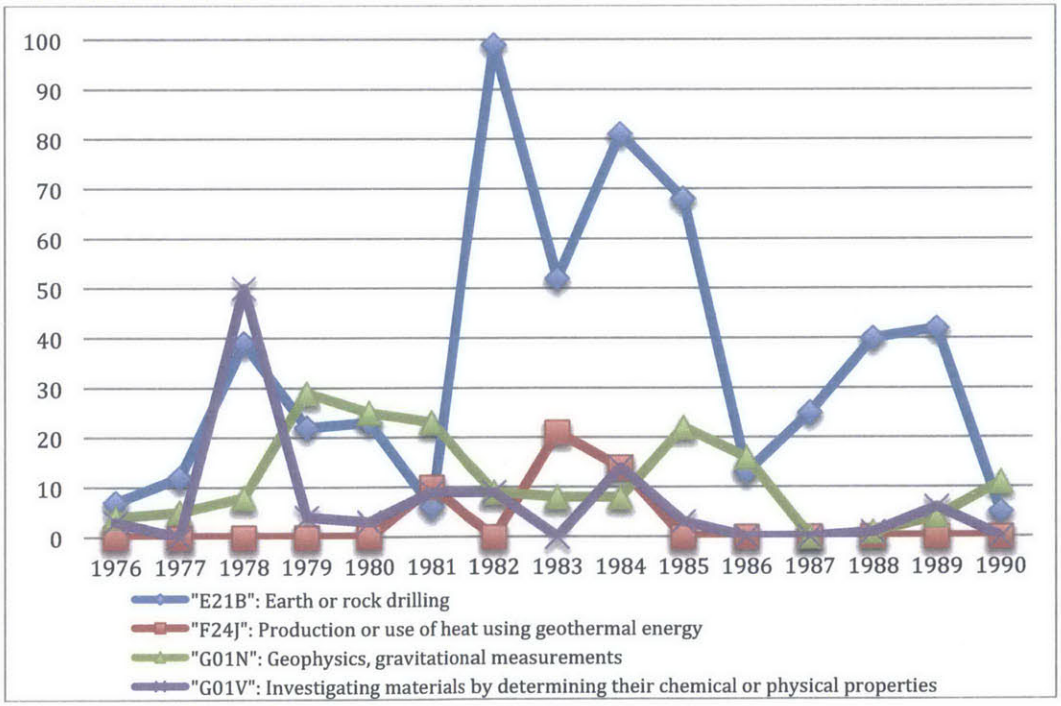
A large share of the stock of Phillips' geothermal-related patents are self-cited. This is confirmed by Figure 14, which details the sources of citations for all of 1,549 Phillips' geothermal related patents. Of these citations, 20% are linked to Phillips, which is evidence of the influence of the firm's knowledge base on its diversification. The second and third most influential sources for patenting come from Texaco and Mobil with only 7% and 5% respectively.

Figure 25: Direct sources of Phillips' geothermal knowledge(Hall et al., 2001)



As seen in Figure 15, there was an important increase in the number of Unocal patent applications between 1981 and 1985, which was driven by the "earth or rock drilling " (E21B) classification, representing 63% of the total Unocal geothermal-related patents (the largest share of the classification of patents)[120].

Figure 26: Trends in patent applications per year and per classification code (Hall et al., 2001)



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[120] All classification codes are identified under Appendix III

Table 6 illustrates the relevance of internal and external sources of knowledge on Phillips' geothermal-related patenting activity. It can be seen that in the geothermal topics, where the firm had the most patents, (E21B and G01N), the share of self-citation dominates, whereas for classification codes with a lower patenting rate, the patents from external organizations are more influential (like G01V). It is interesting to note the frequent citations to oil companies or vendors for the oil industry such as Mobil, Marathon Oil, Texaco, UOP and Standard Oil[121].

Table 10: Top 5% of cited organizations by Phillips' geothermal related patents (for each type of classification code) (Hall et al., 2001)

Patent classification	Fraction of patents without citations in total number of Phillips' geothermal-related patents	Number of citations from Phillips geothermal-related patent stock (under this classification code)	Name of organization
"F24J": Production or use of heat using geothermal energy	24/45	2	Raytheon Co.
		2	One Design Inc.
		2	Consuntrator Inc.
"E21B": Earth or rock drilling	27/534	157	Phillips Petroleum
		29	Mobil Oil Corp
		25	Marathon Oil
		82	Texaco Inc.
"G01N": Geophysics, gravitational measurements	21/173	46	Phillips Petroleum
		6	Ei Du Pont de Neumours & Co.
		5	UOP LLC.
"G01V": Investigating materials by determining their chemical or physical properties	3/102	14	Texas Instruments Inc.
		7	Standard Oil

Backward patent citation analysis yields no evidence of direct links with previous government funded patents. Yet this does not rule out the possibility that there could be an indirect influence, for example, through citing a patent that directly cites government-sponsored research (second level of linkage). Indeed, the DOE-report "Linkages from DOE's Geothermal R&D to commercial power generation" identifies Phillips as the 7th organization with the highest share of geothermal energy patents linked to earlier DOE-attributed geothermal energy patents. In summary, government patenting had an indirect influence on

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[121] In addition to the classifications that were considered representative of the geothermal technologies, I analyzed the most relevant citations for other patent classifications that were regarded as geothermal-related for the Unocal case: B01D, C09K and C02F are strongly dominated by self-citations to early Phillips patents (35%, 31% and 20% respectively).

Phillips' patenting activity, showing that Phillips was probably skilled enough to capture the valuable knowledge available in the industrial ecosystem.

Sources of learning

Phillips' learning in geothermal occurred primarily from experience in the field, yet a fair amount of knowledge came from interaction with other professionals from the geothermal industry, through organizations like the Geothermal Resources Council (Berge was its founder and one of its presidents) (W. R. Benoit, 2014; Johnson, 2014). Unocal's activity in the geothermal business since the mid-1960s was an important influence on the knowledge of the industry's ecosystem (and to Phillips' learning). Several new techniques and technical contributions were made available due to the disclosure conditions from the federal grants that supported Unocal's participation on research consortiums. John Baza (reservoir engineer for Phillips' Geothermal Division) recalls:

> *"So even though we might have not got the information directly from Unocal, we were able to see enough of the work they were doing through published reports. And some of the start-ups that came to be from the 1980s were learning a lot from Unocal's experience and Phillips, through published reports and published papers. Those things that were in the public field"* (Baza, 2014).

Furthermore, based on these facts and according to some of the interviewees, it can be assumed that there was some indirect transfer of capabilities from first-movers like Unocal to the vendors. Quoting Baza:

> *"If a company finds success in one part of the country working for one operator, they will try to show that success in other areas by working with different operators and certainly as long as they are not violating proprietary agreements or patent infringements" (Baza, 2014)*

In addition, Phillips was actively supporting research activity done by universities, to gain new insights into exploration techniques. For example, the University of Utah had a strong research group, with very competitive capabilities in terms of geophysics and geochemistry, which helped Phillips understand the behavior of the Roosevelt Hot Springs field, the chemical effects of scale precipitation, and reinjection potential. Surprisingly, from the various sources of the industrial ecosystem under creation, the National Labs were not mentioned as a relevant source of knowledge for Phillips' geothermal energy development (Baza, 2014; Johnson, 2014).

The rest of this chapter is devoted to explaining the most significant technical developments necessary to meet the challenges confronted by RHSU and Desert Peak. These technical challenges are the units of analysis for the Phillips' case, with data consolidated from the various interviweees and extended literature on geothermal reseach. For each challenge, I identify the source of the knowledge required to overcome technical difficulties and the transfer mechanisms. It is important to emphasize that these technical challenges are not exclusive to one geothermal field. Rather, they are linked to the characteristic hurdles confronted by the firm on that specific project.

The Roosevelt Hot Springs Field - Utah

The Roosevelt Hot Springs is a geothermal field located on the eastern edge of the province in south central Utah, approximately 15 miles northeast of the town of Milford. The Roosevelt Hot Spring Unit (abridged as RHSU) is a highly fractured water-dominated reservoir (Open Energy Information, 2014b). This field is characterized by an unusually high temperature (over 500 °F), low salinity (8,000 TDS), and has been documented not to require stimulation to enable high flow (W. Benoit & Butler, 1983; Kerna & Allen, 1984).

In the early 1970s, several companies were performing **exploration** activities in this field, mainly Phillips Petroleum, Thermal Power, Getty Oil, and AMAX Exploration (Department of Energy, 2010a; Open Energy Information, 2014b). In 1974, Phillips became the operator for the acreage of the RHSU, which was unitized from several leases assigned to other companies exploring in this area. This was the first geothermal unit approved by the Department of the Interior (W. Benoit & Butler, 1983; Kerna & Allen, 1984; Phillip M. Wright, 1991). The discovery well was drilled in 1975 and as a result of a comprehensive three-year exploration program comprising government grants to fund this operation, Phillips was able confirm the geothermal resource of RHSU through a second well. This important achievement and finding made RHSU an attractive site for further geological, geophysical, and geochemical research by the University of Utah (W. Benoit & Butler, 1983; W. R. Benoit, 2014)

The purpose of the RHSU exploration was to mimic what happened with the Geysers, given that by the mid-1970s there was no referent in the U.S. of an operational water-dominated field with temperatures above 500 °F. The option was to follow the example of any other dry-steam field, and for that Phillips contracted as consultants an Italian team that had direct experience working at the Lardarello field. The support from the Italian mentors was critical to complement Phillips' internal capabilities and to **identify the hidden steam resources**, considering that the RHSU did not have any active hot springs or visible steam manifestations (Johnson, 2014).

Initially, Phillips' R&D group with the support of consultants and the University of Utah delivered the reservoir engineering analyses. By the late 1970s, reservoir engineering was still in its infancy, so these assessments were done as if the field consisted of a static system (like petroleum reservoirs) rather than a dynamic system (which was the correct approach for a geothermal reservoir). This static approach created a lot of distortions with respect to the real behavior of the field.[122] Later, the firm gained staff that had experience in reservoir engineering of geothermal fields from Stanford University (like John Baza) and with the acquisition of the assets at the Geysers' field in 1984, but this happened at the end of the period of Phillips' venture into geothermal energy (Baza, 2014; W. R. Benoit, 2014; Johnson, 2014).

On another topic, the **drill bits** had a short lifetime and required frequent replacements, since these were not suitable for drilling hard granite under the very abrasive conditions of deep geothermal holes. There were no technological alternatives to address such a problem, since these were the drill bits commonly used for hard rock drilling in upstream oil operations (Baza, 2014; W. R. Benoit, 2014; Johnson, 2014).

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[122] For example, the initial models expected that the RHSU had the potential to provide 200 MW of capacity, but contrastingly the operational reality today is around 32 MW (Baza, 2014).

Drilling fluids required adaptations to function in high temperature conditions. So instead of using bentonite muds, Phillips used a sepiolite mud, which, by the second half of the 1970s, was already applied in places like the Imperial Valley (Zilch et al., 1991). Interviewees suspect that this alternative was recommended by vendors like Halliburton, which could have transferred it from their experience working at Unocal's operations, but there is no conclusive evidence of this (W. R. Benoit, 2014; Johnson, 2014).

The first geothermal wells were drilled as oil wells, since operators were unfamiliar with some of the challenges of geothermal drilling, such an abrasive hard rock, lost circulation, and loss of well control[123]. Most of the knowledge to address these challenges came with the transfer of Ott Rolls, who was the drilling engineer in charge of Phillips' offshore drilling operations at the North Sea (an area characterized by a harsh environment and temperatures similar to a geothermal reservoir[124]). Rolls knew how to safely drill high temperature and high pressure systems, given that he understood the capabilities of the drill rig, the **mud systems, and the tools for well control** (W. R. Benoit, 2014; Johnson, 2014). Stuart Johnson recalls Rolls in the following way:

> *"He was a very meticulous drilling engineer and knew what to expect in terms of blowout and lost of well control. He was the man that directed the successful drilling program for the Blundell Plant* (RHSU)*"* (Johnson, 2014).

On a secondary level, Phillips also took lessons on **loss of well control** from the mistakes of its competitors, such as from a firm called Thermal Resources, which was drilling at the RHSU, where it suffered a well blowout. Finally, valve manufacturer WKM (which had experience working at offshore and overseas fields) partnered with Phillips to choose and adapt equipment to high temperatures and assure quality well completions[125] to prevent blowouts (Baza, 2014; W. R. Benoit, 2014).

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[123] Another important mismatch between upstream oil and geothermal happened when operators drilled with the belief that they had to stop once they hit granite. Fortunately, oilfield geologists learned at the field that the heat was deeper than the granite contact (W. R. Benoit, 2014; Johnson, 2014).

[124] Near 500 °F.

[125] Well completions: All the specialized hardware and techniques required to produce the well, once a well has been drilled (Schlumberger, 1998).

Air drilling was used to mitigate **lost circulation**, but this technique was not fully implemented by Phillips until the early 1980s. The knowledge of air drilling came from the firm's personnel at its oil operations and from vendors that had compressors waiting to be used (W. R. Benoit, 2014; Johnson, 2014).

The diameter of the casing had to be increased to deal with higher flow rates than those commonly used in upstream oil operations. Yet this size casing was already being used for high volume oil wells in Saudi Arabia. The recommendation to increase the casing diameters came primarily from the reservoir engineers, and it implied recombining existing equipment from the oil industry (Baza, 2014; W. R. Benoit, 2014; Johnson, 2014). As Baza describes:

> *It wasn't that were retooling and remanufacturing things in order to fit the purpose. We were basically adapting the equipment that was already somewhere else in the world* (Baza, 2014).

The RHSU and the Desert Peak field were not particularly aggressive in terms of **corrosion**. Therefore, the wellbores used conventional heavy weight carbon steel casings and **cement blends** similar to what was already being used at the Geysers field. The firm relied on the recommendations of cementing companies like Halliburton, which already understood the appropriate cement blends from assisting in the operation of fields such as the Geysers (W. R. Benoit, 2014; Johnson, 2014).

Silica scaling became an issue of concern for the operation of RHSU, given the high temperature of the geothermal resource (over 500 °F). For example, a few months after beginning operation, the power unit had to be stopped every six weeks to remove the scaling deposited outside the wellbore in the turbine blades and the seals[126] (Wright et al., 1990). Additional difficulties occurred from the formation of **calcite scale** inside the wellbores, which was solved by implementing downhole delivery of chemicals to keep the

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[126] The Rotary Separator Turbine (RST) was intended to be a relevant technology to mitigate the silica scaling occurring outside the wellbore. However, as described below, the technology may have proved effective for power generation, but it did not have good performance in separating the steam from the brine (Baza, 2014).

wells from clogging up[127]. This solution was the result of collaboration between the Geothermal Division and the R&D group to refine and test different threshold inhibitors. Continuing research on this topic was provided by the Geothermal Division's staff, and some chemical companies[128] that received permanent updates on what was happening in fields like the Imperial Valley (operated by Chevron and Unocal), Coso (operated by CalEnergy) and Dixie Valley (operated by Oxbow) (Asperger, 1982; Baza, 2014; W. R. Benoit, 2014; Johnson, 2014). The R&D group studied methods for rapid field-testing of calcite scale inhibitors for high temperature geothermal brines, while the vendors became the transfer mechanism for this knowledge among the different operators. As acknowledged by Benoit:

> *"There was a bunch of plants that began operating in the mid-80s at the same time and all of these had the carbonate scale problems. The word got around on 'who was doing what' and the companies saw that quite quickly"* (W. R. Benoit, 2014).

Logging geothermal wells was a challenging task, given the high temperatures and the harsh conditions of the reservoirs. During that time, the technology for monitoring geothermal wells was still new, so some equipment would get burned. Phillips' Geothermal Division tried to overcome this issue by pumping cold water to cool down the hole and by insulating some of the equipment. By this time, the depths of the holes (4,000 feet) were not as deep as the depths of the holes drilled nowadays (9,000 feet), which can reach even higher temperatures. In addition, Schlumberger had monitoring equipment (for gamma testing, resistivity, and the acoustic log) capable of handling temperatures in the range of 500 °F (like the conditions of RHSU and Desert Peak) and vendor Pruett Industries installed capillary tubing systems for long-term monitoring under the very extreme conditions of down-hole pressure[129]. On a secondary level, the R&D group built equipment to measure the flowing temperature, pressure and enthalpy[130], in addition to sporadic gas and water

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[127] Organic polymers and phosphoric acid materials were successfully used for dealing with the deposition of calcite solid but only for low temperatures. In the case of the RHSU, the scaling threshold inhibitor tested successfully was either phosphanates or polyacrolates in very small ppm dosages in the flow stream of the geothermal fluids, which were introduced through capillary tubing downhole. These worked to distort any crystals that started to form. If calcite scale was formed, hydrochloric acid was pumped down the well to dissolve it (Asperger, 1982; Johnson, 2014).

[128] Some vendors mentioned by the interviewees who were the dominant in this area were Melco, Rand, Drew, Betz and Nalco (W. R. Benoit, 2014; Johnson, 2014).

[129] This technology can also be combined with a temperature device such as thermocouple to measure temperature (Pruett Tech Inc., 2014).

[130] No evidence has been found to prove that the R&D group's development became a commercial solution.

sampling services (Baza, 2014; W. R. Benoit, 2014; Johnson, 2014). Additional drilling challenges (like mitigation of the noise from operations and the measurement of a two-phase steam/water flow) relied on a combination of ideas from previous operators[131] (Harban, 1975).

The first power generated from RHSU came in 1981 from a small 1,6 MW pilot with a very particular technology. This was a rotary separator turbine (RST) provided by Transamerica Delaval Biphase Energy Systems[132], which avoided the need for an additional separating unit and for flashing to reduce the pressure (which would exacerbate scaling). The turbine increased the power output from the well system since it relied on converting the kinetic energy from the flow into shaft torque and transforming the thermal energy from the steam. The Electric Power Research Institute sponsored the original development of the RST, and Phillips supported the final testing for its future use in some of Phillips' geothermal operations. The RST pilot operated properly for more than one year with very good performance[133] (Baza, 2014; Cerini, Diddle, & Gonser, 1984; Dickson & Fanelli, 2013; Phillip M. Wright, 1991; Studhalter, 1986).

Phillips did not want to become a regulated utility to commercialize the value of their steam, so they had to attract the interest of the local utility, Utah Power & Light Co (UP&L). It took almost five years for Phillips to reach an agreement with UP&L for the purchase of the steam. The contract signed in 1980 was similar to that of the Geysers project: Phillips would be in charge of providing the steam, while UP&L would build and operate a 120 MW[134] power plant and return to Phillips the brine re-pressured, so it could be injected for disposal (W. R. Benoit, 2014; Bloomquist, Geyer, & Sifford, 1989; Phillip M. Wright, 1991). In

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[131] For example, the use of mufflers to deal with the noise of the operations and dissipate the flow was the outcome of a recommendation by Unocal professionals based on their use of such devices at their Valles Caldera field. Similarly, in order to measure the two-phase steam/water flow, Phillips used a steam-water separator technology suited for geothermal bores and developed in New Zealand (Harban, 1975).

[132] Even though the company owner of this technology went bankrupt, the concept is still under consideration by other turbine manufacturers (Dickson & Fanelli, 2013).

[133] At the RHSU, the RST system proved (with a dual admission steam turbine) that operating at one million lbm/hr of total flow the power could increase from 4.8 MW to 15 MW (Cerini et al., 1984)

[134] This installed capacity was heavily overrated considering the inexperience in reservoir engineering for geothermal. The project would serve a first unit of only 20 MW.

1984, UP&L started the operation of a first 20 MW commercial unit (Blundell power plant). Thanks to this achievement, Phillips earned a DOE award in 1984 for being the first U.S. commercial plant producing geothermal energy outside of California (Chiasson, 2004).

The Desert Peak Field - Nevada

The Desert Peak geothermal field is located approximately 50 miles northeast of Reno (Nevada), in the Hot Springs Mountains. This field is characterized by a hot water dominated resource with a medium temperature (326 °F, lower than RHSU) and no active superficial thermal features[135]. This makes the Desert Peak field one of the first blind geothermal discoveries[136] in the Basin and Range province of the southwestern U.S. (W. R. Benoit et al., 1980; Cerini et al., 1984).

Phillips was the first operator that relied on **shallow thermal gradient holes**[137] to efficiently analyze the water chemistry of hot systems in the western U.S. and to evaluate the potential of the firm's land options[138]. This achievement was possible because of the firm's incentive to learn at the field (W. R. Benoit, 2014; Johnson, 2014). Benoit recalls:

> *"We drilled a 7600 foot deep unsuccessful well at Desert Peak that was a classical case of not understanding the shallow temperature data. We then had the incentive and money to get things right the second time. We did not have any pre-conceived ideas about how to do things so we let the temperature data tell us how it was done* (W. R. Benoit, 2014)*".*

Phillips' exploration of the Desert Peak field started in July 1973 with shallow temperature-gradient holes that helped outline and later (in 1976) discover the Desert Peak reservoir by measuring only temperature, making it less necessary to apply alternative exploration methods for this field[139][140]. The **shallow temperature-gradient holes** were developed and

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[135] This was confirmed through infrared imagery in 1978.

[136] A blind geothermal system is a geothermal reservoir with no surface manifestation (Open Energy Information, 2014a).

[137] Thermal gradient holes are shallow holes, with a depth of less than 500 feet, drilled to determine the thermal gradient ("Thermal Gradient Holes | Open Energy Information," n.d.)

[138] Phillips had options on 5 million hectares of land along the railroads in Nevada and Utah (Johnson, 2014).

[139] There are three main reasons why shallow temperature gradients streamlined the discovery of the Desert Peak geothermal reservoir: First, there were neither significant temperature changes nor

interpreted by the Geothermal Division, with consultancy assistance from Southern Methodist University (Baza, 2014; W. R. Benoit et al., 1980; W. R. Benoit, 1978, 2014). Later, in 1979, Phillips started a deep exploration program to drill test wells at Desert Peak, with the sponsorship of DOE's Coupled Confirmation Drilling Program[141] (W. R. Benoit et al., 1980).

Calcite scale can become a problem for any high-temperature geothermal reservoir. To address this problem at Desert Peak, Phillips received vendor assistance through a scale inhibition test (done by EFP Systems Inc.) using recycled carbon dioxide in a gas form, which helped increase the wellhead pressure and reduce the pH of the brine, so as to prevent scaling in the wellbore (W. Benoit & Butler, 1983).

The new regulatory conditions promoted by the Federal Energy Regulatory Commission (FERC) and enacted through the PURPA Act of 1978 enabled the entrance of new actors in the U.S. electricity market that could sell directly to the regulated utility through long-term contracts. This encouraged Phillips to, in addition to operating the Desert Peak field, **become an Independent Power Producer** (IPP) operating a 9 MW power facility with a 10-year bilateral contract to sell electricity to the local utility (Sierra Pacific Co.), starting in late 1985[142]. Consequently, the firm was more in control of its revenue stream, given that it is easier to measure the electricity than to measure the flow and quality of the steam supply. This is the first geothermal project entirely designed, built and operated by Phillips, which was a vehicle for the company to leverage their in-house expertise to design power plants (Bloomquist et al., 1989; Johnson, 2014). Unfortunately, Phillips sold its geothermal

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relevant differences in the temperature gradients between the depths of 300 and 500 feet. Second, the thermal anomaly appeared to be so intense that it could be easily defined with 300-foot-deep holes. Third, costs could be reduced by limiting the depth of the shallow temperature wells to 300 feet (W. R. Benoit et al., 1980; W. R. Benoit, 1978).

[140] Other organizations that were also interested in the Desert Peak field and drilled shallow temperature-gradient holes included the U.S. Geological Survey, the U. S. Bureau of Reclamation, and Unocal (W. R. Benoit et al., 1980).

[141] This involved the drilling of deep holes designed to penetrate the probable geothermal reservoir, either through a narrow diameter exploration "slim hole" or with a large-diameter production well.

[142] This new model was the result of a long learning period. It took Phillips nearly 10 years to reach a Power Purchase Agreement with a utility (PPA) (W. R. Benoit, 2014).

properties to Chevron Resources Company in late 1985, including the Desert Peak field and the power plant (U.S. Department of Energy, 2009).

The **design of the power plant** for the conditions of Desert Peak was a challenge, given the lower pressure, lower temperature, and lower flow[143] relative to RHSU. The design of the power cycle was accomplished in a very short time frame thanks to the internal development of the "Desert Peak Simulator" (DPSIMF), which could model the different plant configurations available for the unit (single flash, dual flash or the RST system, including the injection of the flow back in to the field and all auxiliary systems). This simulator was developed by C. P. Diddle (W. R. Benoit, 2014; Cerini et al., 1984)

Phillips also did the **manufacturing of the power unit** internally, with assistance from the developers of the RST technology (Transamerica Delaval Biphase Energy Systems). Phillips decided to include the RST technology in Desert Peak's power cycle, considering the high performance that the RST pilot achieved at the RHSU[144]. The expectation was to achieve a 21% increase in conversion efficiency and lower capital costs, relative to a binary system. Still, the RST technology had to be adapted to the site conditions of the Desert Peak field, since its geothermal resource had less temperature than that of RHSU. Unfortunately, the difference in inlet temperature and pressure between the RHSU and Desert Peak was too large to make the RST a feasible technology, so it was discarded and replaced by a more conventional turbine and an independent separator. Desert Peak's lower temperature and pressure did not provide enough steam to pay for the RST, but at least it had a good separation, whereas at the RHSU the resource provided ample rotational and generation capacity but it was not a good separator (W. R. Benoit, 2014; Bloomquist et al., 1989; Cerini et al., 1984; Johnson, 2014).

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[143] Roosevelt wells were extremely prolific (flow of 1 million pounds / hour of mass and a temperature above 400°F), whereas Desert Peak had much less flow and lower temperature (400 thousand pounds/hour of mass and a temperature of 326 °F) (Johnson, 2014)

[144] The RST technology at Blundell was only a temporary pilot, whereas the use of RST at Desert Peak was originally conceived as part of the power cycle.

Discussion of the case

Figure 27 and Figure 28 show graphically the structure proposed in Chapter III to synthetically represent the units of analysis. These figures are used repeatedly to summarize the main sources of knowledge and the transfer mechanisms for each of the technical challenges studied. The large rectangles represent the boundaries of the different knowledge sources available, whereas the smaller squares represent the different transfer mechanisms to access those sources of knowledge. From the inside out, the large rectangles and their respective small squares are: on the first level, the Geothermal Division's internal capabilities (including capabilities inherited from upstream oil and recruitment); on the second level, the assistance from the firm's in-house R&D group (including direct assistance and labor reallocation); on the third level, the support from the ecosystem beyond the firm's boundaries[145] (including service contract, a consortium and public available information)[146]. If a rectangle or square is white, it means that it was not a relevant source of know-how or was not used as a transfer mechanism. It is important to remember that the technical challenges represented as units of analysis do not necessarily apply to the whole geothermal field; instead, they are hurdles confronted by the firm within a specific project.

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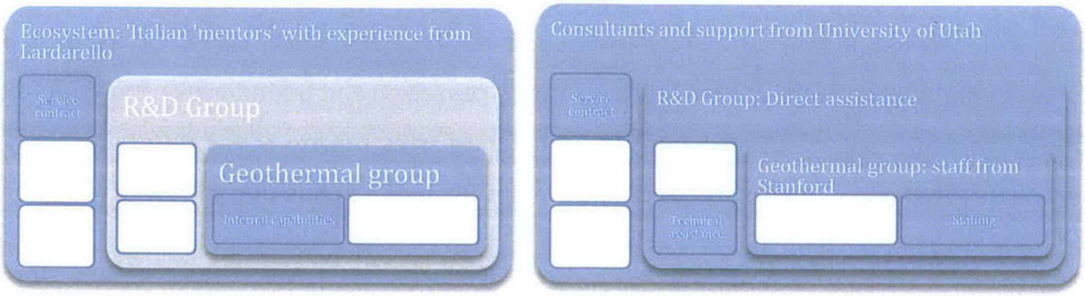
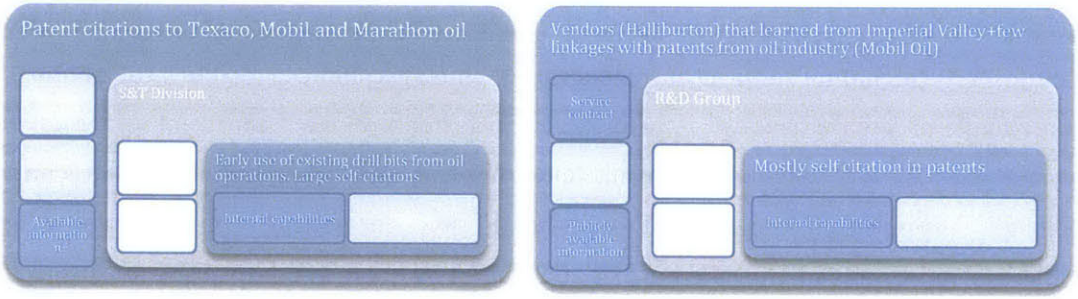
[145] Including other operators, vendors or government-sponsored research projects that could be implemented by National Labs.

[146] A consortium is defined as when the risk is shared and there is government sponsorship. A service contract is when there is no risk shared with the vendor.

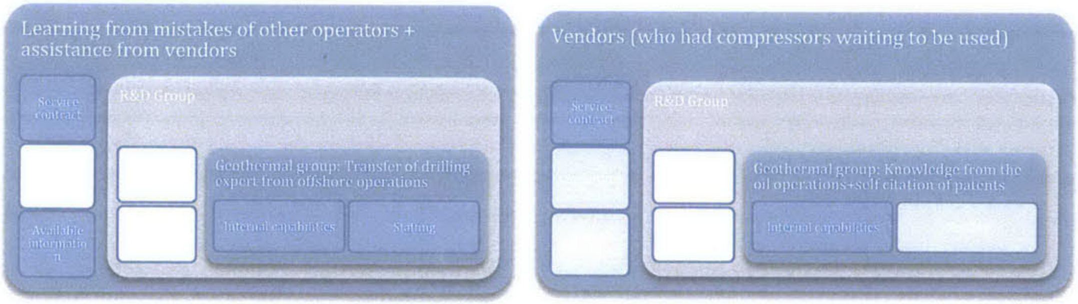
Figure 27: Source of knowledge and transfer mechanisms for the technological developments of the Roosevelt Hot Springs project.


Exploration of a resource with no surface manifestation

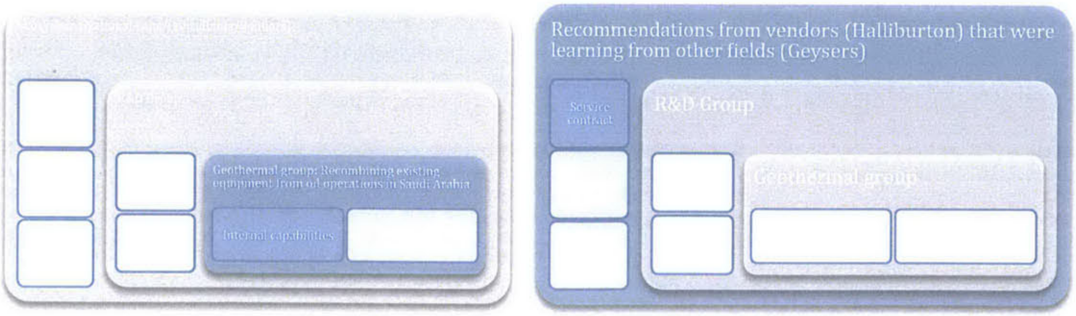
Dynamic models for reservoir engineering


Hard-rock drilling

Third generation drilling mud

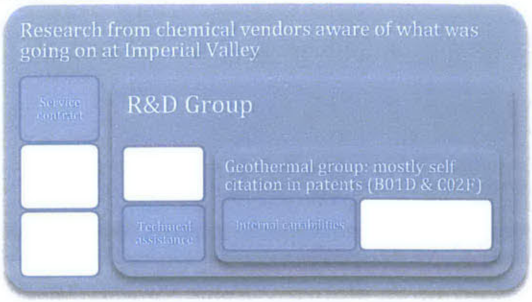

Properly manage loss of well control

Use of air drilling to handle lost circulation

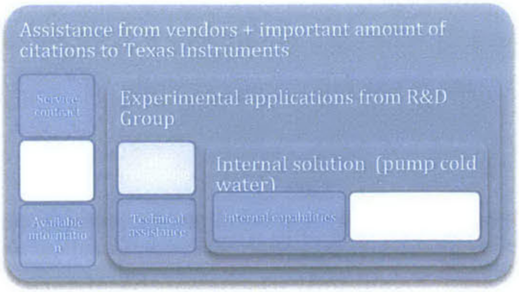

Increase diameter of the casing

Handle corrossion on cements

Chemicals to inhibit the formation of calcite scale



Logging high-temperature geothermal wells



Development of the rotary separator turbine

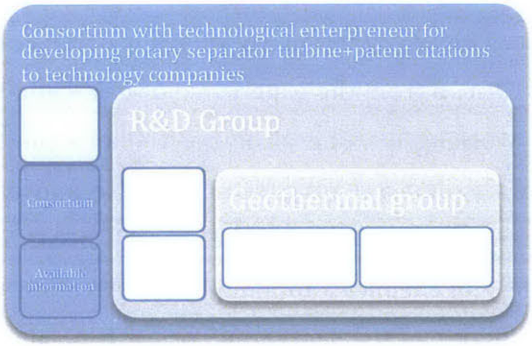
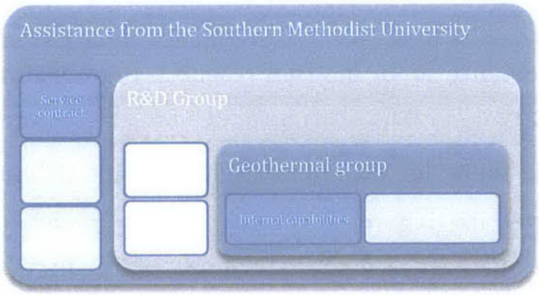


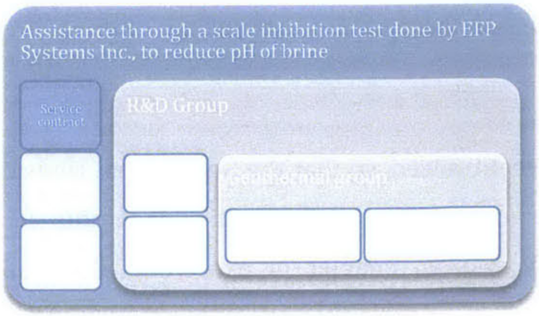
Figure 28: Source of knowledge and transfer mechanisms for the technnological developments of the Desert Peak project

Thermal gradient holes to efficiently characterize potential



Designing, operating the field and the power plant

Address calcite scaling.



Based on this case study, some deductions can be drawn with respect to the capabilities required for Phillips to successfully diversify into the geothermal business.

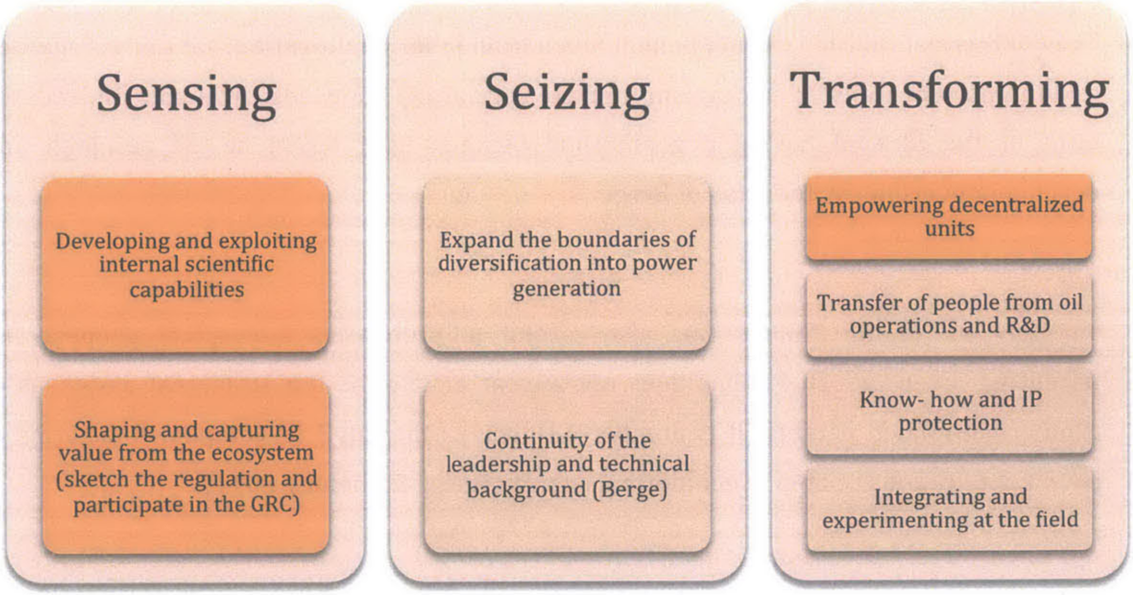
First, Phillips was able to acquire and exploit the knowledge available from the ecosystem of the geothermal industry. It can be observed, by looking at Figure 27 and Figure 28, that Phillips had a persistent reliance on the industry (especially vendors) to complement the internal capabilities of the Geothermal Division. This was particularly relevant because of the indirect transfer of knowledge, by vendors, drawn from the experience of first-comers in geothermal development (like Halliburton working for Unocal or the Italian experts working at Lardarello). Phillips benefited from this indirect transfer in order to address topics such as suitable drilling muds, the treatment of cements to resist the conditions of the geothermal reservoir, and the down-hole delivery of chemicals to inhibit the formation of calcite scale. Furthermore, Phillips was also a 'shaper' of the geothermal ecosystem, given that it was an active party during the ruling process on geothermal licenses (after the enactment of the Geothermal Steam Act of 1970) and was closely connected to the Geothermal Resource Council through Bill Berge.

Second, Phillips benefited from the direct assistance of an internal research organization that was closely tied to the geothermal business units. The R&D group's assistance to the Geothermal Division was limited to topics that were not the core activities of the drilling process (such as new measuring devices for well logging, reservoir engineering models to study the behavior of the well and mitigating the scaling occurring inside the wellbore). Even though the R&D group was not considered the most up-to-date source of geothermal knowledge, probably because their approach might have been too exploratory, they were still regarded as an essential support for Phillips' geothermal business units.

Third, Phillips' organizational structure was decentralized, so that the Geothermal Division was empowered with sufficient financial resources and was under the leadership of a technically minded manager. Such autonomy was an enabler of experimentation and learning at the field, such as the experience using thermal gradient wells as an efficient technique for geothermal exploration.

All of the relevant dynamic capabilities described throughout this chapter are summarized in Figure 29, emphasizing in orange the dynamic capabilities that are part of the hypotheses of this thesis.

Figure 29 Main dynamic capabilities for Phillips' related diversification into geothermal energy technologies[147]



Aside from the three dynamic capabilities highlighted in orange cells, which confirm the vality of the propositions of this research, other interesting dynamic capabilities became relevant drivers for Phillips' related diversification into geothermal (and which is worth describing). These are highlighted in blue in Figure 29.

Phillips was the first oil company to use the IPP model to enter into the electricity market through a geothermal. This illustrates the firm's success in **expanding the boundaries of**

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[147] The classification of these dynamic capabilities into the microfoundations of "sensing, seizing and transforming" is merely exploratory. Obviously, for example, the act of "shaping and capturing value" does not play a role only in identifying external sources of knowledge and opportunity (sensing), but also in helping transform the boundaries of the firm (transforming).

their diversification toward an unrelated field with respect to operating an oil field. In this way, the firm was able to hedge the value of their steam operations directly into the market (not through a secondary market with an intermediary acting as a buyer).

The role of a permanent Geothermal Division's manager (Berge) with suitable cognitive capabilities and technical background was deemed critical for **leading a continuous process of change** and innovation inside the company.

The Geothermal Division did not benefit much from **labor reallocation**, yet this is regarded as an important transfer mechanism to make specialized knowledge available. Indeed, the birth of the idea of having a geothermal business unit began in the research and development group, by the hand of Berge.

Similarly to Unocal, Phillips was also careful to protect its intellectual property by **patenting**. Even though Phillips does not appear among the top 10 largest assignees of geothermal-related patents (it is number 13), it is in the top 3 oil companies in terms of patent applications related to geothermal energy (Ruegg & Thomas, 2011).

Finally, Phillips was capable of orchestrating **different sources** of knowledge and testing them by **experimenting** at the field. Phillips' Geothermal Division took the ideas from the R&D group (and other external sources of knowledge) and experiemented with them at the field, thus encouraging a culture of risk overcoming problems.

VIII. Discussion

This chapter aims first to validate that the original propositions of this thesis have been proved based on the evidence of the two case studies from Chapter VI and Chapter VII. Second, this chapter also aims to identify other dynamic capabilities possessed by both Unocal and Phillips that assisted their diversification into geothermal energy technology. Third, this chapter presents a set of new inquiries regarding the core of the strategic decisions for the diversification of an extractive industry into low carbon energy technologies.

The results are based on 28 different units of analysis within the two case studies selected. Table 11 summarizes the main sources of knowledge and the transfer mechanisms for each of the technical challenges studied (which have been chosen as the units of analysis of this work) for the diversification from oil to geothermal by the two focal firms. The technical challenges documented here for every field are those that had clear evidence avaialable. This doesn't preclude that the activities not documented did not occur, however the evidence have not shown them as relevant challenges. Yet, the main purpose has been to document for every firm the knowledge transfer of all the technical challenges listed[148].

As explained by the legend on Table 12, red cells indicate those technical challenges that are drawn from pre-existing internal capabilities (like those inherited from the upstream oil operations), whereas cells in orange correspond to knowledge that is transferred into the geothermal division by contracting new staff (which I have interpreted as internalizing a previously external source of knowledge). The yellow and green cells represent the knowledge transferred from the firm's R&D division as labor reallocation and direct assistance, respectively. The various shades of blue represent sources of knowledge outside the boundaries of the firm that is made available through service contracts, consortia or is publicly available through patent documents.

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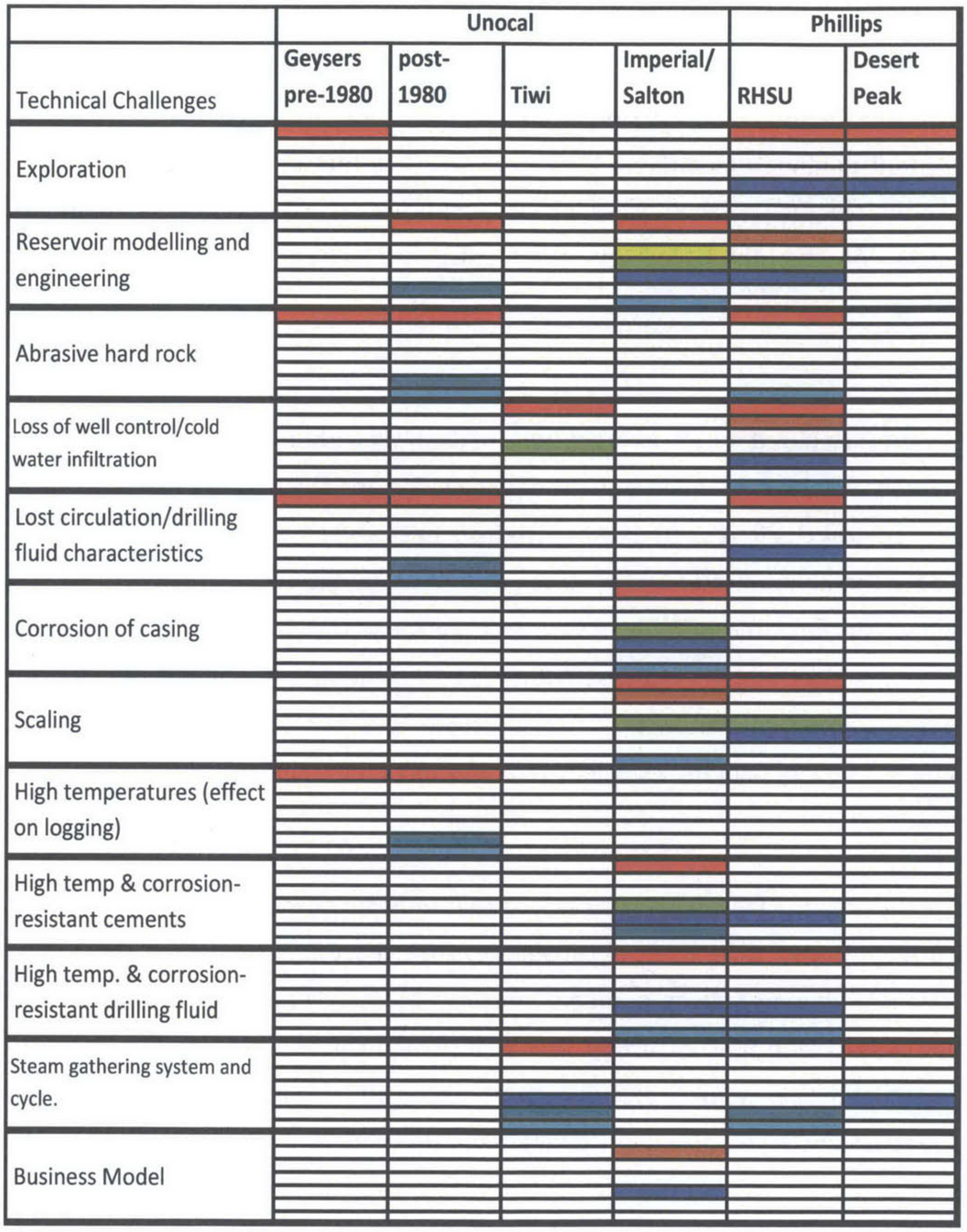
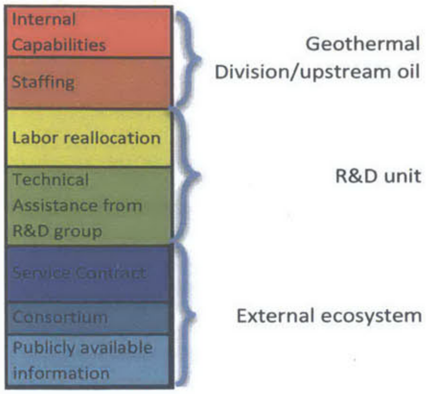
[148] The only expection is that on Unocal's knowledge transfer on the challenge of the business model because the evidence did not presented it as a critical factor.

Table 11: Summary of knowledge sources and transfer mechanisms for the diversification into geothermal energy of Unocal and Phillips



	Unocal				Phillips	
Technical Challenges	Geysers pre-1980	post-1980	Tiwi	Imperial/ Salton	RHSU	Desert Peak
Exploration	🟥				🟥 🟦	🟥 🟦
Reservoir modelling and engineering		🟥 🟦		🟥 🟨 🟩 🟦 🟦	🟫 🟩 🟦	
Abrasive hard rock	🟥	🟥 🟦 🟦			🟥 🟦	
Loss of well control/cold water infiltration			🟥 🟩		🟥 🟫 🟦 🟦	
Lost circulation/drilling fluid characteristics	🟥	🟥 🟦 🟦			🟥 🟦	
Corrosion of casing				🟥 🟩 🟦 🟦		
Scaling				🟥 🟫 🟩 🟦	🟥 🟩 🟦	🟦
High temperatures (effect on logging)	🟥	🟥 🟦 🟦				
High temp & corrosion-resistant cements				🟥 🟩 🟦 🟦	🟦	
High temp. & corrosion-resistant drilling fluid				🟥 🟦 🟦	🟥 🟦 🟦	
Steam gathering system and cycle.			🟥 🟦 🟦 🟦		🟦 🟦	🟥 🟦
Business Model				🟫 🟦		

Table 12: Legend of previous chart, knowledge sources and transfer mechanisms



Internal Capabilities	Geothermal Division/upstream oil
Staffing	
Labor reallocation	R&D unit
Technical Assistance from R&D group	
Service Contract	External ecosystem
Consortium	
Publicly available information	

The following specific findings can be drawn from this figure:

- For the pre-1980 period of the Geysers project, the related-diversification from oil to geothermal consisted of a direct transfer of existing capabilities from upstream oil operations (at most an adaptation of such capabilities), in order to address the issues of lost-circulation, hard-rock drilling and to search for alternatives for monitoring and cementing under high temperature conditions. For The Geysers (after 1980) and for the rest of the business units of Unocal and all of the Phillips' projects, there is no evident pure relatedness (or direct transfer from oil to geothermal), so the firms required complementary knowledge from the geothermal ecosystem (on a first instance) and from the firm's R&D group.
- Generally, the main source of know-how lay in the geothermal division (23 out of 28 or 23/28) but this was almost always complemented with knowledge captured from the ecosystem (19/28), and in the majority of the cases through the transfer mechanism of a service contract (14/28). There are only three examples of technical challenges that were solved entirely depending on a third party outside the firm's boundaries (3/28 - development of the power cycle, scaling at Desert Peak and solving corrosion on cements at the RHSU). The backward patent citation analysis supports this statement by showing that linkages are largely self-citations complemented with citations to other oil operators and vendors[149] (mainly for drilling bits, drilling fluids & logging instruments) and government-sponsored

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[149] It can be seen that the share of self-citation dominates in the geothermal topics where the oil firm patented most (classification codes E21B and G01N), whereas for classification codes with a lower patenting rate, the patents from external organizations are more influential (like G01V). It is interesting to emphasize the frequent citation to oil companies or vendors for the oil industry such as Mobil, Marathon Oil, Texaco, UOP and Standard Oil.

research (Unocal has the 3rd highest share of geothermal patents linked to earlier DOE-attributed geothermal energy patents while Phillips has the 7th highest) (Ruegg & Thomas, 2011).

- Whenever a technical challenge is supported by a firm's R&D group (7/28), it was almost always complemented with knowledge available from the ecosystem (6/28). This is probably because the R&D group owned a heterogeneous stock of knowledge (from a broad set of products of the oil industry), which helped to capture and translate the value from external sources. The R&D groups assisted issues like corrosion, scaling, high temperature logging tools and specialized services like reservoir engineering or infiltration of cold water.
- The combination of transfer mechanisms to address the technical challenges that is most recurrent (12/28) is that of "internal capabilities" together with "service contract". This evidences the preference for an immediate supplier to complement the internal knowledge, instead of engaging in a relationship of consortium or relying on the Science and Technology Division's assistance. Yet, the knowledge transfer mechanisms are hard to classify since these are hard to measure and can imply tacit knowldge.
- The transfer mechanisms of "staffing" and "labor reallocation" are the least used for the diversification into geothermal energy (4 and 1 time respectively). This is evidence that both companies might have relied less on transferring knowledge through people and more through collaboration or service by other entities.
- Both firms share the fact that to overcome the technical challenges related with the operation of geothermal fields, they drew of internal and external sources of knowledge. Unocal faced an increasing degree of complexity in the operation of its geothermal fields, transitioning from leveraging its core competencies of upstream oil to depending heavily on external sources of knowledge. Whereas, Phillips took immediate advantage of the available knowledge from the ecosystem so as to complement is internal know-how.

The consolidated assessment of the cases confirms the three initial propositions. These are described below:

- First, "**shaping and capturing value from the ecosystem**" is proved as a key dynamic capability for a related-diversification, confirming the first proposition and also previous work in this field (C. E. Helfat & Peteraf, 2003). The cases denote the relative importance of the external ecosystem's knowledge (nurtured mostly by government-sponsored research), whether to complement what was lacking in the firm's internal know-how (inherited from upstream oil operations)[150] or to provide a technical solution, which was far from the capabilities that the geothermal division had[151]. The ecosystem's knowledge became a valuable resource because it responded to the technology needs that the field operators had originally posted through academic workshops, special boards to guide DOE's GTP, active collaboration through the Geothermal Resource Council or feedback on the Geothermal Steam Act. Through these actions, the operators were able to "shape" the value of the ecosystem and later absorb it and scale-up the technology for commercial implementation.

- Second, based on the evidence provided, we can state that each firm's R&D unit complied an auxiliary role in bridging the gaps of knowledge of the geothermal divisions, to solve their complex scientific and engineering problems[152] and link with the outside source of knowledge. The R&D unit was a reservoir of the firm's knowledge stock, accumulated from its broad set of business pathways (summarized by Figure 10 and Figure 21), which helped not only to leverage the existing skills to diversify into geothermal, but also expand the breadth of its engineering solutions[153]. It is also important to emphasize that interviewees recognize that an informal relationship between the R&D unit and the geothermal division enriched the assistance provided, which reflects the common motivation to test new ideas at the field and confirms the findings from previous quantitative analysis on the leverage of capabilities by multi-national companies (Hansen & Løvås, 2004). In summary, I confirm the second proposition by identifying that the firm's dynamic capability of "**developing and exploiting internal scientific capabilities**" was an important factor to help the related-diversification from oil into geothermal, thus corroborating former research on this area (Alonso-Borrego &

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[150] Such as reservoir engineering at the Geysers field or RHSU and scaling at the Imperial Valley.
[151] Development of the power cycle and solving corrosion on cements at the RHSU.
[152] In the case of Phillips on calcite scaling, reservoir engineering, and logging tools for high-temperature wells, while in Unocal for scaling, cements, casing and reduce infiltration of cold water.
[153] Some examples are the infiltration of cold water at Tiwi, handling corrosion and scaling at the Imperial Valley or adapting logging tools and cements to the high temperature conditions of the geothermal fields.

Forcadell, 2010; Døving & Gooderham, 2008). It is yet to be seen what was the effect from the closure of various research and development departments during the 1980s and 1990s, and if these were replaced by decentralization of research and later by outsourcing to external research organizations[154]. Hypothetically, both dynamic capabilities (shaping the ecosystem and capturing knowledge from it and researching to provide "science-base" for this orchestration and to develop specific new solutions to applied challenges) are interconnected, since an organization will not be able to interact properly with the external ecosystem and capture value from it, unless there is a good stock of internal R&D capacity to absorb the value (and the tacit knowledge) from it.

- Third, the proposition that a decentralized approach is beneficial to the newly diversified business areas is also confirmed given the fact that the two companies studied empowered their geothermal divisions with financial and managerial autonomy to connect with other organizations, but more importantly, to encourage experimentation at the field. This validates the findings from Helfat & Eisenhardt, which concluded that decentralized structures provide better conditions for a related diversification (C. Helfat & Eisenhardt, 2004). Therefore, the third dynamic capability of "**empowering decentralized units**" is also validated as a relevant factor for the diversification of oil into geothermal.

The cases presented evidence that although oil firms saw in geothermal energy an opportunity to leverage their capabilities by a related diversification (consistent with the literature exposed in Chapter II), dynamic capabilities (and not its core competencies from upstream oil operations) were ultimately the most influential factor for diversification. That means, no matter how clear the economies of scope seem, it will still imply organizational-learning. Hence, the level of relatedness of a new business field relative to the firm's core occupation becomes a dubious predictor of the real chances of a successful diversification. That is why relying too much on the oil-related knowledge while diversifying into geothermal could become a detriment to the firm's geothermal operations, as anticipated by

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[154] During the 1980s several firms closed their R&D groups since they didn't consider internal science as the best approach to innovation and because there was not enough free cash flow from domestic markets (drop in oil price) to fund this R&D. Initially this reserach activity became decentralized and later outsourced (Teece, 2010).

Leonard-Barton's work on core capabilities and rigidities (W. R. Benoit, 2014; Leonard-Barton, 1992). This time, Mike Barnes[155] makes a very accurate exemplification of this issue, for the context of the cases presented:

"Unocal thought that there was going to be some kind of crossover because the drilling was so similar, but in the final estimation they finally grew apart instead of going together". "Oil companies thought they could takeover easily over geothermal. However in fact it wasn't it, because Unocal found early on that they were reinventing things quite a few times in order to make them work with Geothermal" (Barnes, 2013).

Dynamic capabilities were essential to keep geothermal competitive, specially considering the incremental level of sophistication that Unocal had to confront from the selected fields Geysers, Tiwi and Imperial.

In addition to the three dynamic capabilities represented by the propositions of this thesis, other dynamic capabilities also came into place to assist the diversification from oil into geothermal, on which is worthwhile to spend some words on:

- The continuous presence of a technically minded manager, who had the cognitive capabilities for **leading** the leverage and transfer of knowledge, was essential to overcome the internal rigidities of the firm and successfully diversify from oil to geothermal. Carel Otte and Bill Berge were the heads of the Geothermal Divisions for Unocal and Phillips, respectively, and gave this process a persistency to preserve the valuable stock of knowledge that was being nurtured. The work of Helfat and Peteraf emphasize the importance of the cognitive skills from some individual managers to implement the organization's strategy (C. E. Helfat & Peteraf, 2014).
- The culture of both organizations was to promote **experimenting** at the field with technical proficiency and a problem-solving mindset. The geothermal division of both firms became proficient in the ability of first, integrating knowledge from different sources, and second, testing and adapting these ideas at the field. Examples of such development are on technical challenges like new cement for corrosive environments, and the use of the pH modification treatment and the crystallizer clarifier to handle scaling.
- Both firms emphasized **protecting their proprietary knowledge** as a counterbalance to the absorption from the ecosystem, and hence became highly

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[155] Former Manager of Engineering and VP of Unocal Corp.

influential in terms of the number of geothermal-related patent applications: Unocal had the 2nd largest set of geothermal patents while Phillips is the 13th largest assignee of geothermal-related patents (Ruegg & Thomas, 2011).

- Unocal's Geothermal Division, and to a lesser extent Phillips' Geothermal Division, benefited from **promoting the free flow of people** of their upstream oil operations and of the R&D units. This free-flow of workforce within the organization is a relevant dynamic capability that helps to sustain a healthy transfer of knowledge, which nowadays is in practice at several oil companies.
- Both of the companies saw the opportunity of **expanding the boundaries of their diversification** beyond the operation of the field and into the power generation sector. Initially, the engagement into geothermal was limited to the operation of the field to sell steam to a local utility responsible for converting it to electricity. Later, thanks to the support of the PURPA regulations, the two firms studied became IPPs. Unocal created its own subsidiary called Desert Power Co. for the 47.5 MW Salton Sea Unit 3, while Phillips became an IPP through its 9 MW Desert Peak power project.

This research unveiled other factors that go beyond the scope of this thesis but are relevant to mention since they also influenced the diversification process of these two firms:

- Although Unocal had a fair amount of interaction with the National Labs and vendors to absorb complementary knowledge for its hardest challenges, at the same time it was regarded as purposively secretive[156] to protect its competitive advantage in technology development. So an important knowledge-flow was getting inside Unocal but little was going out (B. Barker, 2013; DiPippo, 2013; Henneberger, 2013; J. Tester, 2013). Since geothermal development is very field-specific, secretiveness could have been justifiable in operations sharing a field with other firms. On the contrary, 'Dick' Benoit from Phillips argues that this secretive policy was detrimental to Unocal's development, and questions the lack of inter-industry collaboration to comprehend the specific behavior of a field:

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[156] Unocal severely restricted the ability of its employees to publish technical papers.

> *"Even though they were successful, there was a lot that they didn't learn. When they came to Nevada, they didn't do very well. They didn't discover anything. They were looking for another Geysers. There is a limit on being secretive"* (W. R. Benoit, 2014).

In this respect, it is interesting to consider if there are incentives that could generate positive spillovers between companies operating the same field. An example of such cooperation of two distinct operators occurred with the consortium that addressed the drop of pressure of the Geysers field, with a reinjection of municipal wastewater (described under the Unocal case).

- Even though Unocal (as well as other operators) was very reserved with respect to its proprietary knowledge, part of it leaked and reached other operators (like Phillips). The knowledge co-existed with the rest of the ecosystem particularly when the transfer mechanism relied on government-sponsored consortiums. The external parties involved (vendors and National Labs) acquired tacit knowledge by working at Unocal's field, which they could later use to pollinize in the context of other geothermal challenges (such at the Phillips' fields). In a very generalizable fashion, it can be said that Unocal was leading the scale up of some geothermal technological developments by leveraging its capabilities from upstream operations, while the Sandia National Lab was providing the necessary complementary knowledge and cross nurturing to other operators and vendors (thus becoming the nexus between oil and geothermal) (DiPippo, 2013; K. Williamson, 2013). Addressing scaling and cement mixes are examples of knowledge transfer across operators, through the intermediation of vendors like Halliburton, who experienced these innovations at the field hosted by first-comers such as Unocal (W. R. Benoit, 2014; Johnson, 2014).
- In addition to the assessment of knowledge sources and transfer mechanisms, this thesis proposed a causal-loop diagram in Figure 3 to explain the different factors that influence the evolution of a firm's knowledge stock, and its implications for related diversification[157]. The analyses based on the data records from both case studies (Figure 12 and Figure 23) provides no conclusive evidence to confirm the systemic representation proposed by the causal-loop diagram, given the gaps of quantitative data. Yet these analyses suggest that there is an apparent causal relationship that

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[157] The path dependency analysis is not core to the original propositions, yet this work includes the analysis of such interactions with the purpose of providing more information on the relevant capabilities and resources of each firm's diversification into geothermal energy technology.

explains the link between the price of oil, the number of geothermal patents (level of capability) and the number of geothermal wells (level of activity) for the case of Unocal, and between the price of oil, the firm's R&D expenditure and the number of patents for the case of Phillips. These causal relations are present only during a subset of the "peak-oil price" years, and they illustrate the loops "economies of scope from activity" for the case of Unocal and "economies of scope from research" for the case of Phillips. Even though this is a quantitative exercise, the proposed diagram of causal interactions on the diversification of a firm can be improved through a larger set of case studies with better data.

- There is an unresolved incompatibility between the operation of the field (high risk with a high return) and selling electricity to a utility company (low risk with a low return on equity), which was one of the main factors that discouraged oil and gas operators from remaining in the geothermal business. Oil and gas operators were used to high-risk exploration and expected a high return, which worked for the early geothermal developments because the old contracting scheme allowed sharing the risk with the utility. The incorporation of Unocal and Phillips into the electricity market meant not only that they could no longer share the risk of the resource with a third party, but also that they had to match the available steam with the size of the turbine and its remuneration. An IPP cannot transfer the resource risk (or fuel risk) to the customers, as a regulated utility can through the rate structure. So once the power plant's risk became tied to the resource risk, geothermal energy did not provide the expected rate of return for its associated high risk (S. Pye, 2013).

IX. Conclusions and proposed research

Initial inspiration and approach

Inspired by the works from Hausmann and Hidalgo (Hausmann et al., 2011; Hidalgo & Hausmann, 2009), I became interested in diversification as a relevant path for technology catch-up and economic development. Yet I knew that there were a lot of insights that this top-down analysis approach at the country level was not going to grasp (and which was not intended to do so). Therefore, I proposed to myself to unveil the mechanisms and interactions behind diversification at the organization-level, so as to obtain granular evidence on how capabilities evolve and help an organization learn and become more productive and competitive under unfamiliar business fields. I framed this research from the perspective of capabilities since these are the drivers that influence technical and economic change in the modern world (Powell & Snellman, 2004). Concurrently, I recognized environmental sustainability as one of the key values that will determine country and corporate competitiveness (ESTY & PORTER, 2005; Kolk & Pinkse, 2013). I was then ready to integrate the topics of diversification and sustainable development by using the case of oil firms that diversified into geothermal energy, since this is a practical example of a diversification from an extractive industry into a low-carbon intensive business, close to the firm's knowledge space and also considering that I had several case examples to use as reference. This example represents a possible future scenario stressing the need of a shift in the global business paradigm, from a carbon-intensive industry to a business choice with less environmental implications.

This thesis started with an in-depth review in Chapter II of the prior literature on innovation management and knowledge management, to define the theoretical propositions that would guide the case study analysis. This literature review claims that firms tend to follow a coherent (or related) pattern of transition into industries where they can leverage an internal asset or knowledge (Penrose, 1996), and that this evolution of the firm's boundaries (and knowledge base) can only be explained through the framework of "dynamic capabilities" (Dosi & Teece, 1998). As described in Chapter II, these dynamic capabilities are responsible for moving the organization beyond its rigidities and not only "doing things right", but also "do the right things" (Shuen & Teece, 2014).

Twenty-eight units of analysis were constructed to represent the sources of knowledge and the transfer mechanisms to overcome the technological challenges emphasized by the differences between upstream oil operations and geothermal development, in the cases of Union Oil Company of California (Unocal) and Phillips Petroleum (Phillips). Complementary information was included and classified accordingly to describe in detail the different elements present in each firm's diversification into geothermal energy development.

What can be learnt from the case studies presented

The two case studies of Unocal and Phillips demonstrate that core competencies inherited from upstream oil are necessary but not sufficient to diversify into a related business field (and sustain a competitive advantage). The evidence provided by both case studies supports the initial propositions that the dynamic capabilities of "Shaping and capturing value from the ecosystem", "Developing and exploiting internal scientific capabilities" and "Empowering decentralized units" were instrumental in the successful diversification from upstream oil into geothermal. Building on these dynamic capabilities, Unocal and Phillips became orchestrators of different sources of knowledge to overcome the technical challenges they had for exploring and operating different types of geothermal fields. This is the first and main contribution of this work.

The second contribution of this thesis is that the two case studies evidence the presence of 5 other dynamic capabilities that proved to be relevant on the diversification from oil to geothermal (see Chapter VIII). Overall, the major conclusion is that economies of scope from leveraging knowledge cannot be gained unless the firm exercises its dynamic capabilities. The third contribution, although not conclusive, has been to integrate referential literature on the topic of technology strategy under a causal-loop representation of the different factors that influence the evolution of a firm's knowledge stock and the expansion of a firm's business frontier. This systemic representation has been tested with data of annual records for both case studies (geothermal patents, geothermal wells and R&D expenditures) and their response to exogenous factors (price of oil and U.S. Government R&D expenditures on geothermal energy), evidencing an apparent causal relationship to explain the interplay of dynamic capabilities in the evolution of each firm's knowledge base.

There is an inherent trade-off in a firm's diversification into a related business field, between leveraging existing capabilities (or operational capabilities) and exercising dynamic capabilities (to learn and continuously expand the breadth and depth of the firm's knowledge base). Relying too much on the oil-related knowledge while diversifying into geothermal could become a detriment to the firm's geothermal operations, as anticipated by Leonard-Barton's work on core capabilities and rigidities and confirmed by some of the interviewees (W. R. Benoit, 2014; Leonard-Barton, 1992). Instead, dynamic capabilities can become useful for the firm's competitive advantage, only if these are exercised repeatedly and are embedded in the company culture throughout the organization (Kleiner, 2013). Dynamic capabilities reflect the speed and degree to which the firm's idiosyncratic resources/competences can be aligned and realigned to match the opportunities and requirements of the business environment.

The policy insights that can be derived from this thesis' findings are threefold. First, a product diversification strategy rooted in leveraging core assets or operational capabilities will likely be thwarted if there is not an effort to make sure organizations have dynamic capabilities required to learn from the industrial ecosystem, experiment at the fieldwork and integrate several sources of knowledge to address the challenges from unfamiliar business settings. Second, the diffusion and deployment of new energy technologies can be understood not only as a source of energy supply but also as a diversification opportunity for firms that want to leverage their assets or capabilities (just like oil firms did in many different new energy technologies during the oil price crisis, as explained in Chapter IV). Still, as this work has reflected, such venture requires relying on dynamic capabilities that can drive the company beyond its internal rigidities and prepare it to learn. Third, large extractive industries can become an attractive hub for intermediaries to challenge their knowledge, test their capabilities and pilot new technologies, thus spurring collectiive learning with evident positive externalities to the whole industrial ecosystem.

Further research

This thesis unveils a large set of new questions that can be translated into research topics. The most profitable inquiries from my perspective are:

- **Test the propositions presented with a case of a flawed diversification from oil to geothermal:** From all of the 12 major oil firms that decided to diversify into the geothermal energy business, during the peak oil price period of the 1970s and the first half of the 1980s, some of them didn't succeed in becoming operators of a field. It is interesting to study what differences can be found between a case of failure and the two successful experiences of Unocal and Phillips.
- **Rigidities from a company's size**: Are large oil firms less "dynamic" and therefore more rigid with respect to small firms, on the diversification opportunities into a related business field? Does this rigidity translate into the financial benchmarks required by the firm's management? Unocal was big enough to make large investments, but small enough that the returns on those investments made a difference to the corporate bottom line. Some of the interviewees suggested that larger firms than Unocal and Phillips (like Chevron, Shell or Exxon) would not have stayed with geothermal for as long as Unocal did, simply because they were too big (and risk adverse) to take the detour away from the core business (Baza, 2014; Henneberger, 2013; Johnson, 2014; Kitz, 2013), and that damaged the entrepreneurial approach and autonomy of the geothermal business unit (Barnes, 2013). This proposed research path aims to question whether size can be detrimental in the dynamic capability to integrate skills within the company.
- **First-mover's access to competitive endowments:** Unocal had the vision (and the luck) to early engage in the development of the Geysers field, which was an appropriate field for learning[158]. This got Unocal into a status of leadership and far ahead of many of the other oil firms that were aspiring to diversify into geothermal energy, which helped the firm to capitalize its nascent geothermal business in the Philippines (Johnson, 2014). Further research could consider the effect of some competitive endowments (like The Geysers' field) for taking a position of leadership

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[158] It is an appropriate field for learning because it can be considered an "easier" context relative to the fields that were developed later (no corrosive environment, less scaling, surface manifestation and leverage an important rise in oil prices).

within a promising industry, assuming that fields are unique and context dependent, and test if success garnered from innovation can lead to market concentration (Teece, 2010).

- **Effects from crossing international borders in the diversification:** Although both companies studied had several similarities which have been identified in Chapter III, Phillips' involvement was much more short-lived (1971-1985) and constrained to activities occurring only in the U.S[159]. Contrastingly, Unocal expanded its geothermal business units abroad, yet the firm did not operate a U.S. field outside of California (where Unocal had its headquarters). It is yet to be studied what could be the effects of internationalization on the diversification process of energy companies.
- **Related-diversification and level of technological maturity.** This thesis has build on Teece's work to state in Chapter II that better economies of scope can be present on immature industries, from where it is less possible to monetize the surplus resources of the firm via transactions because there are fewer intermediaries able to acquire those resources. It is interesting to confirm this claim and evaluate if this is happening because some resources (licenses and perhaps know-how) are context dependent, or because knowledge assets are tacit to varying degrees and costly to transfer.
- **The strategic role of the government in nurturing industrial ecosystems**: The U.S. government's sponsorship was a catalyst for the development of the geothermal industry during the 1970s and 1980s. This enabled the availability of new technologies on the field of drill bits, cements, reservoir engineering modeling tools and power cycles for binary power units (Gallaher et al., 2012). It also supported the creation of programs for geothermal exploration and several others described in Chapter IV. Yet, the lack of continuity of public funding triggered an important loss of momentum, which harmed the rate of growth in installed capacity of this energy source. It is interesting to ask how government funding can help to strengthen the networks that build this ecosystem, so as to accelerate knowledge transfer and promote positive spillovers between companies operating in the same field.

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[159] Based on what the interviewees that used to work for Phillips, given that Phillips could have evolved into this.

- **The utility of the future as another business diversification case in the energy industry**: It is interesting to study if some of the theoretical propositions are tested under a different context of application, beyond the oil price crisis time frame and into other energy industries. Regulated utilities had diversified in the past to the telecommunications sector (Osorio Urzúa, 2004), but now they need to diversify further in order to add new energy services to their customer base, considering the recent challenges for bidirectional flows from distributed generation and demand side management. Can we extrapolate the dynamic capabilities framework to this industry's space?

- **Performance of internal R&D units:** Throughout this work I have emphasized the relevance of developing and exploiting internal scientific capabilities, which for the case of Unocal and Phillips, was done through an internal research organization. During the late 1980s and early 1990s, some companies (including Phillips Petroleum and Unocal), closed their internal R&D divisions so as to transition in the decentralization of R&D and later, the outsourcing of R&D. It is necessary to reflect further on what is the importance of an internal R&D unit relative to the knowledge base of the firm. In particular, how can we measure the effectiveness of an R&D unit to orchestrate the different internal and external sources of knowledge to address technical challenges?

- **Basis of diversification for extractive industries:** This thesis has studied only cases of related-diversification using knowledge as the basis of such diversification. I can confirm through conversations with extractive industries aware of the current sustainability challenges, that they need to strategically define technology choices beyond the use of knowledge as the basis of diversification (leveraging for example the firm's operations or the system were they are embedded in).

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Appendix I: Interviewees

List of people interviewed for the Unocal case:

- Darrell Gallup: Senior R&D consultant for Unocal and Chevron. 1979 - 2005
- Mike Barnes: Manager of Engineering and VP of Unocal Corp. Philippines 1972-2005
- Courtney Isselhardt: Geologist who worked for Unocal since 1969
- Carl Otte: President of Unocal's geothermal division
- Benjamin Barker: Geothermal and petroleum engineering at Unocal
- Bill Amend: Science and Technology Division
- Paul Atkinson: 24 years at Unocal later Halliburton
- Kevin Kitz: Arrived to Unocal in 1985 to work at Imperial, Geysers and Tiwi
- Stephen D. Pye: Drilling and R&D Manager: 35 years of service with Unocal Corporation.
- Ken Williamson: General Manager,. Geothermal Technology & Services,. Unocal Corporation.
- Ron Di Pippo: UMass faculty expert on geothermal
- Jeff Tester: Prof. of Cornell

List of people interviewed for the Phillips case:

- John Baza: Reservoir engineer at Phillips' Geothermal Division
- Walter 'Dick' Benoit: Geologist for 12 years at Phillips.
- Stuart Johnson: Geologist and chief of the geochemistry unit at Phillips' Geothermal Division

Appendix II :Case study research protocol

Probably you will not be able to answer some of the following questions. Still, these questions can help guide an open conversation about the technological transfer needed from the oil industry for the development of geothermal energy innovations during the 1965-1990 period.

1. Please summarize your professional experience and its relation with the upstream oil industry and the geothermal industry.
2. Why did the company decided to get into this business field?
3. How was the organizational structure for the company's geothermal activities during the 1970-1990 period? How did the company reached to this organizational structure?
4. What type of people was brought initially into the Geothermal Division?
5. Was there supervision from the corporate group to the Geothermal Division's technical and strategic decisions and in what way this influenced the level of uncertainty and risk that the Division incurred on?
6. Can you recognize if any of the following where requirements for the Geothermal Division?: Frequency of division reporting to centralized control, cross-division teams, criteria to evaluate performance of divisions and incentives for organizational performance.
7. From your perspective which are the main technological challenges for each of the following projects?[160]
8. To address such technological challenges, how much did the firm relied on internal knowledge from the Geothermal Division and at what point they relied more on knowledge from outside sources (such as the Science and Technology division, other oil firms, government funded research, vendors, or local vendors from foreign countries)?[161]
9. Are you aware of the organizational structure that was needed for the implementation of such particular technical challenges? Do you believe that this influences the success of the development of new technological results?
10. What are the particular skills from the managers that you think were useful to integrate knowledge from several sources and internally address the technological

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[160] For the Unocal case the business units in question were the Geysers, Tiwi and the fields at the Imperial Valley and the Salton Sea. For the Phillips case the business units in questions were the Roosevelt Hot Springs and the Desert Peak project.

[161] In consistency with what is explained under the Chapter of Methodology, the technical challenges studied are Exploration, reservoir Modeling & engineering, drilling and wellbore completion (including abrasive hard rock, loss of well control, lost circulation, corrosion, scaling, high temperatures), steam gathering system and power cycle and business model.

challenges of geothermal projects? How important where the managers' abilities to transform what they know in a way that was useful for the whole organization?

11. How did the pre-existence of a local industry for geothermal energy (composed by experts and service companies) helped to nurture the firm's development into this technology?
12. What type of innovations where actually patented by the oil firm and which were not? Did the firm use an alternative scheme to protect the IP from these inventions?
13. Do you recognize any other business unit that was relevant in geothermal development?
14. What was more influential for the success of developing geothermal technology: the organizational structure / the support of an existing knowledge base from public-funded research? / the internal R&D capabilities of the firm? / the familiarity with a business full of uncertainties in the natural resources industry? all of the above are equally important?
15. Which oil companies had better outcomes on adapting technology from upstream operations into geothermal energy? Which is the reason for that difference? Was the size of the company a relevant feature that influenced its dynamism to adapt its competences?
16. Do you know anybody from Phillips/Unocal that could be of use for this research?

List of topics for the classification of statements from in-depth interviews:

- Exploration
- Reservoir Modeling & Engineering (including reinjection)
- Drilling and wellbore completion
    - Abrasive hard rock
    - Loss of well control
    - Lost circulation
    - Corrosion
    - Scaling
    - High temperatures
- Steam gathering system and steam cycle.
- Business Model

Additional topics for classification not originally defined as technical hurdles for the development of geothermal energy:

- Capabilities for diversification (for each of the business units in analysis)
- Control from central headquarters to subsidiary
- Cross-fertilization from geothermal to oil.
- Geothermal ecosystem
- Focus of research
- Incremental sophistication within geothermal business units.
- Leadership
- Patents as a valid measure for innovation
- Risk-versus profitability of the diversification
- Role of vendors
- Science and technology Division.

Appendix III: International patent classification codes from the World Intellectual Property Organization

Table 13: International Patent Codes (IPC) that represent families of geothermal patent records (World Intellectual Property Organization, 2014)

Family International Patent Classification Code	Name (from WIPO's International classification Code)	Examples of what it includes	Link with geothermal technical challenge
"B01D"	Separation	Condensation of vapors / separation to manage the brine and prevent scaling / Purification of waste gases	Treatment and removal of scale.
"C01B"	Non-metallic elements	Preparation or recovery of sulfur	Removal of hydrogen sulfide
"C02F"	Treatment of water, wastewater, sewage or sludge	Prevention of scaling / Adding scale removers to water	Treatment and removal of scale.
"C09K"	Materials for applications not otherwise provided for	Compositions for drilling of boreholes or wells / casing to resist corrosive environments	Dealing with loss-circulation and corrosion
"E21B"	Earth or rock drilling	Methods or apparatus for cleaning wells or obtaining steam / corrosion and erosion resistant-wellhousing	Drilling abrasive hard rock and corrosion of casing
"F03G"	Mechanical power producing devices or mechanisms	Mechanical-power-producing mechanisms, not otherwise provided for or using energy sources	Improve the efficiency of the power cycle
"F24J"	Production or use of heat not otherwise	Production or use of heat using	Improve the steam gathering system and the efficiency

	provided for	geothermal energy	of the power cycle
"G01N"	Investigating materials by determining their chemical or physical properties	Measuring or testing chemical or physical properties	High-temperature logging equipment
"G01V"	Geophysics, gravitational measurements	Gravitational measurements	High-temperature logging equipment

It is important to emphasize that the classification codes from **Error! Reference source ot found.** are only meant as a reference for representing the geothermal-related knowledge of the companies studied, and by no means do they correspond perfectly to the patents that were used in geothermal developments[162].

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[162] Such outcome would require the lengthily revision of each abstract for all Unocal patents, and that would still not be representative, given that some patents may not make any explicit mention to the geothermal in their application documents.

Appendix IV: Geothermal glossary

(Schlumberger, 1998)

Annulus: any void between any piping, tubing or casing and the piping, tubing, or casing immediately surrounding it. It is named after the corresponding geometric concept. The presence of an annulus gives the ability to circulate fluid in the well, provided that excess drill cuttings have not accumulated in the annulus, preventing fluid movement and possibly sticking the pipe in the borehole.

Artesian aquifer: Confined aquifer containing groundwater under positive pressure

Bits: A Drill bit, is a device attached to the end of the drill string that breaks apart, cuts or crushes the rock formations when drilling a wellbore, such as those drilled to extract water, gas, or oil.

Brine: Water containing more dissolved inorganic salt than typical seawater.

Casing: Large-diameter pipe lowered into an openhole and cemented in place. The well designer must design casing to withstand a variety of forces, such as collapse, burst, and tensile failure, as well as chemically aggressive brines

Clogging: obstructing

Completions: The hardware used to optimize the production of hydrocarbons from the well. This may range from nothing but a packer on tubing above an openhole completion ("barefoot" completion), to a system of mechanical filtering elements outside of perforated pipe, to a fully automated measurement and control system that optimizes reservoir economics without human intervention (an "intelligent" completion).

Cuttings: Small pieces of rock that break away due to the action of the bit teeth.

Heel row: the outer row of teeth on a cone of roller-cone bit

Logging unit: The cabin that contains the surface hardware needed to make wireline-logging measurements. The logging unit contains at the minimum the surface instrumentation, a winch, a depth recording system and a data recorder. The surface instrumentation controls the logging tool, processes the data received and records the results digitally and on hard copy.

Positive displacement motor: A downhole motor used in the oil field to drive the drill bit or other downhole tools during directional drilling or performance drilling applications. As drilling fluid is pumped through the positive displacement motor, it converts the hydraulic power of the fluid into mechanical power to cause the bit to rotate.

Rig: The machine used to drill a wellbore

Roller-cone bit: drill bit used for drilling through rock, for example when drilling for oil and gas.

Well completions: All the specialized hardware and techniques required to produce the well, once a well has been drilled

Appendix V: Acronyms

Table 14: Acronyms

Acronyms	Definition
DOE	Department of Energy
ERDA	Energy Research and Development Administration
FERC	Federal Energy Regulatory Commission
GDO	Geothermal Development Organization
GDO	Geothermal Drilling Organization
GLEF	Geothermal Loop Experimental Facility
GLID	Geothermal Logging Instrumentation Development
GRWSP	Geothermal Reservoir Well Stimulation Program
GTP	Geothermal Technology Program
HDR	Hot-dry rock
IPP	Independent Power Producer
NACE	National Association of Corrosion Engineers
NPC	National Power Corporation (of Philippines)
NSF	National Science Foundation
PDC	Polycrystalline diamond compact
PG&E	Pacific Gas and Electric Company
PGI	Philippine Geothermal Inc
PURPA	Public Utilities Regulatory Policies Act
QF	Qualifying facilities
RHSU	Roosevelt Hot Spring Unit
RST	Rotary separator turbine
S&T	Science and Technology
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TOUGH	Transport Of Unsaturated Groundwater and Heat
Unocal	Union Oil Company of California