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How do technology clusters emerge and become sustainable? Social network formation and inter-firm mobility within the San Diego biotechnology cluster

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Abstract

Regional technology clusters are an important source of economic development, yet in biotechnology few successful clusters exist. Previous research links successful clusters to heightened innovation capacity achieved through the existence of social ties linking individuals across companies. Less understood are the mechanisms by which such networks emerge. The article uses social network analysis to examine the emergence of social networks linking senior managers employed in biotechnology firms in San Diego, California. Labor mobility within the region has forged a large network linking managers and firms, while ties linking managers of an early company, Hybritech, formed a network backbone anchoring growth in the region.

Keywords: Biotechnology; Social network analysis; Careers; Technology clusters; Innovation

1. Introduction

Clusters of high-technology firms have become an important source of economic development across the advanced industrial economies, and a central focus of technology policy. Studies of technology clusters have yielded persuasive accounts of how successful clusters work, when they work. A central explanation focuses on social networks and labor market mobility within technology clusters. In an influential study of the success of Silicon Valley, Saxenian (1994) argues that a culture of decentralized social ties linking scientists and engineers across local companies helps diffuse innovation, while from the point of view of skilled individuals, manage the career risks of working in failure-prone companies. This creates a strong justification for approaches stressing the social embeddedness of economic action, as companies embedded within regions with a decentralized culture of high mobility and knowledge diffusion will have a "regional advantage" over companies that are not (Saxenian, 1994; Herrigel, 1993; Sabel, 1992; Storper, 1997).

While providing a persuasive explanation for the success of some clusters over others, a problem with the inter-firm mobility hypothesis is that it only makes sense once a large agglomeration of companies coupled with norms and social networks facilitating mobility exist. Left unexplored are the mechanisms by which regions move from a starting position in which neither the agglomeration of companies or social networks underpinning mobility exist to one in which they do. How do regional technology clusters, and the social networks underpinning them, emerge?

This article examines the emergence and sustainability of social networks linking senior managers of biotechnology firms in San Diego, California. It

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investigates how a region went from having virtually no presence in commercial biotechnology to developing one of the world's most vibrant biotechnology clusters. Drawing on career histories of over 900 managers employed in San Diego biotechnology firms, the paper uses social network analysis tools to trace the development career affiliation networks linking senior managers who worked together at one or more San Diego biotechnology firms during their careers. Over a 27-year period, a tiny network of less than a dozen people working in a very small number of firms incrementally expanded into a large, efficient, and sustainable social network linking several hundred senior managers working in an agglomeration of over 120 high-risk biotechnology companies.

The study is motivated by two analytic goals. A first is to address the debate as to how technology clusters become sustainable. The career history data allows the generation of career affiliation networks linking senior managers on a year by year basis over the history of the cluster. This facilitates a year by year analysis of the cluster's emergence. Did the cluster emerge and become sustainable slowly, or quickly? The paper draws on a number of simple measures developed by social network theorists to explore sustainability. These include year by year measures of the usefulness of the network in terms of its size and connectivity, its efficiency in developing ties linking senior managers to firms in the region, and its durability or robustness given company failures. This analysis provides strong support for the notion that sustainable clusters are linked to the existence of dense social networks across key personnel supporting career mobility. However, the San Diego case indicates that sustainable social networks emerge relatively slowly; it took about 15 years for this cluster to become sustainable, at least in terms of social network organization.

The second objective is to examine the mechanisms by which social networks linked to career mobility emerge. How does a regional economy develop a social structure favoring job mobility? An important literature, which has roots in studies of Silicon Valley's engineering industries, emphasizes the role of companies in promoting job mobility. The company focused explanation is of central importance to the development of San Diego's biotechnology cluster. Managers linked to one phenomenally successful early start-up company called Hybritech played a dominant role in seeding the development of two generations of successor companies in San Diego, and while doing so helped form the backbone of social networks linking managers during the early history of the cluster. Without this cohort of experienced biotechnology executives willing to embrace and commercialize local university technologies (see Higgins, 2005), it is likely that San Diego's biotechnology cluster would not have developed as successfully as it did.

2. Labor market mobility and the sustainability of high-technology clusters

The social structure and career mobility explanation draws on a large literature linking environmental factors to the innovative performance of firms within new technology industries such as semiconductors, software, or biotechnology. Many of the core arguments underlying approach were developed by Saxenian (1994) in her comparison of the Silicon Valley and Route 128/Boston regional semiconductor industries. Saxenian argues that Silicon Valley's success is linked to the development of a social structure encouraging the development of numerous informal links across the region's scientists, engineers, and managers. These links raised the innovative capacity of Silicon Valley's firms through diffusing technological and market intelligence. Drawing on Granovetter's (1973) research on referral networks within labor markets, Saxenian argues that social networks within Silicon Valley increased labor mobility across firms and by doing so created an additional mechanism of knowledge diffusion. The declining fortunes of Route 128's computer and semiconductor industry, on the other hand, is influenced by autarkic practices of long-term employment within its companies that hindered the creation of flexible labor markets, coupled with very limited informal sharing across firms through social networks. Almeida and Kogut (1999) followed-up Saxenian's research with a quantitative study using patent data from 12 US semiconductor clusters. In their study, patent data were used to gather information on levels of inter-firm mobility of inventors within each cluster and as an indicator of aggregate innovativeness. Their study supported Saxenian's argument, showing that only Silicon Valley had both high levels of job mobility and markedly higher levels of patenting.

The strength of the labor market mobility research stream is its ability to connect career mobility to heightened innovative capacity of start-up firms specializing within new technology industries, while also establishing a mechanism by which presumably risk-averse skilled employees commit to failure prone jobs. Most start-up companies within new technology industries such as biotechnology, software, or semiconductors begin life as relatively simple project-based firms developed to recruit and incentivize teams of talented scientists and engineers to work on well defined technology development goals (Whitley, 2004; Baron and Hannan, 2002). Their success is in part determined by their ability to entice skilled managers and employees to leave lucrative and often 'safe' jobs in established companies or university labs to join a new venture. Common patterns of financing and organizing start-ups enhance the attractiveness of working in a start-up. A founding team of managers and employees usually share ownership of the team with venture capitalists and other investors. Direct ownership stakes provide extremely high performance incentives for employees of early stage start-up companies. Should the company succeed and "go public" through a stock offering or be acquired at a favorable valuation early employees can earn vast payouts. Moreover, though demanding, careers at start-ups are often described as exhilarating due to their fast pace and broad range of activities.

The potential benefits of working within a start-up are countered by a high likelihood that employment tenures within start-ups will be short due to dismissals or outright failure. Most start-ups fail to reach a lucrative exit, be it an initial public offering or acquisition by a larger firm at a favorable valuation. Start-up companies are usually funded by venture capitalists through a series of financing rounds as the firm passes through a series of technical and market milestones developed by its board (Kenney and Florida, 1998). Venture capitalists often decide to halt investments in companies that fail to meet key milestones. Dismissals of top management are often a common response by VC-led boards to firms that have failed to meet development milestones. Managers and employees within start-ups also find themselves at risk of dismissal due to strategic decisions to change the competency structure of the firm. Moreover, as a condition for funding many venture capitalists insists on the right to replace early technical founders of companies with professional managers as a company develops.

From the point of view of individuals, there is a strong rationale for choosing to work only within start-up companies embedded within an agglomeration in which social ties promoting mobility are strong. Doing so can dramatically lower the career risk for founding teams and R&D staffs by creating numerous alternate employment options should a given venture fail, undergo managerial shakeups at the behest of investors, or need to change its competency structure due to technological volatility. According to this logic, successful technology clusters develop what Bahrami and Evans (1999) call "recycling mechanisms" to help preserve the value of assets committed to failed enterprises. To quote Saxenian, "Moving from job to job in Silicon Valley was not as disruptive of personal, social, or professional ties as it could be elsewhere" (Saxenian, 1994: 35). This helps explain why successful and presumably risk adverse scientists and managers would give up prestigious careers in established companies or university labs to work within lucrative but highly risky start-ups: within successful clusters the embeddedness of individuals within social networks makes it safe to do so.

In addition to creating a regional recruiting advantage, social structures facilitating mobility may provide competitive advantage for firms operating in market segments in which technological cumulativeness is low. During the early phase of new industries, technological paradigms are still being established (Utterback, 1996). Companies compete to validate technological approaches and secure property rights over the approach or, at times, develop a dominant design (Teece, 1986). To give an example from biotechnology, Penan (1996) conducted a bibliometric survey of approaches being used to develop therapies for Alzheimer's disease and found over 20 distinct technological approaches being pursued by competing teams of biotechnology firms, basic research labs, and large pharmaceutical companies. Within highly uncertain technological environments companies may need to routinely adjust their portfolio of approaches. If embedded within a regional economy with high labor market mobility, firms can more easily use "hire and fire" practices to alter research and development strategies. This returns to Saxenian's core argument: in addition to providing a recruiting advantage, inter-firm mobility helps create informal social ties across a region's firms. Informal ties may provide market or technological intelligence, allowing companies to make superior decisions as to which technologies to adopt or, at times discontinue. Firms may be able to react to market developments faster than competitors.

While focusing attention on explaining successful cases, and especially Silicon Valley, the career mobility approach also contains an explanation of why most regional economies fail. Most clusters, even if they reach sufficient size, do not develop the social networks or norms of high labor market flexibility needed to create the 'regional advantage' associated with Silicon Valley. Lacking a safety net provided by career affiliation networks, leaving a safe job to work within a failure prone start-up is truly a risky proposition, one that most rational and risk-averse individuals will resist. Individuals do however have an incentive to relocate themselves, abandoning disadvantaged regions to join firms located in a more successful cluster. Agglomeration or scale effects may develop from such human capital migration and, following the Marshall tradition (see, e.g. Krugman, 1991), provide "first mover" type advantages to successful regional clusters. However, the labor market mobility theory provides an important complement to the scale effect explanation, as high labor market mobility within a region, and a social structure of dense inter-firm ties supporting it, may be a necessary condition for the region to sustain high levels of innovation by a sizeable number of companies.

The mobility explanation is in core aspects similar to a game theoretic equilibrium model. It links the rational behavior of talented individuals to different labor market equilibriums which are then linked to the generation of different innovative capacities for companies. Inter-firm mobility helps diffuse technology across companies and, from the point of view of skilled personnel, generates the formation of social networks that can be used to offset the career risk of leaving a 'safe' job to work in a high-risk start-up. However, most localities have neither the agglomeration of firms and people nor the social ties needed to sustain high-risk firms. In such regions key personnel are unable to reduce the risk of participating in a high-risk firm. This leads to a second, much more common equilibrium, that of failed cluster development. A structure promoting extensive career mobility does not exist. From the career perspective, leaving a safe job in an established company or university to join a start-up truly is a high-risk proposition that most will choose not to do. It becomes easier to understand why most localities fail to develop successful technology clusters: talented individuals might populate a region, but they face a collective action problem. They lack the appropriate social ties needed to reduce the risk of working within a high-risk venture.

The failure equilibrium is the most common occurrence. Much comparative institutional research has pinpointed the United States as a country with an ideal institutional infrastructure to support clusters of technology firms (Hall and Soskice, 2001; Casper and Whitley, 2004). Yet even in the United States most regions, even those housing leading universities, are not home to successful technology clusters. Almeida and Kogut (1999) semiconductor study found only 1 cluster out of a sample of 12, Silicon Valley, that had both exceptional levels of innovation and career mobility. Systematic comparative studies are lacking in the biotechnology area, but industry surveys suggest that there are only three large clusters that analysts universally agree are performing well: those in San Francisco, San Diego, and Boston (see DeVol et al., 2005). In Europe, there are at best two well-performing biotechnology clusters, located in Cambridge, UK, and Munich, Germany (Casper and Murray, 2004); both are much smaller than the successful American clusters in terms of number of independent R&D intensive companies.

The emergence of successful biotechnology clusters is a problem of social coordination that may be difficult to resolve. The decentralized social infrastructure characterizing successful technology clusters is in some ways analogous to a collective or public good: its benefits accrue to most if not all individuals and companies within the regional economy (though perhaps disproportionately depending on position within the network, see Owen-Smith and Powell, 2004). However, unlike traditional public goods (roadways, the air), social infrastructures supporting technology clusters may be difficult to orchestrate or maintain in a systematic fashion. Rather, it is an emergent property, a product of the collective behavior of individuals and firms within a regional economy. As such, it is unlikely that individuals or firms can single-handedly develop the necessary mesh of social ties needed to sustain a highly innovative cluster. A relatively large number of individuals must develop and mobilize social ties in order to develop a density of ties sufficient to generate useful networks. What are the mechanisms by which regions move from a starting position in which neither the agglomeration of companies or social networks underpinning mobility exist to one in which they do? If their development has collective action problems, how do social ties develop into useful and sustainable networks?

A plausible scenario is that social networks develop slowly or incrementally. Early entrants to a cluster might be particularly risk acceptant individuals. Over time, they could plausibly seed a nucleus of companies and establish social ties between them. As these ties expand they become a so-called backbone to a social infrastructure that other entrants, both individuals and new companies, can draw upon. It is possible that, after reaching a certain size and rate of mobility, a tipping point could be reached whereby the cluster becomes sustainable and regional innovation effects begin to accrue. Once sustainable, agglomeration effects might become established as jobs within the cluster become attractive to more risk adverse individuals.

A difficulty with this explanation is that social network effects may only be pronounced once a large number of individuals participate in the network; benefits may only develop as social networks become relatively large and efficiently organized. If so, early pioneers within a cluster may be particularly failure prone. Early failures are likely to be much more costly, in terms of their effects on network growth, than later failures. If so, nascent technology clusters might never reach the critical mass to become sustainable. This could lead to the outright collapse of a cluster or the decision by individuals and companies to abandon "radically innovative" strategies in order to pursue safer and more incremental innovation strategies. Companies would then adopt more internally focused research and development strategies that draw less on external ties and accommodate safer jobs with relatively long employment expectations.

The rarity of well-performing clusters suggests that the emergence of appropriate social infrastructures is a difficult problem, perhaps one rarely solved. A key issue then becomes one of emergence. How do individuals within a region develop the social infrastructure needed to sustain agglomeration of high-risk firms? This issue, of moving essentially from "nothing" to the generation of a decentralized social infrastructure capable of diffusing innovation and facilitating career management, has been largely ignored in studies of high-technology clusters. It motivates the present study.

3. Research design

The study traces the emergence and sustainability of social networks linking senior managers employed over the history of a successful biotechnology cluster located in San Diego, California. It examines year by year employment histories of several hundred top managers from the cluster's early formation, starting in 1978, to 2005. This data gathering strategy allows us to trace the growth of San Diego biotechnology firms and an analysis of both agglomeration patterns (people moving to San Diego) and mobility across firms. Moreover, career histories allow us to construct and study a relatively complete set of social ties formed between managers through joint employment in the same biotechnology firms.

In terms of social networks, the study examines the emergence of *career affiliation networks* formed between senior managers on the basis of ties between individuals that are formed through joint employment at the same organization (see Casper and Murray, 2004). A focus on career affiliation ties is warranted due to the study's emphasis on mobility patterns. Moreover, we can plausibly assume that through serving on senior management teams, individuals form durable social ties with one another and have obtained relatively full information about one another. These ties should be particularly useful when used for job referrals.

The study explores the emergence of career affiliation networks linking *senior managers*. Within the biotechnology industry, senior management usually includes a company's chief executive, chief scientific officer, chief finance officer, and a number of vice presidents and senior personnel involved in research and development, business development, and, within some companies, human resources and legal affairs. Senior managers must define a firm's strategy and mobilize the necessary resources to implement it. Recruiting talented senior management is strongly linked to the success of biotechnology companies (Higgins and Gulati, 2003). In this respect, an emphasis on top management again links directly to the emphasis on career mobility.

The biotechnology industry was chosen for study due to its status as a high technology industry containing high technological volatility (see Henderson et al., 1999). Large, multi-billion dollar markets exist for drug and diagnostics products meeting unmet medical needs, and intellectual regimes surrounding new treatments are strong. While a few successful firms have generated enormous profits, failure rates are high in the biotechnology industry. Most companies will fail or be cheaply acquired and integrated into competitors or large pharmaceutical companies. An Internet database located within Biotech Career Center (2005) lists several hundred failed companies. Finally, a key theme emerging from research on the biotechnology industry is the decentralization of knowledge within the industry and the need for companies to develop and tap into a variety of external networks if they are to succeed (Powell, 1996; Powell et al., 1996; Shan et al., 1994).

The study's research design selects a successful case, San Diego. Given that social networks linked to mobility have been identified in several other cluster studies, this research design is biased towards a finding that strong career affiliation networks do exist (as is indeed the outcome). However, the goal of the study is to rigorously explore the emergence of social networks within high technology industry, an area that has only very recently begun to be investigated (see, e.g. Uzzi and Spiro, 2005; Fleming et al., 2006) and were unknown with regards to the San Diego biotechnology cluster. Moreover, given that Silicon Valley is the only success case identified in the literature linking social networks and mobility to cluster performance, an exploration of San Diego will facilitate broader comparative analysis. If social network development within clusters is rare, carefully documenting mechanisms of emergence across the few successful clusters is an important step in designing comparative research capable of yielding generalizations applicable across clusters.

San Diego is an excellent laboratory to study cluster development. The region went from having virtually no presence in commercial biotechnology at the start of the 1980s to developing one of the world's most vibrant biotechnology clusters by the late 1990s (DeVol et al., 2005). While San Diego has recently developed a cluster of wireless telecom companies to complement its biotechnology presence (see Simard, 2004), the region did not have a presence in high technology industry during the late 1970s, and was primarily known for its large naval base and defense contractors. This suggests that its biotechnology was the first high-technology industry to develop in the region, with the implication that early companies could not draw on previously established local venture capitalists, labor market pools, or other resources. The San Diego biotechnology industry was founded in 1978 and gained critical mass in the late 1980s. While this was early in the history of biotechnology (Genentech was founded in 1976), San Diego companies did benefit from the demonstration effect of Genentech's success as well as the ability of some early companies to establish links with San Francisco venture capitalists.

San Diego has long been home to several world class biomedical research institutes, such as the Scripps Research Institute and the Salk Institute, while the University of California, San Diego (UCSD) has developed a medical school and strong departments in chemistry, biology, and other fields with links to biotechnology. Through the early 2000s, these institutes were collectively receiving over $500 million federal funding for biomedical research from the US National Science Foundation and National Institute of Health (Brookings Institute, 2002). Considerable research has demonstrated that the performance of biotechnology companies is improved by the existence of ties to leading academic scientists (Zucker et al., 1998; Murray, 2004). The importance of university-firm ties has led to the establishment of most biotechnology clusters in close proximity to leading universities. Without a supply of world class science, it is unlikely that a biotechnology cluster would exist in San Diego.

San Diego is also one of very few successful biotechnology clusters within the United States (Brookings Institute, 2002). Although San Diego has very favorable conditions for development, there exist many more world class universities than biotechnology clusters, and several US regions are home to world-class biomedical research bases, such as Los Angeles, Chicago, or New York, but have not developed sizeable biotechnology clusters. Thus, while San Diego might be considered a "most favorable" place to develop a biotechnology cluster, we should keep in mind that many other favorable locations within the United States have failed to match the region's success. How was this area able to grow a viable biotechnology industry, while others have not?

4. Methods: data gathering and network construction

The research process for this study had three steps: locating firms, gathering career histories, and then using social network analysis tools and related descriptive statistics to gather and analyze results.

4.1. Locating firms

High failure rates within the biotechnology industry make the identification of firms over the history of a regional cluster difficult. A two-step approach was used to identify firms. Industry directories were used to locate biotechnology companies active in the San Diego region during the years 2004 and 2005 (AlexanderX, 2004, 2005). The San Diego region was defined as San Diego, La Jolla, Carlsbad, and other communities located within San Diego, but excluded San Juan Capistrano and other coastal communities located approximately 25 miles north within Orange County. Industry guides list hundreds of companies, including consultancies, contract research organizations, equipment manufacturers, and subsidies of companies with central headquarters located elsewhere. Only research intensive and independent biotechnology companies were included in the database. As a criteria to aid company selection, only companies that had published at least one scientific article were included (Casper and Murray, 2003). Searches on the Web of Science and Pubmed on-line databases were used to search for company publications. This search strategy yielded 125 active companies for 2004 and 121 companies for 2005.

Due to the high failure rate of biotechnology companies, it was important to locate as many companies that failed or lost independence as possible. A primary source of failed companies were career histories of senior managers working in active firms, which often listed jobs in failed local biotechnology companies that were added to our database. While a useful strategy of identifying firms, the exclusive use of career histories to locate failed firms could create biases in the social network data. As will be discussed below, social network ties will be created through mobility across firms. If the only source of locating failed companies was career histories, this could create a potential bias in the network data towards increasing network connectivity, as chains of ties will exist between all failed firms and all on-going firms. To minimize this potential bias, it is important to locate as many failed firms as possible, ideally from sources other than career histories. Two useful lists of San Diego biotechnology companies active at earlier points in time were used to locate additional firms. The first source was a newspaper article from 1993 that contained a list of 106 San Diego biotechnology companies active during that year, many of which had failed by 2005. Second, a report on the commercialization of academic science within the San Diego region (Lee and Walshok, 2000) listed over 120 companies spun-out of UCSD, the Scripps Research Institute, and the Salk Institute prior to 2002, a majority of which were biotechnology related. While information on many of these companies could not be located, presumably because they failed very quickly due to an inability to secure finance or other reasons, information was found for a small number of companies located through this list.

In sum, 193 San Diego biotechnology companies were identified for inclusion in the study, 70 of which had failed. This implies a failure rate of 36%. This figure is probably lower than the actual failure rate within San Diego biotechnology, for two reasons. First, many firms in the study are relatively young, having been founded in the post-2000 period, and may not have had sufficient opportunity to fail. Second, only firms for which information on senior managers could be found were included in the database. This creates a biased towards the inclusion of firms that have secured significant venture capital financing needed to recruit sophisticated senior management teams The inability to find information on managers for many of the companies listed in the study of university spin-outs suggests that numerous small companies were founded and quickly failed due to an inability to secure capital.

4.2. Gathering career histories

Several sources were used to gather career histories. The most important are SEC company filings. Filings are available from 1994 onwards for most firms in the on-line Edgar database. Annual reports (10k forms) and prospectus documents filed when selling shares usually provide career histories for senior managers, whom are required to include information on the past 5 years employment but, in practice, almost always include complete career histories, including graduate and postgraduate training.

The availability of SEC company documents over several years allows direct tracing of top management personnel changes within companies. As a result, the database contains both founding senior management teams and subsequent senior managers who were hired as firms expanded or went through periods of management turnover. Additional sources of information used were company web pages, which usually contain career histories for current top managers as well as press releases documenting personnel changes. Finally, in some cases, general Google searches were used to search for missing data.

Career histories were constructed for 923 senior managers of San Diego biotechnology firms employed in at least one firm listed in our database between 1978 and 2005. This includes all types of senior management positions, both those in scientific and general management positions. Sixty two percent (573) had a graduate science degree (PhD) or, in a few cases, were medical doctors. The remaining individuals had no graduate science training and were presumably general managers. Only 61 had received PhDs or held postdoctoral or professor positions from UCSD, Scripps or the Salk Institute. Well over 90% of the scientists (512) had their last place of scientific employment (graduate training, postdoctoral student, or in rare cases, professor) outside of San Diego, and more generally most non-scientists also moved to their first San Diego biotechnology job from outside the region. This suggests that ties forged through joint employment at San Diego biotechnology firms will be an important resource for both scientists and non-scientists.

While this search strategy yielded career histories for a large number of senior managers within the region, there are important sources of missing data that could bias the results. A first issue is incomplete data on companies obtained through SEC searches. Companies are only required to make public SEC filings once they reach certain financial and ownership distribution thresholds, and hence do not make filings during their early years of operation. For companies founded during the period of 2000 onwards that had not filed SEC documents, extensive information on senior management teams was available through company websites and press releases. However, for companies founded less recently data available through Internet searches was less available, creating a source of missing data on senior managers that left companies during their early history. If such managers obtained a job within another San Diego biotechnology firm, however, missing data would be recovered through career histories of that individual identified through subsequent employment in the region.

A second problem with the SEC filing data is that files are only easily accessible on-line for the post-1994 period. This leads to the possibility of missing information on the composition of top management teams for all companies active prior to 1994. This means that the main source of data for the pre-1994 data are the career history information of managers working within the cluster during the post-1994 period. Managers that worked in a San Diego biotechnology firm during the 1980s early

1990s and left the region prior to 1994 are likely to be excluded from the database. How frequent are exits from the region? From the 923 individuals that were located, 106 left the region for jobs outside of San Diego. This suggests that while exits do occur, close to 90% of individuals have not exited the region during the time period sampled. If the exit rate is assumed to be constant over the cluster's history, this would imply that only a modest number of individuals exited prior to 1994 and have been excluded from the database.

The issue of missing data during the early history of the cluster is significant, as a major goal of this study is trace mechanisms of social network emergence during those early years. Missing data could result in important ties linking senior managers from early companies being excluded from the data, suggesting that less connectivity exists within the network than is actually the case. An important finding surrounding the emergence of the network, discussed at length in Section 5, is that a group of senior managers sharing joint affiliations with an early company named Hybritech were responsible for creating connectivity within the network during the key period between 1986 and the early 1990s. It is unlikely that this result has been impacted by missing data. Multiple sources of evidence for this result will be presented from the social network data and will also be supported with evidence from secondary sources surrounding the growth of San Diego biotechnology.

A final problem concerns the consistency of data. Firms have different definitions of what positions constitute senior management. A few firms only include the chief executive officer, chief financial officer, and chief science officer. Most list vice presidents, and a few list directors or "key personnel." All individuals listed as senior management in SEC filings or web-ages were included in the project database. The result is that some firms have more senior managers contained in the network in any given year than others or similar size. This could impact the calculation of some social network statistics in which aggregate count measures of ties (or degrees) are important. For example, some network centrality measures use counts of ties as an indicator; these measures could be biased. Certain individuals or companies may be assigned a more central position in the network due to their association with a company which provides exhaustive information on the composition of their senior management team. While we are unable to control for this effect, we do not believe it strongly impacts more general measures of overall network connectivity or density, which will be used to examine the general level and sustainability of social ties within the region.

4.3. Constructing career affiliation networks

All career histories were entered into a database listing each senior manager and the name and years worked at each organization during their career. Ties between individuals are created through joint employment within the same organization. Under this rule of tie formation, ties linking individuals across organizations are only formed through mobility. Upon changing jobs a manager maintains ties with members of the old organization, while creating new ties at the new place of employment. Networks were created for each year between 1978 and 2005. The yearly network data allows detailed process tracing as to the formation of the network.

An important issue surrounding the construction of networks is how long ties should be assumed to last once an individual leaves an organization. Once an individual moves jobs there is a probability that ties will decay, or weaken over time as people lose contact with one another. From a theoretical perspective, if ties are assumed to last indefinitely, dense social networks become much easier to produce and the problem of sustaining the network drops away. By creating a model where ties decay, new ties must be continuously generated in order for a network to become sustainable. As ties linking organizations are only produced through mobility, this assumption generates a system in which relatively high levels of labor market mobility will be needed to maintain useful networks. Following an approach implemented in similar network emergence studies by Uzzi and Spiro (2005) and Fleming et al. (2006), the study assumes that ties linking an individual to others within an organization cease to exist *5 years* after an individual changes jobs, unless renewed by subsequent joint employment at the same organization. The 5-year decay rule is a strict assumption, allowing an empirical analysis of the emergence of social networks when it is hard to generate and sustain connectivity.[1]

[1] As one of the anonymous reviewers to the article pointed out, individuals commonly maintain ties long after joint employment through meeting at industry conferences or through informal contact. This might warrant using a longer, more generous decay model. To test the robustness of the 5-year decay rule, models using decay rules of 3 and 10 years were also tested. Reporting on the final, 2004 networks and referring to results reported later in the paper in Table 1, the longer decay model increases both connectivity and density within the resulting network, but only marginally. Using a 10-year decay rule increases connectivity, defined as the number of individual's linked together in the network's giant or main component from 95% using the 5 year rule to 99%, while the density of ties increases from 2 to 2.8%. Adopting a stricter decay model of 3 years, however, has a more pronounced impact on connectivity within the network, which decreases to 51%,

Table 1
San Diego biotechnology company statistics, 1978–2005

Year	Total firms	Growth rate (%)	Entrants	Exits	Public firms
1978	1	100	1	0	0
1979	1	0	0	0	0
1980	1	0	0	0	0
1981	2	100	1	0	0
1982	5	150	3	0	0
1983	7	40	2	0	0
1984	11	57	4	0	0
1985	11	0	1	1	0
1986	15	36	4	0	0
1987	22	47	7	0	2
1988	30	36	9	1	0
1989	38	27	8	1	0
1990	38	0	3	3	5
1991	46	21	8	0	7
1992	55	20	10	1	9
1993	61	11	8	1	15
1994	64	5	7	5	17
1995	69	8	6	1	19
1996	77	12	10	3	24
1997	95	23	16	6	30
1998	103	8	20	6	36
1999	108	5	11	3	39
2000	124	15	25	10	50
2001	127	2	15	9	52
2002	131	3	7	4	56
2003	127	−3	5	7	57
2004	125	−2	2	3	63
2005	121	−3	0	5	64

5. Results

Findings from the study are reported in two parts. First, a variety of indicators are used to investigate the sustainability of career affiliation networks among San Diego senior managers. Several indicators are assessed, including the general connectivity and density of social ties within the network, a measure of the usefulness of these ties for individuals in securing referrals to other firms, and an examination of the robustness of the network to failure. The second section examines mechanisms of emergence. How was connectivity within the network established?

5.1. Network properties and sustainability

Table 1 displays descriptive statistics surrounding the growth of companies in the San Diego region, while Table 2 displays information on the organization of career affiliation networks linking senior managers. Turning first to companies, the size of the cluster grew incrementally from an initial start-up launched in 1978, Hybritech, to a relatively large agglomeration of over 125 companies from the year 2000 onwards. The pattern of growth within the region is incremental. On average, the growth of rate for the number of firms in the region is about 15% a year. A significant percentage of San Diego biotechnology firms were able to attain funding from stock markets, an important indicator of success. While few firms completed initial public offerings during the 1980s, during the 1990s and early 200s over 60 companies completed IPOs.

Turning to Table 2, the region also experienced dramatic growth in the number of senior managers employed. Starting in 1978 with the two initial founders of the region's first company, Hybritech, the number of individuals grew incrementally to over 100 by 1988, 500 by 1998, and 867 by 2005. The growth rate of senior managers within the area was also relatively incremental, at about 20% per year. The higher growth rate for individuals suggests that, in addition to new start-ups, firms were consistently expanding their senior management teams. Note also that the average number of individuals working per company increases over time. This is in part due to the ability of over 60 companies to complete initial public offerings during the mid 1990s; cash infusions from going public are usually used to grow companies. However, as mentioned in the methodology discussion, it is also possible that there is less missing data for the post-1994 network history, which would be reflected in larger numbers of individuals per company.

The impressive growth rate of both firms and senior managers attests to the success of the San Diego biotechnology industry. But did this growth occur in conjunction with the development of social networks linking the senior managers? An important measure related to the development of sustainable networks is connectivity. Connectivity relates to the usefulness of the network in terms of the number of individuals linked together. Most networks initially consist of several fragmented clusters of individuals with ties to one another, called network components. As ties continue to form, these clusters begin to coalesce, eventually forming one giant or main component. Table 2 displays the size of the main component linking individuals, as well as the percent of people in the main component and the total number of components in the network, all on a yearly basis. Three distinct periods of development occurred. During the early 1980s, the network was fragmented,

while density decreased to 1.3%. Overall, the 5-year decay rule appears to provide robust results while adopting a relatively strict assumption about tie maintenance needed to provide a strong test of the social networks and mobility explanation for cluster development.

Table 2
Descriptive statistics, San Diego career affiliation networks, 1978–2005

Year	Total individuals	Avg. people per firm	Size of main component	Percent in main component	Average path length	Network density
1978	2	2.0	2	1	1.0	1.00
1979	4	4.0	3	75%	1.0	0.50
1980	7	7.0	4	57%	1.0	0.33
1981	9	4.5	4	44%	1.0	0.19
1982	19	3.8	9	47%	1.0	0.25
1983	27	3.9	15	56%	1.0	0.33
1984	39	3.5	17	44%	1.1	0.21
1985	47	4.3	24	51%	1.2	0.25
1986	59	3.9	35	59%	1.8	0.19
1987	78	3.5	57	73%	2.8	0.13
1988	107	3.6	81	76%	3.1	0.10
1989	132	3.5	103	78%	3.3	0.07
1990	165	4.3	135	82%	3.9	0.06
1991	188	4.1	151	80%	3.7	0.05
1992	232	4.2	204	88%	3.8	0.05
1993	273	4.5	243	89%	4.1	0.04
1994	317	5.0	290	92%	4.0	0.04
1995	342	5.0	300	88%	3.6	0.04
1996	397	5.2	347	87%	3.5	0.04
1997	452	4.8	409	91%	3.6	0.03
1998	503	4.9	466	93%	3.6	0.03
1999	547	5.1	498	91%	3.6	0.03
2000	624	5.0	559	90%	3.8	0.02
2001	702	5.5	648	92%	3.8	0.02
2002	771	5.9	719	93%	3.8	0.02
2003	817	6.4	760	93%	3.8	0.02
2004	852	6.8	806	95%	3.9	0.02
2005	867	7.2	824	95%	4.2	0.02

with no more than roughly one-half of a relatively small network of senior managers linked into the main component. During the late 1980s and early 1990s, the network begins to gain coherence, as over two-thirds of the members of a larger network consisting of more than 100 people are members of the main component. From the post-1993 period onwards, the network continues to grow but has gained coherence; over 95% of its members are connected to the main component by 2005.

The very high level of connectivity points to the existence of a potentially vibrant network, at least in terms of the availability of most senior managers in San Diego to contact peers through career affiliation ties. It is important to note that connectivity within the network remained high through the mid 1990s onwards despite a dramatic growth in the overall size of the network; over 700 individuals joined the network from 1990 onwards. One measure of the impact of movement of new individuals is a decline in network density over time. Network density is defined as the ratio of actual ties within the network to possible ties. Table 2 indicates that declined from a relatively high ratio of 20% or more during the early history of the network to less than 10% by 1988, to 5% by 1992, and about 2% from the year 2000 onwards. These data differs from findings by Powell et al. (2004) on the general increase of network density in alliance activity within the biotechnology industry over time. The main driver of declining density within the San Diego network is the 5-year decay rule of ties. In essence, new individuals are joining the network at a faster rate than new ties are forming through mobility.

A large pool of senior managers are connected into San Diego career affiliation networks, but how useful is the network to its members? The declining density of network suggests that the efficiency of the network, in terms of the ability of individuals to use the network effectively, might be low. While this study does not measure the innovative capacity of companies, it can examine the degree to which the network becomes useful to its members from the point of view of career mobility. It does through examining whether structure of the network, as it evolves over time, becomes efficient in developing ties between senior managers and other companies. The more ties created between senior managers at different companies, the lower the career risk of working within a firm connected within this network becomes. If the labor market mobility hypothesis is correct, the social network began to link a large population of companies and lowered the risk of individuals joining high-risk technology start-ups and simultaneously increased the innovative capacity of its companies.

How easy is it, on average, for members of the network to develop ties to other individuals and firms in any given year? Referrals are often developed by "working the network" or asking acquaintances for contacts that may know at target companies. A common statistic to measure indirect ties is average path length, or "degrees of separation," between individuals in the network. Table 2 displays path length between individuals located within the network main component on a yearly basis. During the early history of the region, path length data is low, at less than 2 ties, due to the small size of the network. However, from 1990 onwards, the average path length averages at about 3.5–4. Given that the size of the network increased seven-fold during this period, the relatively constant path length statistics is impressive. Despite the increasing size and sparseness of the network over time, inter-firm mobility was sufficient to generate a sufficient number of new ties linking individuals across companies to maintain network efficiency.

While useful, the path length statistic only measures tie structures linking individuals, not between individuals and firms. It is also biased by the clustering of direct contacts between people working within the same firm. A more measure of network usefulness would measure the number of *companies* accessible to individuals at various degrees of separation, i.e. how many direct contacts, how many contacts linked through one individual, two individuals, and so forth. If a significant number of companies were accessible to individuals at a low number of intermediaries, this would be a strong indicator that social ties have are linked to career mobility within the network.

To develop an indicator of links between individuals and companies, path length information for each individual was recalculated on a yearly basis to examine the average number of contacts each senior manager had at other companies at each degree of separation. This was calculated by obtaining the minimum path length between each individual and each company on a year by year basis, and then calculating the average number of companies a manager could contact at each degree of freedom. All senior managers that were members of the network main component for each year starting in 1985 (the first year, the main component was of significant size) up to 2004 were included.[2]

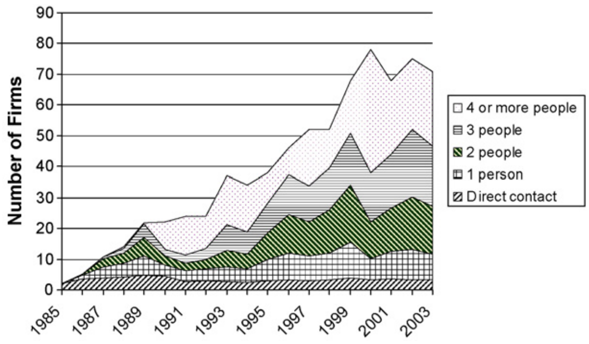

Fig. 1. Average network distance of San Diego managers to companies at given degrees of freedom, 1985–2004.

Fig. 1 displays the results of this analysis. The figure shows the number of companies available to the average individual within the network at each degree of freedom on a yearly basis. For example, throughout most of the history of the network, the average individual has direct contacts to three San Diego biotech companies, which by definition were forged through prior employment at these firms. As the network grew, however, progressively more companies become accessible to San Diego senior managers. It is open to debate as to how many people a given manager can easily use as intermediaries when "working the network" to gain access to a given firm. It is reasonable to suggest, however, that companies requiring two or less intermediaries to contact are readily accessible to most senior managers. In this respect, an interesting result from this figure is that the usefulness of the network is strongly dependent upon size. For example, during the early years of the network, fewer than 10 companies were reachable to the average manager with two or fewer contacts. By the late 1990s onwards, this figure increases to about 30 companies for most years. These results are strongly driven by the 5-year decay rule. If ties were allowed to persist, then the percentage of companies within close contact would accumulate over time. However, the demonstration that relatively high numbers of companies are at close reach to managers during much of its history under conservative modeling assumptions

[2] Data from an earlier version of the network analysis including 602 individuals and 142 San Diego firms are used in this calculation. As UCINET and other network analysis software does not support this type of calculation, the analysis was performed manually using Microsoft Excel and was very labor intensive. While I could not replicate the calculation for larger network used elsewhere in this paper, the results generally confirm the usefulness of San Diego career affiliation networks in linking individuals to firms.

supports the argument that social ties are supportive of career mobility under risky employment conditions that typify the biotechnology industry.

A final indicator of sustainability is the network's robustness to failure. What happens to connectivity within the network when biotechnology firms fail, as they are prone to do? If managers exit the network after failure, presumably through retirement or an inability to find a job at another local biotechnology firm, then connectivity within the network will be lost after ties decay. Seventy San Diego biotechnology firms failed or were acquired during the 1978–2005 time period. Fifty-seven of these failures, or about 80%, occurred in the post-1995 period, during which network connectivity regularly achieved 90% or more. During this same period, over 500 senior managers entered the network, and 117 new firms appeared. The robustness of connectivity within this career affiliation network, given the turbulence created by large numbers of company failures and start-ups, should be considered strong evidence of extensive job mobility within the region. The career risk of joining a biotechnology firm that ultimately loses its independence appears to be relatively low.

How robust is the network to more catastrophic failure? Many of the companies that failed were small firms that failed to gain critical mass. Managers working within these firms tend to have peripheral positions in the network. What happens to network connectivity if larger firms whose managers occupy central position in career affiliation networks fail? To examine this possibility, the most central firm was identified for every year using a measured called the betweeness centrality, a commonly used indicator of brokerage within social networks (see Wassermann and Faust, 1994). To investigate the impact of more catastrophic failure, this company and all ties linking individuals to it were removed from the network for that year. Network statistics for the new network were calculated and then compared to the size of the main component of the original network.

Fig. 2 displays the percentage of individuals in the original main component and the main component after removing the most central company for each year. During the early 1980s, the removal of the most central firm has a pronounced effect on network coherence. Senior managers from the early entrant Hybritech dominated the early formation of social networks within San Diego biotechnology. Hybritech was the network's most central firm between 1978 and 1989. During this period, removal of Hybritech firm from the network results in a loss of between 30 and 40% of connectivity. Beginning in 1991, however, the robustness of the network to catastrophic failure increases significantly. Hybritech was acquired in 1986 with the result that most of its managers left to join a wave of start-ups formed during the late 1980s. A series of companies founded by former Hybritech alums, Idec, Gensia, Ligand, and Amylin, occupied the position of most central company between 1990 and 1997. By 1991, a cohesive network linking these and other firms in the region exists to the extent that the removal of the largest firm has a relatively minor impact on network connectivity. Less than 10% of connectivity is lost in the early 1990s, and from 1995 onwards the loss is between 1 and 3%. This result complements the evidence on network usefulness, suggesting that from 1995 onwards San Diego career affiliation networks were both extremely well connected and durable. In general, the sustainability of San Diego career affiliation networks is high.

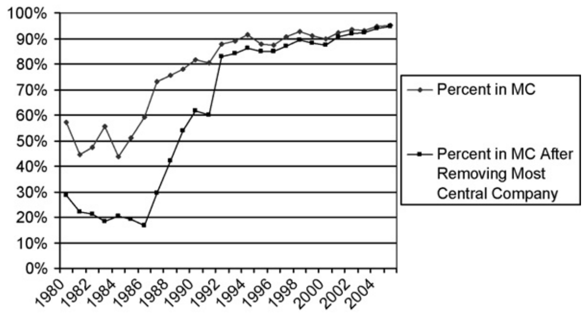

Fig. 2. Effect on size of network main component of removing most central company.

5.2. *Mechanisms of emergence: the role of Hybritech managers in creating a network backbone*

Given the organic pattern of growth in San Diego, a key issue to investigate is whether a mechanism developed to overcome collective action problems surrounding the early growth of flexible labor markets. Through coupling network analysis with a closer analysis of history of the cluster's key firms it is possible to examine the mechanisms by which the network emerged. An important catalyst of a network's development is the emergence of what network theorists call a "backbone" or group of initial ties that later entrants to a network can latch on to, stimulating the growth of a cohesive network (see Powell et al., 2004). An interesting finding in San Diego is that a network backbone did develop, and can be attributed almost entirely to the career strategies of a set senior managers with ties to Hybritech, a prominent early San Diego biotech company.

While a small number of biotechnology companies existed in San Diego by the early 1980s, only Hybritech was launched by a world class team of venture capitalists, scientific founders, and general managers.

Hybritech,was founded in late 1978. The company commercialized molecular diagnostics technology developed at UCSD by Ivor Royston and Howard Birndorf. Hybritech received immediate credibility due to its ability to attract funding from the by the same team of Silicon Valley venture capitalists at Kleiner, Perkins, and Byers that launched Genentech in San Francisco a few years earlier. The Kleiner Perkins venture capitalists were able to recruit a strong management team, lead by Howard Greene, one of several up and coming young general managers who left the medical device firm Baxter to accept leadership positions within the first generation of US biotechnology start-ups (Higgins, 2005).

In 1986, Hybritech was acquired by the large pharmaceutical firm Lilly for $300 million, a princely sum given the time period and the fact that few biotechnology firms had at this point successfully commercialized a product (Crabtree, 2003). This acquisition had the immediate effect of transforming Hybritech's top management team, all of whom owned shares in the company, into extremely wealthy individuals. As part of the acquisition, the top management team was encouraged to remain, but Hybritech became a subsidiary of a large Indiana based pharmaceutical company with a relatively conservative managerial ethos. Hybritech had developed a free-flowing, informal corporate culture typical of technology start-ups. This created immediate clashes with the Lilly managers. Tina Nova, one of the senior scientists at Hybritech, reflects that "It was like 'Animal House' meets 'The Waltons' (Fikes, 1999). Lilly also began a practice of rotating its managers into and out of the Hybritech facility at frequent intervals, making it difficult for the original Hybritech managerial crew to develop working relationships with the Lilly managers. Lilly was ultimately unable to integrate Hybritech's management and scientific team into its corporate culture, and in the years immediately following the acquisition most of the former Hybritech senior managers, including all managers located in this study's database, left. Hybritech is now regularly referred to as a failed acquisition.

The cadre of former Hybritech managers are now widely credited within San Diego for "seeding" the San Diego biotechnology industry. This group of managers could serve as a reliable and trusted referral network to one another. Their credibility as successful biotech entrepreneurs was also important in recruiting highly skilled individuals to join San Diego start-ups to which the Hybritech managers were linked. These managers had the financial resources, managerial experience, and a reputation for developing one of the biotechnology industry's early and rare success stories. A litany of important San Diego companies were founded by former Hybritech managers, including Amylin, IDEC, Gensia, Gen-probe, Ligand, Nanogen, Immune Response,

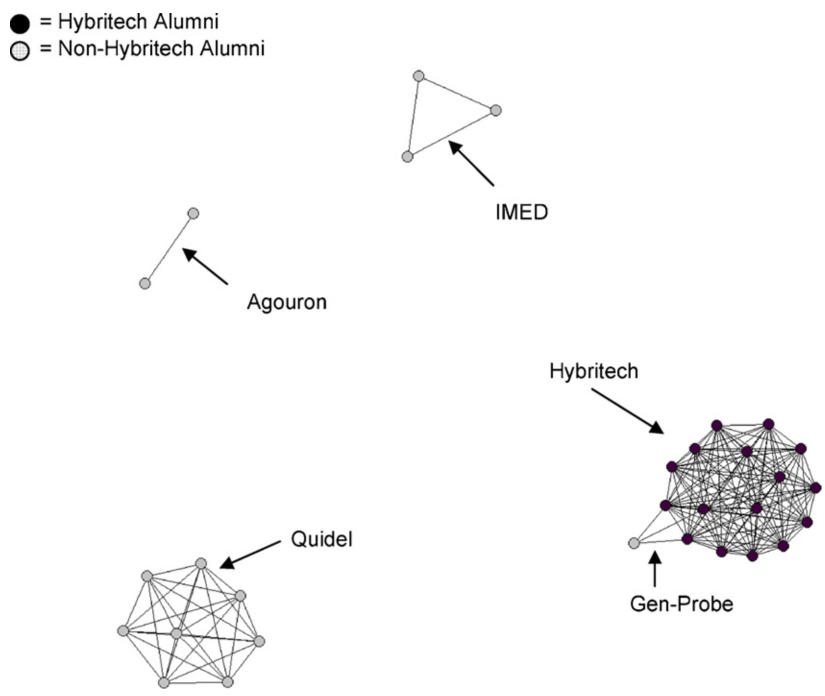

Fig. 3. San Diego career affiliation network 1984.

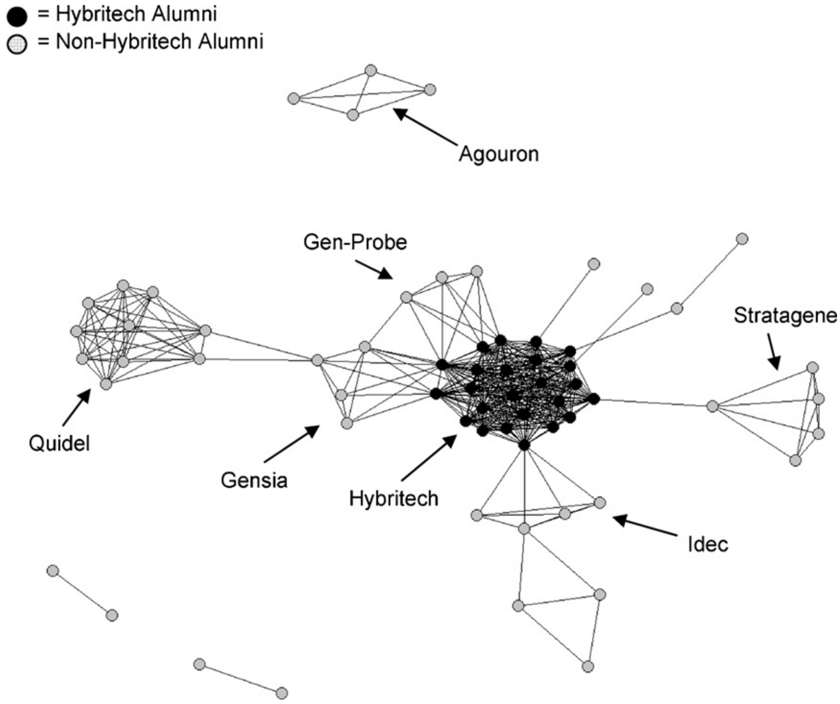

Fig. 4. San Diego career affiliation network 1987.

Biosite, and many others. One recent study found over 40 biotechnology companies in San Diego employing a senior manager or board advisor linked to Hybritech (Fikes, 1999). Moreover, Greene and Royston, two of the original three founders of Hybritech, eventually became important venture capitalists within the region. Birndorf, the third founder, developed a reputation with local venture capitalists as an excellent CEO of early stage

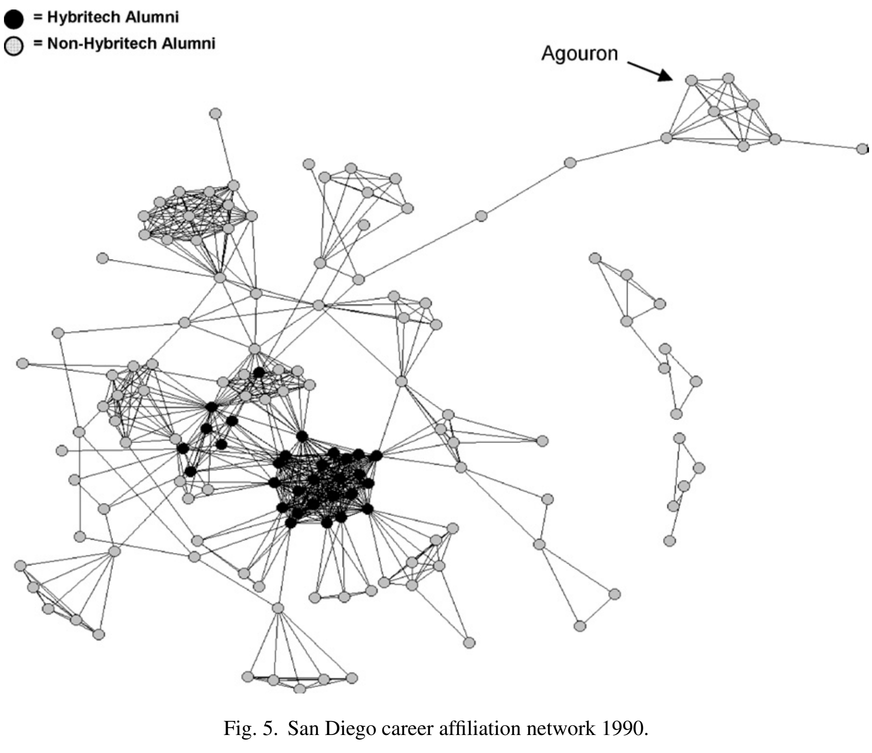

Fig. 5. San Diego career affiliation network 1990.

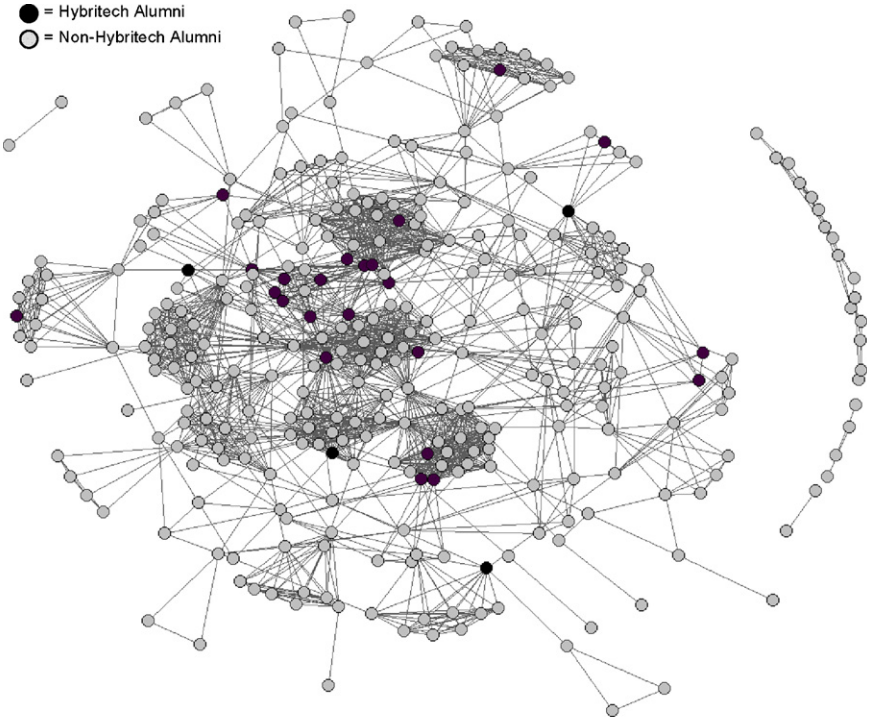

Fig. 6. San Diego career affiliation network 1995.

biotechnology companies, and became a short-term CEO of several companies.

Network visualization can help tracing the role of the former Hybritech managers in forging connectivity within the San Diego biotechnology community. Figs. 3–6 display career affiliations for several years between 1984 and 1995. Within these figures, the dots, or nodes, represent senior managers while the lines connecting dots represent ties. Companies are represented by groups of individuals sharing ties to one another. To simplify the network figures, individuals with no ties to other people within the network (so-called isolates) were removed from the analysis. Managers with career affiliations to Hybritech are colored black, while all other individuals are shaded gray.

Fig. 3 displays San Diego career affiliation networks for 1984. At this time, the network comprised a few distinct clusters of individuals, each representing companies founded during the early formation of the region's biotechnology industry. While Hybritech has over a dozen senior managers represented in the network in 1984, most of the other companies are smaller. During the 1979–1984 period, there was very little labor mobility across firms. The only instance of mobility across firms in the network surrounded the formation of Gen-Probe in 1983, in which three Hybritech managers joined a new entrant to the network to found the company.

Fig. 4 displays career affiliation networks in 1987, a year after the acquisition of Hybritech by Lilly. This network diagram shows the formation of new two companies formed by Hybritech alumni, Gensia and Idec, as well as the general growth of the network main component as Quidel and Strategene established initial ties to the growing cluster of individuals linked through Hybritech. By 1990 (Fig. 5), the main component had grown significantly, in part through the formation of several more companies founded by Hybritech alumni. At this point, it appears a network backbone had emerged, though it is fragile in some places. For example, while connectivity linking individuals is high surrounding the core group of Hybritech alumni, senior managers working at Agouron are weakly connected to the main component through two individual ties. The 1990 network also shows that, due to the 5-year decay model, direct ties linking some former Hybritech managers to one another had ended, though these individuals still occupied central positions within the network. By 1995 (Fig. 6), a robust network has formed linking a large number of companies. All ties to Hybritech had decayed from the network, and, while most former Hybritech managers were still active within the biotechnology community, their central role in holding the network together appears to have declined. Labor market mobility within the region was sufficient to create sustainable

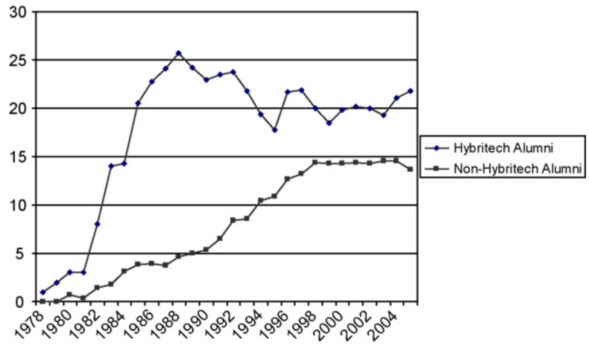

Fig. 7. Average degree centrality of Hybritech alumni and non-Hybritech alumni, 1978–2005.

career affiliation networks linking most firms in the region.

To help document more systematically, the role of Hybritech managers in shaping robust career affiliation networks in San Diego. Fig. 7 displays the average number of ties held by Hybritech alumni through the 1978–1995 period as opposed to all other alumni. While this evidence shows that the Hybritech alumni hold more ties, on average, than non-Hybritech alumni through all years, the evidence for the years 1987–1992 is particularly striking. These are the years in which the Hybritech managers left to found new companies. During these years, the Hybritech alumni held between 23 and 26 ties on average, about 5 times the average connectedness of the non-Hybritech alumni. This evidence is consistent with the explanation that the Hybritech alumni, when founding companies during the 1987–1992 period, created a network backbone of social ties while doing so.

As discussed in Section 4, a problem surrounding the early formation of social networks in San Diego biotechnology are possible biases created by the exclusion of individuals due to the reliance of career history data only to locate senior managers working in San Diego before 1994. It is reasonable to conclude that missing data has not biased the evidence surrounding the key role of Hybritech managers in forming a viable network backbone. The role of Hybritech managers in seeding the network is substantiated by both the network visualization and network centrality results. Moreover, the Hybritech story generally well known within the San Diego area and reported in local newspaper articles and academic reports (see Fikes, 1999; Crabtree, 2003). Given that most of the key firms launched between 1986 and the early 2000s were founded by former Hybritech managers, it also seems unlikely that missing data has hidden additional mechanisms by which the network emerged.

In sum, the mechanism of network emergence surrounding the failed Hybritech acquisition helps justify the claim that dynamics surrounding the formation of an appropriate social structure within the region were important in explaining the success of the region in developing a large cluster of companies. Through both seeding a generation of follow-on companies to Hybritech and, through mobility to and from these firms, creating a web of social ties across the new firms, a credible network backbone emerged. Referring back to the earlier game theoretic analogy, career expectations across senior managers within San Diego "flipped" from out of the low commitment equilibrium into one where the career risk of taking jobs within regional biotechnology firms was reduced by the existence of large, vibrant social networks linking managers within the region.

6. Conclusion

This study helped identify mechanisms by which social networks linked to career mobility emerged and became sustainable within the San Diego biotechnology cluster. How does a regional economy develop a social structure favoring job mobility? Process tracing through a year by year analysis of the network reveals that viable social networks linking San Diego senior managers were initially created by a small cadre of former Hybritech managers that created a number of new companies in the region. These new firms initially were linked through their former ties to Hybritech, but soon developed a shared labor market pool that helped consolidate and then expand a viable network backbone for the San Diego biotechnology industry. During the mid-1990s onwards, patterns of career mobility across San Diego managers became sufficient to generate and sustain social networks.

While this study does not attempt to relate social networks to the innovative performance of area firms, it did develop a number of measures to evaluate the usefulness of networks on a yearly basis. Social networks linking San Diego networks are large, have maintained their efficiency despite a doubling of the network over the last several years, and are robust to failure. Moreover, as the network grew most managers developed numerous ties to other companies through direct career mobility, and could gain access to two dozen or more companies through only one or two intermediaries. This evidence supports the core claims of the labor market mobility research stream: San Diego networks facilitate career mobility, reducing the risk of talented individuals working within a start-up company and supporting innovation strategies within technologically volatile industries.

While the social network results for San Diego suggest that cohesive ties exist senior managers in the region, one important area not investigated in this study is whether the organization of networks differ across different types of managers. For example, once entering commercial biotechnology, do scientists display a bias towards the formation of ties with other scientists, perhaps on the basis of shared technical knowledge, or are shared experience within companies the primary basis by which ties are formed? The findings on Hybritech also demonstrate the possibility that networks linking company founders may be particularly important. Do founder networks exhibit different characteristics than the more general career affiliation networks examined in this research? Future research might usefully investigate these and other issues surrounding the micro-dynamics of social network formation.

How do these results fit into the larger debate surrounding the economic development of technology clusters? One interesting puzzle is why there is so much variation in the success of technology clusters within given economies. Much research has emphasized the attractiveness of the United States in generating high-technology technology clusters (see, e.g. Hall and Soskice, 2001). Reinforcing this theme is a more specialized literature linking the American success in commercializing science to favorable regulatory frameworks, such as the Bayh–Dole Act (Mowery et al., 2004). Yet there is tremendous variation in the success and failure of clusters even within the United States. A key assertion emerging from the social network approach is that more than attractive national frameworks are needed for clusters to develop. In the San Diego case, effective social ties were able to coalesce around a group of managers linked to the failed Hybritech acquisition. Combined with access to world class technology from local universities, a small hub of activity was able coalesce into a world class biotechnology cluster. One interesting question for future research is whether social networks, especially those promoting mobility, can spur cluster formation in business systems that have been identified as disadvantageous for cluster formation. The appearance of wireless telecommunication clusters in Scandinavia, or biotechnology in Southern Germany, are attractive cases to explore.

If cluster development depends on the formation of social networks that have primary origins through shared career experiences, what is the role for governments? Governments across the world are spending large sums of money in attempts to orchestrate the development of technology clusters. In the field of biotechnology, these policies usually link subsidized venture capital with policies to encourage and hasten the commercialization of university science. One finding of this study is that sustainable social networks emerge relatively slowly; it took about 15 years for this cluster to become sustainable, at least in terms of social network organization. While this might seem like a relatively short time period, it is a much longer time-span than that assumed in many political projects scattered across the world that seek to rapidly create new biotechnology clusters through technology policies, but within the confines of short electoral cycles.

Moreover, there is little empirical research suggesting that the social networks underpinning the development of clusters of high-risk entrepreneurial firm can quickly be orchestrated solely by non-market activities. While the commercialization of university of science may be an effective instrument to catalyze regional cluster creation, the San Diego case shows that critical ties linking senior managers within the region were formed primarily through shared market experience. In this respect, a disturbing implication of this study is that the event catalyzing tie formation in San Diego—a failed acquisition of a highly successful company-may be rare and in any case helps accumulate little knowledge useful to individuals or governments interested in developing successful clusters. The creation of social structures capable of supporting high labor market mobility within a region may be outside the purview of direct government policy. In this respect, research investigating how policy may shape the formation of shared market experiences by experienced scientists and managers could help reveal alternative mechanisms by which decentralized social networks within emerging high-technology clusters could be forged.

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