

Bedrock Depth and the Formation of the Manhattan Skyline, 1890-1915*

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RUTGERS UNIVERSITY, NEWARK WORKING PAPER #2009-006
October 2009

Abstract

Skyscrapers in Manhattan need to be anchored to bedrock to prevent (possibly uneven) settling. This can potentially increase construction costs if the bedrock lies deep below the surface. The conventional wisdom holds that Manhattan developed two business centers—downtown and midtown—because the depth to the bedrock is close to the surface in these locations, with a bedrock “valley” in between. We measure the effects of building costs associated with bedrock depths, relative to other important economic variables in the location of early Manhattan skyscrapers (1890-1915). We find that bedrock depths had very little influence on the skyline; rather its polycentric development was due to residential and manufacturing patterns, and public transportation hubs.

Key words: skyscrapers, geology, bedrock, sprawl, urban agglomeration

JEL Classifications: N61, N92, R14, R33

*We thank Gideon S. Sorkin for his expertise in engineering and history of architecture, Robert Snyder for his expertise on New York City history, and Patrick Brock and Stephanie Tassier-Surine for assisting us with their geological expertise. We would like to thank Howard Bodenhorn, Mary Beth Combs, Alec Gates, Alex Marshall, Brendan O’Flaherty, and Rosemary Wakeman for helpful conversations and comments on previous drafts. We are grateful to the Skyscraper Museum for access to its data. We appreciate the comments from participants of seminars at CUNY Queens and Emory University. Support for this project was generously provided by a Rutgers University Research Council Grant and Fordham University Faculty Research Grant. Any errors belong to the authors.

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*Hour by hour the caissons reach down to the rock of the earth and hold the building
to a turning planet*

- Carl Sandburg, "Skyscraper"

1 Introduction

The earth's terrain has always had a strong influence on the location of cities. In the United States, for example, New York, Philadelphia and Boston were founded because of their easy access to the sea. Chicago was founded because of its central location between east and west and because it was a topographically flat region near several major waterways. Further, many early cities were located on hilltops to provide protection.

Less visible, however, is the role that geology can play in urban growth and in the spatial distribution of economic activity. A region's geology can affect access to drinking water and the ability to remove human waste. Geology can also affect access to building materials, such as limestone and marble.

In addition, geology can have strong impacts on buildings and their foundations. Structures in Mexico City, for example, are sinking because the drinking water in the aquifers beneath the city are being depleted. The Leaning Tower of Pisa is perhaps the most famous example of a building constructed without proper regard for the earth that supports it. More broadly, however, geology can effect the spatial distribution of economic activity within a city or region. For instance, geology can enhance agglomeration economies by funneling activity to geologically convenient areas; or geology can push economic activity apart when there are natural barriers.

In this paper we study the effect of geology on the spatial distribution of economic activity and the creation of the Manhattan skyline. In the late-19th century, a set of technological innovations allowed for the construction of skyscrapers. High-strength steel beams obviated the use of thick load-bearing masonry walls. The introduction of electric elevators with safety breaks made vertical transport both safe and fast. However, when skyscrapers become technologically feasible, developers had to consider the geology below the buildings. Due to their heavy load these buildings needed to be anchored to bedrock to prevent sinking and

uneven settling. Often digging to bedrock in Manhattan was difficult because of wet subsoil, and caissons were needed to prepare the foundation (Landau and Condit, 1996).

A frequently-cited story in New York City’s history is that there are two separate business districts—one centered near Wall Street, and one centered near Grand Central Station—because of a deep bedrock “valley” between these two areas, where bedrock is up to 4 to 5 times deeper below the surface than on other parts of Manhattan Island. The conventional wisdom is that skyscraper developers shied away from building where the bedrock depths were too deep.

For example, New York geologist Christopher Schubert (1968) writes, “[T]he skyscrapers of New York City are clustered together into the midtown group, where the bedrock is within several feet of the surface, and the downtown group, where the bedrock again reappears to within forty feet of the surface near Wall Street....In any event, it is readily seen how clearly the accessibility of the bedrock has, to some degree, controlled the architectural planning of the city” (pps. 81-82).¹

Though this story has become a New York legend, it has never been empirically tested. In this paper we explore the degree to which the geology of Manhattan Island played a role in its subsequent development using newly collected data that links skyscraper construction, bedrock depths, building costs, and other relevant economic variables.

To the best of our knowledge no other paper has directly addressed the effect of bedrock on the Manhattan skyline. The effects of geology on agglomeration have been explored in a few works, including Rosenthal and Strange (2008) and Combes, et al. (2008). These papers use geological features as econometric instruments in order to measure the effects of agglomeration economies on wages and productivity. Our results show that the bedrock depths have very little influence on the placement of skyscrapers and therefore on agglomeration economies. Since Manhattan business districts emerged from other economic forces, it appears that geological factors are not a strong, exogenous correlate with agglomeration on the island.

In addition to the historical interest in the development of New York City, this paper

¹Evidently, Schubert’s words sparked the widespread belief that bedrock depths have determined the skyline. Our results show that other economic factors were at work, with bedrock depths playing a small role, at best. We thank Gideon Sorkin for providing the source of this legend.

also contributes to broader questions about city formation and spatial structure. The Alonso (1964) and Mills (1972) models of land values assume one center within a city or region; the models generate steep rent gradients as one moves away from the central business district. Gradients have been estimated for New York City by Atack and Margo (1998) for the years 1835 to 1900. One problem with the assumption of a monotonic gradient is that by the 1890's in Manhattan it no longer applies. Rather by the end of the 19th century, Manhattan was becoming polycentric.

There have been several theoretical models that address the emergence of intra-urban subcenters, such as Fujita and Ogawa (1982) and Helsley and Sullivan (1991). McMillen and Smith (2003) conclude that the theory points to two important variables that drive the number of subcenters within a metropolitan region: population and commuting costs, with the number of subcenters positively related to both. They empirically test these hypotheses and find that population and traffic congestion can account for close to 80% of the variation in the number of subcenters across the U.S., as of 1990.

To the best of our knowledge, however, no work has directly addressed historical subcenter formation. The implication of these models is that subcenter formation and “sprawl” are post-World War II phenomena, or at least contingent upon the widespread use of the automobile (Glaeser and Kahn, 2004). The evidence here suggests, however, that polycentric urban development is a much earlier phenomenon. Jackson (1987), for example, demonstrates that the process of “suburbanization” in New York City began in the first half of the 18th century, with the introduction of steam ferries and railroads. Our work shows that intra-city (rather than intra-regional) subcenter formation was occurring in New York City during the 19th century. As such, midtown Manhattan perhaps represents one of America's earliest “edge cities” (Marshall, 2007; Garreau, 1991).

Despite our findings, the role that geology can play in the spatial structure of cities and regions needs to be further explored. Anas et al.'s (1998) paper “Urban Spatial Structure,” focuses on how agglomeration economies drive economic location choices with only a passing mention of the role of say “a unique resource such as a harbor” (p. 1427). Davis and Weinstein (2002) conclude, however, that “locational fundamentals” are a driving force behind the distribution of regional economic activity and growth. Though they don't elaborate on

what these locational fundamentals might be, the implication is that regions have some underlying inherent differences, and that these differences may be geological.² A recent paper by Burchfield et al. (2006) find that geological features have important effects for sprawl. For example, they find that the presence of mountains in the urban fringe is negatively related to sprawl, while more gentle changes in terrain is positively related to sprawl. Also, they find that the greater the spread of underlying aquifers in a region the more likely there will be sprawl.

In order to investigate the role of geology in the creation of Manhattan’s skyline, we have compiled two new data sets. With the first, we investigate how the bedrock depth affected construction costs for 53 large commercial buildings completed in New York City between 1899 and 1915. We find that having to dig to bedrock deep below the surface did not dramatically increase construction costs for these projects. We find the increase in constructions costs associated with digging to bedrock to be small relative to the overall construction costs of a skyscraper, and relative to the land values of building lots.

We construct a second data set to investigate the location choices of skyscraper developers. In this data set we have collected depth to bedrock information at the location of 74 skyscrapers built in Manhattan between 1890-1915 (prior to the first zoning requirements). Along with this information we also collected information on demographic characteristics of residents, availability of public transportation, land values, and other economically relevant information near each of the 74 skyscraper locations. Finally, as a control group, we collect the same information for 99 randomly selected non-skyscraper locations throughout Manhattan (south of Central Park). We then estimate the probability of a skyscraper being constructed at these locations as a function of the various explanatory variables.

Overall, our results suggest that bedrock had, at most, a small effect on the formation of the skyline. Rather, developers were most affected by the other economic factors, such as agglomeration economies in the already established centers, the distance to public transportation, the desire to avoid being near slums and manufacturing districts and to be closer to upper- and middle-class citizens in Manhattan. That is to say, the evidence strongly

²To Davis and Weinstein (2002), “locational fundamentals” are described as Ricardian technological coefficients and Hecksher-Olin endowments. More directly they also suggest that these fundamentals might be related to the presence of ports or plains.

Variable	Mean	Std. Dev.	Min.	Max.
Building Height (meters)	100.39	31.26	80	241
Building Height (stories)	23.74	7.79	12	57
Headquarters Dummy	0.41			
Lower Manhattan Dummy	0.53			

Table 1: Skyscraper descriptive statistics, 1890-1915. # obs=74. Sources: See Appendix.

suggests that the polycentric nature of Manhattan was driven more by the demand for skyscrapers and agglomeration benefits in particular neighborhoods rather than the inability of suppliers to provide skyscrapers in other places.

The rest of the paper proceeds as follows. In the next section, we discuss Manhattan’s history and geology. Then, in section 3 we provide a simple model of the supply and demand for skyscrapers. Next, section 4 provides the results of the empirical analyses. Lastly section 5 provides some concluding remarks. An Appendix provides information about data sources and preparation.

2 Manhattan

In this paper we focus on the first generation of Manhattan skyscrapers in the period 1890 to 1915. The Tower Building, which was completed in 1889, is often considered New York’s first “skyscraper”; it was only 11 stories.³ The following year Joseph Pulitzer’s World building was completed. At 94 meters it set the standard for New York skyscraper height, given it was the world’s tallest building at the time.⁴ In the ensuing years buildings of 80 meters or taller were relatively common in Manhattan and to simplify the discussion, for the remainder of the paper, we define a “skyscraper” as a building that is 80 meters or taller.⁵

Because of the implementation of zoning regulations in 1916, and the building lull which followed due to World War I and a subsequent recession, we focus on the first generation of

³The Tower Building was considered a skyscraper because it was the first building in New York to use an all-steel cage design, instead of load-bearing masonry walls.

⁴There is debate about the World building’s actual number of stories; various sources put its range between 16 and 20 stories.

⁵We can describe the relationship between stories and height via the OLS-derived equation: $\widehat{floors} = 0.173 + 0.235 meters$, $R^2 = 0.89$, # obs.=74; robust standard errors below estimates. Source: see Appendix.

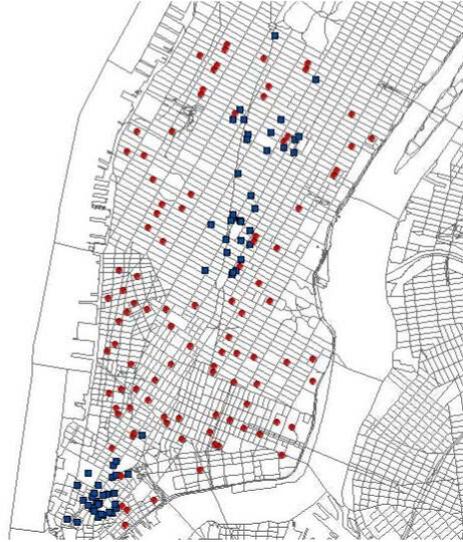


Figure 1: Skyscrapers and non-skyscrapers in Manhattan, 1915. Skyscrapers are blue squares and other buildings are circles. Sources: see Appendix.

skyscrapers, which ended in 1915.⁶ Table 1 provides some descriptive statistics about the skyscrapers in our data set. From 1890 to 1915 we have found there were 74 skyscraper completions, with the height ranging from 12 to 57 stories. Figure 1 displays the location of these 74 skyscrapers as blue squares. The figure also shows the locations of a control group of 99 randomly selected non-skyscraper buildings as red circles. (These are discussed in more detail below.) The figure clearly shows the multi-centered nature of Manhattan. Roughly one-half of the skyscrapers were built in lower Manhattan, with the rest built north of 14th Street. About 40% of the skyscrapers were built as a “headquarters,” where we define this to mean that a major corporation, such as a bank or newspaper publisher, had a major equity stake in the building. The remaining buildings were either speculative office projects, residential, or entertainment-related buildings.

⁶In 1916, New York City implemented a comprehensive zoning ordinance, which zoned economic activity to specific areas and regulated building height. In particular, builders had to set back the higher floors away from the street line. These buildings were qualitatively different than in the early period, and were notably “Art-Deco” in style.

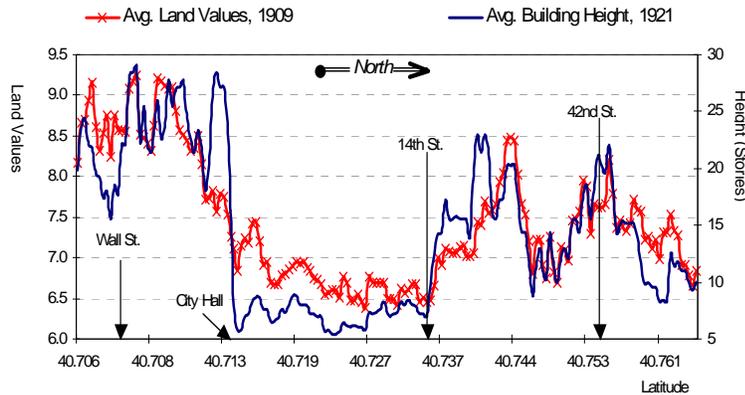


Figure 2: Natural log of average land values in 1909 and average building heights in 1921 versus degrees latitude in Manhattan. Sources: see Appendix.

2.1 The “Great Leap”

During the late-19th century, New York developed three “centers” as defined by land values and building heights. Figure 2 further illustrates the polycentric nature of Manhattan in the early 20th century.⁷ The first center is that of lower Manhattan, with high land values and tall buildings between Wall Street and City Hall. Another center developed between 14th and 23rd Streets—between Union and Madison Squares. Finally another center developed around Grand Central Station on 42nd Street.

As the figure clearly shows, between approximately latitudes 40.714° and 40.736° , average land values and building heights are much lower. This is the area of Manhattan north of City Hall and south of 14th Street. The conventional wisdom is that this area of low heights was due to a bedrock valley.

Also note the magnitude of the variation in land values, measured in dollars per foot of street frontage. In particular, land values near Wall Street were far higher than land values elsewhere in the city. Based on our data set, average land values (as measured per foot of street frontage) south of latitude 40.713° (roughly City Hall) were \$7,223; between latitudes 40.713° and 40.736° (roughly 14th Street) average land values were \$927; and north

⁷Average building heights are taken from our data set (discussed below), which contains skyscrapers and randomly selected non-skyscrapers. As such, the average heights here do not directly measure the average height of buildings, but rather represent a graphical depiction of the skyline itself. Also note that the island of Manhattan is situated in a north-easterly direction, thus the locational markers on this graph and the following ones are only approximate. Finally, for New York City 1 degree latitude is approximately 70 miles.

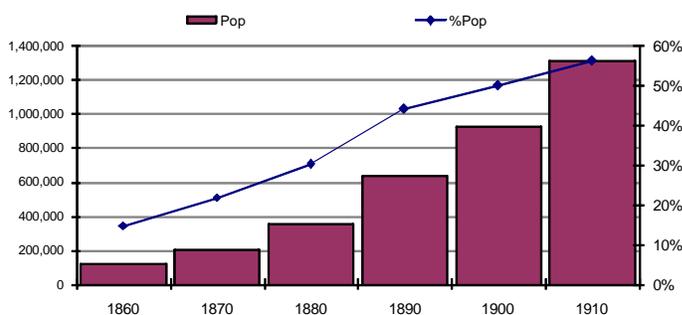


Figure 4: Manhattan population and percent of population living above 40th Street. Source: see Appendix.

movement as they fled encroachment by commercial activity in the more southern districts of the city.

As Figure 4 shows, both the population count and the fraction of the population living above 40th Street steadily increased throughout the late-19th and early-20th centuries. Thus, this northward movement of the population may have presented office-based firms with an opportunity. By moving northward they could attract the high-quality labor force needed for the developing service-based economy and pay lower wages due to workers' lower commuting costs. That is to say, the northward movement of skyscrapers may have represented an adjustment toward a new spatial equilibrium.

Furthermore, Figure 5 shows the spatial distribution of two demographic groups in Manhattan in 1890: foreign born residents and white native born citizens with two native parents. The figure shows that the two groups are generally segregated, with native whites most highly clustered between Union Square (14th Street) and Madison Square Park (23rd Street). Furthermore, foreign born residents are most highly clustered between 40.705° and 40.730° , *the very area where the bedrock is the deepest*.⁸ This correlation between foreign born residents and bedrock depth is most likely a coincidence, since the first skyscraper was completed in 1890, several years after neighborhoods like Five Points (Anbinder, 2001) and the Lower East Side (Riis, 1890) became poor tenement districts.⁹ In theory, the developers of skyscrapers

⁸In fact, the correlation coefficient between the percent of residents in each sanitation district that is foreign born and the depth to bedrock is 0.50.

⁹There may be an underlying, indirect causation, however. Areas with bedrock near the surface are likely to have better natural drainage and are therefore less "swampy." Thus areas with deep bedrock may have

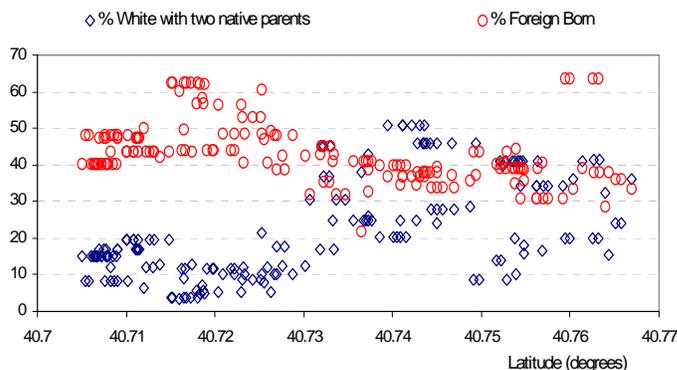


Figure 5: Percent foreign born and native white residents in the various sanitation districts in Manhattan. Sources: see Appendix.

may have had a disincentive to place tall buildings in these poorer neighborhoods.

2.2 Manhattan Geology

As Landau and Condit (1996) write, “In theory, the geology of Manhattan Island is ideal for skyscrapers” (p. 24). Bedrock generally lies near the surface, though there is a fair degree of variation from north to south. Virtually all of Manhattan south of central park is comprised of strong metamorphic rock, which is part of a larger formation known as the New England Upland. The particular type of rock is referred to as Manhattan schist (Tamaro, et al., 2000; Baskerville, 1994; Baskerville, 1982).

Figure 6 gives an indication of how bedrock depths vary from the southern tip of Manhattan to Central Park South. At the southern tip of Manhattan bedrock depths start at about 8 meters below the surface; going north, the bedrock dips down into a kind of bedrock valley, which reaches its greatest depth between City Hall and Canal Street. The bedrock depths then decrease up to around 14th Street, where, on average they remain relatively close to the surface, moving northward.

In addition to the depth to bedrock, Figure 6 also indicates the location of skyscrapers throughout Manhattan south of Central Park. The triangles are locations of the 74 sky-

been less desirable properties for commercial activity in the 17th and 18th centuries, which, in turn, evolved into manufacturing and low-income neighborhoods in the 19th century. We thank geologist Alec Gates for this comment.

scrapers in our data and the circles are the additional 99 randomly chosen non-skyscraper locations. As the figure shows, there are two concentrations of skyscrapers, one between Bowling Green and City Hall, and the other from 14th to 42nd Street.

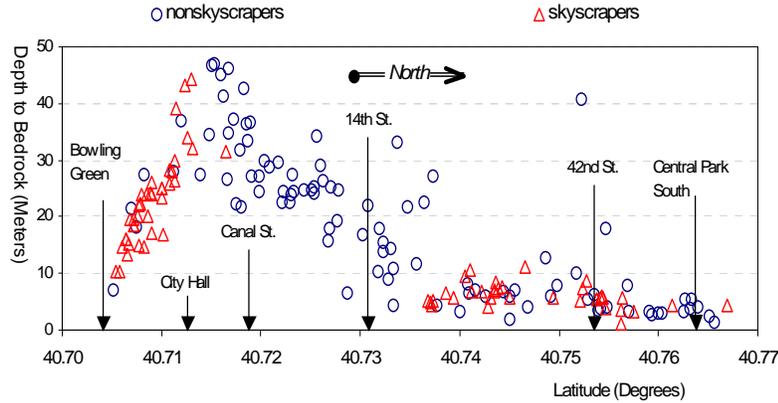


Figure 6: Depths to bedrock for Manhattan, south of Central Park. Depth is measured relative to the surface. Sources: see Appendix.

In regard to the effect of depth to bedrock on skyscraper locations, there are at least four hypotheses. First, bedrock may have been a strong technological determinant that prevented skyscrapers in the bedrock valley, even in the face of agglomeration benefits. Simply put, it may have been technologically infeasible to build a skyscraper if the depth to bedrock was too great. However, Figure 6 indicates that this was not the case. The deepest bedrock in our data set is just over 45 meters but some skyscrapers built during this time period were anchored to bedrock 40 meters below the surface. Second, if building above deep bedrock was technologically feasible it may be that skyscraper construction in the bedrock valley was too costly relative to the benefits. Again, this possibility is somewhat disproved by Figure 6. Skyscrapers were built above some of the deepest bedrock in the city. Thus it appears that it was economically feasible to build over deep bedrock when there were also sufficient demand-side benefits. These first two hypotheses contain the conventional wisdom of New York City folklore.

A third possibility is that small changes in the foundation costs may have produced large changes in the location decisions of developers. That is to say, depth to bedrock may have generated a “tipping effect” so that at some point, a small increase in depth to bedrock

increased construction costs just enough so that developers decided to choose a location north of the bedrock valley where bedrock was close to the surface. Finally, the effect of depth to bedrock may have been irrelevant or small enough that it did not greatly effect the location choice of builders. We analyze and test these hypotheses in the rest of the paper.

3 A Simple Model

Below we develop a simple supply and demand model that will allow us to parse out the effects of depth to bedrock and agglomeration economies in our data. Throughout the model we assume a linear city on some interval, with locations denoted $j \in [0, \bar{j}]$, with 0 being the exogenously determined city center. (For example, from south to north up Manhattan along Broadway). Let $d(j) = |0 - j| = j$ be a firm's distance from the center. Furthermore, to keep the model simple, we investigate a static model; however we discuss the dynamic implications later in the paper. In short, the aim of the model is to derive a set of testable hypotheses about the effect of bedrock anchoring costs versus other economic factors in accounting for the spatial distribution of the skyline and hence of economic activity.

3.1 The Demand For Height

We assume that each office-based firm has the following profit function:

$$\pi(h) = A(j) f(h, l) - rh - wl - F, \tag{1}$$

where $f(h, l)$ is a production function, with office space (h , for height) and labor, l , as inputs. Assume $f(h, l)$ has the standard features (continuous, positive first derivatives and negative second derivatives, etc.). Without loss of generality plots of land are fixed and normalized to size one.¹⁰ $A(j)$ represents the net agglomeration effects for office-based firms as a function of distance from the center. As will be discussed below, $A(j)$ represents the net effects of both positive centripetal forces (such as knowledge spillovers, reduced communication

¹⁰The 1811 Gridplan of New York set standard plot sizes of 25' by 100'. It has been argued that this small plot size created artificial land scarcity by the 1890s since the large plot assemblages needed for skyscrapers became relatively difficult. See Willis (1995), for example.

costs, etc.) and negative centrifugal forces (such as proximity to manufacturing and “slum” neighborhoods, etc.). Assume, however, that $1 \leq A(j) \leq A(0)$, that is, net agglomeration effects are greatest at the center, and no firms have profits reduced because of a lack of agglomeration benefits. Also assume that $A'(j) < 0$; that is agglomeration effects, ceteris paribus, are strictly decreasing from the center. r is the per floor cost of renting office space. w is the wage, which we assume, for now, is fixed. F is a firm’s fixed costs.

Each firm must choose a building height that will maximize its profits. For now, assume that labor is instantaneously adjustable, so the optimal quantity is always chosen. This gives rise to a demand for height for each firm, via the first order condition:

$$r = A(j) f_h(h).$$

3.2 The Building Decision

Developers, who supply this height, have profit functions given by

$$\pi(h) = rh - c(h, j) - L, \tag{2}$$

where rh is the total revenue that can be earned from a building of height h (assume without loss of generality that a building’s operating costs are zero). $c(h, j)$ is the construction cost, and it is a function of both the height of the building and its location from the center. The reason distance matters for construction costs is because, as will be discussed below, the bedrock underneath the surface varies as one moves away from the center. Thus the costs of digging to bedrock is also a function of distance from the center. Assume that $c_h(\cdot) > 0$, $c_{hh}(\cdot) > 0$, and $c_j(\cdot) \geq 0$. L is the price of land. Via the first order condition, we have the supply function for height:

$$r = c_h(h, j).$$

3.2.1 Choice of Height

Given office-based firms demand for height and developers supply of height, we have for each j an equilibrium height, h^* , which satisfies the following equality:

$$A(j) f_h(h^*) = c_h(h^*, j). \quad (3)$$

Note that we assume that j is an exogenous variable. This accords with the standard land-use models of Alonso and Mills, for example. If land markets are competitive then they will generate a spatial equilibrium where no firm can improve its profits by moving or changing its height decision. Thus height at each location will reflect this no-arbitrage condition and will, in essence, be exogenous for each firm.

Below we analyze the effects of bedrock on the height decision. But, as an example, let's assume that bedrock costs are constant for all locations, so that $c(h, j) = c(h)$. Taking derivatives of equation (3) shows that

$$\frac{dh^*}{dj} = \frac{f_h(h^*) A'(j)}{[c_{hh}(h^*) - A(j) f_{hh}(h^*)]} < 0,$$

which shows that equilibrium height is decreasing from the center; this negative effect is driven by the drop off in agglomeration effects.

3.3 Bedrock Effects and the Supply of Height

Assume that a builder must consider the “bedrock costs” at each location, especially if there is an interaction between the height of a building and the depth to bedrock.¹¹ For instance, as mentioned in the introduction, building above a specified height, denoted \bar{h} , may require that the structure be anchored to the bedrock. Thus the cost function may be

$$c(h, j) = g(h) + \delta(\bar{h}) b(h, j), \quad (4)$$

¹¹We refer to “bedrock costs” as shorthand for the additional costs a builder must pay to anchor a building to bedrock.

where $\delta(\bar{h})$ is an indicator variable equal to one if a building of height \bar{h} or greater is going to be built, and zero otherwise. $b(h, j)$ is the additional costs associated with anchoring the building to the bedrock, with $b_h(h, j) > 0$ and $b_j(h, j) > 0$. $g(h)$ is the construction costs for a building of height h ; with $g'(h) > 0$ and $g''(h) > 0$.

Thus the supply of height is given by

$$r = g'(h) + \delta(\bar{h}) b'(h, j). \quad (5)$$

If the profit maximizing height at location j is less than \bar{h} , then depth to bedrock plays no role in the decision making. However, if at $\bar{h} - \varepsilon$ the marginal benefit is greater than the marginal cost a developer may stop and build at this height, if the marginal bedrock costs of adding ε units of height is very large. Thus whether a developer builds to a height taller than \bar{h} depends on the relationship of the marginal benefits to the marginal costs of height at \bar{h} , which includes the cost of anchoring the building to the bedrock at location j . Specifically, if for location j , $r - g'(\bar{h}) > b'(\bar{h}, j)$ a developer builds to height $h > \bar{h}$; if not, he builds to height $h \leq \bar{h}$.

Furthermore, we can assume that for the developer, $r = r(j)$, such that $r'(j) < 0$. That is, builders will face a lower rent at a greater distance from the center, because of the lower agglomeration benefits to office-based firms. As such the supply of height as a function of distance will depend on both the rents at every location and the degree to which bedrock costs increase or decrease as a function of distance.

3.3.1 Bedrock Depth Function

Assume that bedrock depths follows the shape given in Figure 6. That is, the distance to bedrock initially increases sharply to a peak and then falls off until a plateau is reached. Again, suppose that \bar{h} indicates the height above which it becomes necessary to anchor the building to bedrock. If the height is such that $h < \bar{h}$ the marginal cost is constant with respect to distance from the city center since the depth to bedrock will not play a role in the costs of construction. On the other hand, if $h \geq \bar{h}$, then the marginal cost will be a function of depth to bedrock which is directly specified by distance from the city center in our one

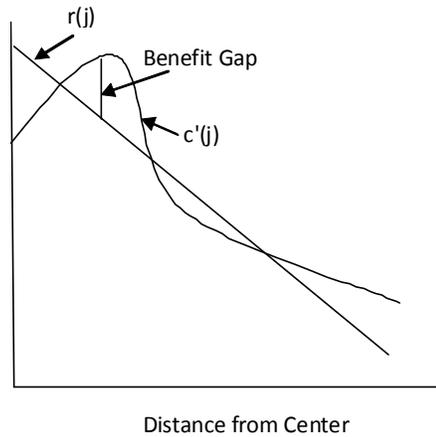


Figure 7: Costs and benefits of skyscrapers as a function of distance.

dimensional model.

Figure 7 shows how the relative marginal benefits and costs of building to bedrock would presumably vary as a function of distance, given the observed bedrock valley north of City Hall. The “benefit gap” depicted in the figure is given by the difference of $r - c'(j)$. If $r - g'(\bar{h})$ is large then we would expect to see a skyscraper since the additional costs of anchoring the building will be less than the additional benefits. If $r - g'(\bar{h})$ is small or negative we would expect to see a non-skyscraper constructed at that location.

In lower Manhattan we would expect to see skyscrapers given the relatively high rents and low costs of anchoring the buildings. As we move away from the center, the effects on the skyline over the bedrock “valley” would be a function of the size of the difference $r - g'(\bar{h})$. Recall that rents that can be charged decrease as one moves away from the city center due to smaller agglomeration benefits. If the difference $r - g'(\bar{h})$ decreased smoothly, and bedrock costs were constant, we should simply see a smooth decline in building heights away from the center. However, if the bedrock costs suddenly become large as one moved slightly north, we would expect to see a plateau; the agglomeration benefits at some point would not compensate for the additional bedrock costs, and builders would only build to height $\bar{h} - \varepsilon$ instead of building a skyscraper.

Figure 8 shows a skyline that we would expect to see if agglomeration benefits remained strong as one moved from the center, but not so strong as to pay for the extra bedrock costs.

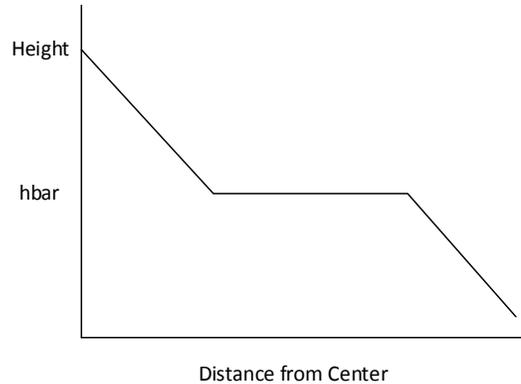


Figure 8: Equilibrium height as a function of the distance from the center.

That is to say, as the depth from the center increased we would expect to see a height plateau over the bedrock valley with building heights slightly lower than in the financial district.

But, given the steep drop-off in building heights observed in Figure 2, it would again suggest that bedrock costs did not provide a strong barrier to skyscraper construction nor did bedrock induce a tipping effect. In that figure we see a sharp and sudden decrease in building height rather than a height plateau. In other words, it appears that the supply side effects, namely bedrock costs, were not responsible for the lack of skyscrapers above the bedrock valley. This strongly implies that other demand side factors were pushing developers away from this area.

3.4 Demand Side Effects

We have not, as of yet, addressed the “great leap,” where skyscrapers emerged in midtown at the beginning of the 20th century. If bedrock effects were enough to cause building heights to drop off as we move from the city center, this begs the question: what caused the building heights to rise again north of 14th Street?

To parse this out, we now turn to the demand side of height and focus on those elements that may drive office-based firms to demand tall buildings further away from downtown. Let’s now assume that there are two kinds of externalities facing firms. First assume there are positive benefits from office-based firms being close to each other. These include knowledge spillovers and reduced communication costs. However, we can also assume that office-based

firms do not want to be near certain kinds of economic activity. In particular, we can assume that being close to factories and low-income neighborhoods provides a negative effect on firms for several reasons. First office-based firms draw their supply of labor mostly from educated white-collar workers. All else equal, firms would like to be closer to their labor force. But if there is a slum district nearby this may provide a barrier keeping white collar workers from residing near their workplaces. Secondly, being next to a manufacturing firm might increase its closeness to pollution and congestion and not project the right image for corporate businesses.

The standard Alonso-type land use model shows that there will be a natural segregation of economic activity, with office-based firms at the center, then manufacturing districts and their workers next, and then, finally, a wealthy suburban ring, with upper and middle class families who commute to the city center. Before 1890, this pattern of land use fit Manhattan quite well. But, if office-based firms seek to expand in a growing city, then they potentially can gain a wage cost reduction if they move closer to their workers. That is, say that there is a middle-class enclave around Madison Square Park (at 23rd Street and Broadway). A potential employee might be indifferent between accepting a lower wage and not having to commute or a higher wage and commuting downtown. This can create an exploitable opportunity for firms: by moving closer to their employees they can pay a lower wage (DiPasquale and Wheaton, 1996 pages 103-111; Moses, 1962). As such, the “great leap” may represent a movement toward a new spatial equilibrium, whereby firms move north to be near their workers; this movement then increases land values, as a new business district emerges. This, in turn, provides incentives for builders to build taller due to the relatively large fixed cost of land acquisition.

3.4.1 Wages and Agglomeration

Now we develop the model to include the effects of labor costs, to see how they affect height at various locations. Assume that office-based firms have a profit function as given by equation (1), but that wages are now given by $w(j) = w_0 + \alpha j$. That is, the wage paid at each location is a function of the marginal product of labor, w_0 , plus an additional component that is the compensation for commuting costs, which are positively related to the distance from the

center; α is a measure of transportation costs.

The first order conditions give

$$\begin{aligned} r &= A(j) f_h(h, l), \\ w_0 + \alpha j &= A(j) f_l(h, l). \end{aligned}$$

These two equations can be solved for the demand for height and labor respectively (assuming the production function can be inverted, etc.) to give

$$h = h(A(j), r, w_0 + \alpha j), \tag{6}$$

$$l = l(A(j), r, w_0 + \alpha j). \tag{7}$$

Inserting the supply equation, eq. (4), into the demand equations (eqs. (6) and (7)), allows us to solve for the two equilibrium equations for labor and height, respectively. Since the height equation is primarily of interest, we then have

$$h^*(j) = h^*(A(j), \mathbf{c}, w_0 + \alpha j),$$

where \mathbf{c} is a vector of parameters that relate to the cost of construction, which include the marginal cost parameter for adding extra height, as well as the bedrock-cost parameters, if a skyscraper is completed.

In short, the equilibrium condition gives us testable predictions: the greater the agglomeration effects, the taller the heights of the buildings; the greater the costs of building (including the bedrock costs), the lower the equilibrium height. Further if capital and labor are substitutes, then increases in wages will increase heights. And, finally, an increase in transportation costs will also increase heights.

Wages and Locational Re-adjustments Now let's assume that because of population growth a firm can “jump” from location j to location $j' > j$, where a large fraction of potential workers reside, and pay a wage of w_0 at location j' (say around 23rd Street and Broadway in Manhattan) instead of $w_0 + \alpha j$ at location j . In other words, let's assume that

there is a critical mass of office workers living at and around location j' , such that firms do not have to pay workers for their commuting costs. If a growing population and reduction in transportation costs causes residential neighborhoods to emerge away from the center, then firms can potentially locate near their workers and pay lower wages. This could potentially set in motion the rise of a new office-based sector within the city.

First, in midtown, the quantity of labor employed will increase as wages fall. Initially, this will have a direct effect of decreasing equilibrium heights (no additional height would be added to the skyline). However, there would be a secondary effect. Assume that agglomeration economies are a function of the total labor at or near a particular location, such that agglomeration economies are given by

$$A(j) = A \left(\int_0^{\bar{j}} l^*(k) d(j, k) dk \right),$$

where $l^*(k)$ is the amount of labor at location k , $d(j, k)$ is the weighting function, based on the distance of k to j , with a greater weight for distances closer to j . Finally, \bar{j} is the edge of the city. Then as workers are hired in the new location, it causes agglomeration economies to increase. This, in turn, causes both the profit maximizing height and labor quantities to increase as well; this then generates a new business district with new skyscrapers. As in Fujita's and Ogawa (1982) model, the transition from a monocentric city to a duocentric city emerges when population increases or when transportation costs increase (which here would be interpreted as a rise in congestion at the city center).

4 Empirical Results

In the remainder of the paper we examine two new data sets that help us to investigate the effect of depth to bedrock on the creation of the Manhattan skyline. First we look at the effect of bedrock depths on skyscraper construction costs. Second, we look at the effect of bedrock depths on the location of skyscrapers. Below we give a brief discussion of each data set. More details are given in the Appendix.

4.1 Data

4.1.1 Construction Cost Data

We have created a data set with actual construction costs for 53 commercial buildings constructed in Manhattan between 1899 and 1915. Total cost and building volume data come from the cost job book of the Fuller Construction Company (housed at The Skyscraper Museum in New York City). Building heights come from either <http://skyscraperpage.com> or the *Atlas of the Borough of Manhattan* (1921). Along with the construction data we also measure the depth to bedrock at each building location. Specifically, bedrock depths relative to sea level were obtained from the “Rock Data Map Of Manhattan” provided by Dr. Klaus Jacob of the Lamont Observatory. The map provides bedrock depth data for specific locations based on geological borings. For most large buildings in our data set the Rock Data Map provides depths for the exact building lot (since borings and measurements were commonly taken during the construction process). In the case of a missing data point on a specific block, an arithmetic average of the surrounding data points has been used. The depth to bedrock measure used in this paper is determined by subtracting the depth to bedrock relative to sea level from the elevation relative to sea level.¹² We control for the costs of construction over time by using the real value of brick costs in New York City at the time of construction, which comes from the *Historical Statistics of the United States*. Costs were normalized so that the year 1896 had a value of 1.0. With this data set we are able to explore the effect of depth to bedrock on the actual construction costs of these large building projects in New York City at the time of interest.

4.1.2 Skyscraper Location Data

In order to investigate the effect of bedrock on the placement of skyscrapers, we have collected depth to bedrock and other relevant economic information on 173 locations in Manhattan. The locations are chosen in the following manner. First, we locate all buildings constructed in New York City 80 meters or taller between 1890 and 1915. We have found that there were 74 buildings meeting this criteria. The building data comes from <http://skyscraperpage.com>

¹²Elevation, longitude and latitude are found via the Google-based software tool DigiPoint2 (<http://www.zomums.com/gmaps/digipoint2.html>). Elevation is relative to sea level.

and/or <http://emporis.com>. For each building, these websites provide the year of completion, the number of floors, and the height. The number of floors was additionally checked against the *Atlas of New York City, Borough of Manhattan* (1921). Information about the location and whether they were the headquarters for a firm comes from historical articles about each building in the New York *Times*.

As a comparison/control group we also selected 99 additional random locations in Manhattan south of Central Park/59th Street. The random locations were chosen in the following manner. Each city block in Manhattan is assigned a unique tax block identification number. We randomly chose 99 city block numbers south of 59th Street using a standard random number generator. (There are approximately 1500 tax blocks below 59th Street.) For each block selected we then randomly chose a lot on the block. The block number and the lot for the skyscraper group are obtained through the NYC Map Portal (<http://gis.nyc.gov/doitt/mp/Portal.do>). This yielded a total of 173 locations in Manhattan south of Central Park. Again, the non-skyscraper lots were checked with the *Atlas of New York City, Borough of Manhattan* (1921) to confirm that no skyscrapers existed on these lots.

For each of the 173 locations we then collected several variables of interest. We collected the depth to bedrock using the same manner described in the construction cost data. In addition, as a robustness check we consulted bedrock depth maps created by the U.S. Geological Survey: “Bedrock And Engineering Geological Maps Of New York County.” The second map provides information in the form of contours for the bedrock surface, with contour intervals of 20 feet. For the probit regressions, depth to bedrock is taken as an average of the depths from the first and second maps.¹³

In addition we have collected data for several variables that may also affect the probability of skyscraper construction at a location. We also have collected demographic information at several geographic levels. By 1890, New York City was divided into Wards, Sanitation Districts (SDs) and state Assembly Districts (ADs). Wards contained one or more SDs (see

¹³The two maps and methods yield very consistent results. The correlation between the two maps/methods is 0.94. In addition, as reported above, we use the average of the two methods in our empirical results below. We note that our empirical results do not significantly change if we use one map or the other independently, or the average of the two.

Table 4 for the average sizes of the districts).

From Pratt (1911), we have AD data for manufacturing worker density. The Census Bureau’s *Vital Statistics of New York and Brooklyn Covering a Period of Six Year Ending May 31, 1890* provides population density, racial demographics and park space information at the SD level. We hypothesize that white collar firms would have an incentive to avoid locating in districts with large numbers of minority or recent immigrant populations, which tended to be lower income districts. We also expect that white collar firms avoided districts where manufacturing firms commonly located and districts that had large numbers of manufacturing workers (as opposed to white collar workers). Park space would be important for skyscrapers for two reasons. First, presumably the more park space the higher the quality of the neighborhood, *ceteris paribus*, and thus the more attractive to white collar workers; second, for the first generation of skyscrapers, access to sunlight was very important, and park space or cemetery space near a building would ensure greater light availability.

Access to public transportation, especially rapid transit, is likely to be a benefit to firms. We counted the number of elevated railway stops within a half-mile radius from each location in our data set from the 1890 Elevated Railway Map of New York (Landers, 2000).¹⁴ We calculated the distance to New York City’s “financial district” (the intersection Wall Street and Broadway) from each location in our data set using the latitude and longitude of each location address. We expect that since this location is the center of commercial and financial activity (which emerged in the early 19th century), a shorter distance will increase the likelihood of a skyscraper being constructed. This may be thought of as a rough proxy for agglomeration benefits.

Lastly, land values are likely to be a determinant of skyscraper activity. As land values increase, holding square footage or volume constant, builders have an incentive to build a taller building on less land instead of a shorter building on more land. Thus skyscrapers are more likely when land values are high. We collect information on the land values from “Tentative Land Value Maps of the City of New York” (1909). Land values are given per foot

¹⁴Note that the New York City subway first opened in 1904. The first line ran from City Hall, up the east side of Manhattan to Grand Central Station, then west along 42nd Street to Times Square, then north along Broadway. Its initial route therefore tended to reinforce or invigorate the commercial centers that were starting to form along 42nd Street.

of street frontage. Note that “land values” are only the value of the land; they exclude the value of improvements. For each location in the data set, average land values are calculated for the block on which the location resides.¹⁵

4.2 The Effect of Depth to Bedrock on Skyscraper Construction Costs

We first discuss the effect of bedrock on construction costs. Table 2 provides the descriptive statistics of the variables contained in the construction cost data set described above. Table 3 presents the results of regressions of the log of total costs on several important variables. Equation (1) in Table 3 includes the depth to bedrock, the building height, the building volume, an index of brick costs in New York City, and an interaction term between the building height and the depth to bedrock. Equation (2) in Table 3 includes an interaction term between the building height, the depth to bedrock and a dummy variable that takes on the value of one if the building is a skyscraper (18 floors or greater), and a zero otherwise. Since bedrock should have the most important effect for a tall building, we interact the depth to bedrock with a skyscraper dummy variable. Presumably a taller skyscraper is even more sensitive to bedrock depth than a “marginally” tall skyscraper. In equation (3) we include the bedrock depth interacted with a skyscraper dummy variable (but not height). In equation (4) we interact the bedrock variable with a downtown dummy variable (south of 14th Street) because downtown the bedrock is generally further down and the subsoil is often wet and comprised of quicksand.

All four specifications give very similar results. We see that the bedrock terms are all significantly different from zero in all specifications. However, the signs on the bedrock terms are more complicated than expected. Deep bedrock, on its own, actually lowers the cost of construction. Presumably this is because having bedrock too near the surface is actually a hinderance to clear space for a foundation. One may have to remove bedrock to build a foundation in some cases. But, if building a skyscraper of sufficient height, deep

¹⁵There is likely to be an endogenous relationship between land values and the presence of skyscrapers, since the land value data is from 1909. Ideally, we would like to have land value calculations for a period prior to initial skyscraper construction, such as 1890, but this data were not available. We include it in our regressions for the sake of comparison, despite the possible endogeneity.

Variable	Mean	Std. Dev.	Min.	Max.
Building Height (stories)	15.43	6.04	3.00	32.00
Bedrock Depth (meters)	14.56	9.61	0.276	51.7
Total Construction Costs (\$000)	1,282.8	1,456.5	117.3	7,568.8
Building Volume (000 cubic feet)	3,151.0	3,202.8	292.5	18,200.0
Real NYC Brick Costs (1896=1.0)	1.012	0.180	0.79	1.40
Skyscraper Dummy	0.434			
Downtown Dummy	0.679			

Table 2: Descriptive statistics for 53 buildings constructed in Manhattan from 1899-1915. Note that brick costs statistics are based on annual time series data. Sources: see Appendix.

bedrock does increase costs as expected. In equation (1), the sum of bedrock depth and the interaction of bedrock depth with building height yields a net increase in construction costs if the building is greater than about 21 stories. If we consider estimation (2), with the height-skyscraper interaction, then for a building of approximately 20 stories or taller, bedrock becomes a net cost. As an extreme example, the tallest building in our cost data set (32 stories) would produce a net coefficient of 0.0071. This would equate to an increase in total construction cost of about \$9,000 for each additional meter of depth to bedrock. If we consider a one-standard deviation change in depth to bedrock from the average (9.61 meters) we get slightly more than a \$90,000 (7%) increase in total building costs for this skyscraper. For a less extreme example, consider a building of 21 stories (the median skyscraper in our data). In this case, each additional foot in depth to bedrock would result in about \$650 in additional building costs. A one standard deviation change in depth to bedrock would result in about \$6,000 of additional building costs (less than a 1/2% increase in total building costs on average).

Recall that in Figure 2 land values varied, on average, by about \$6,000 per linear foot of frontage between the financial district and the bedrock valley zone. Specifically, average land values per foot of street frontage were \$7,223 south of City Hall, \$927 between City Hall and 14th Street, and \$2,354 north of 14th Street. The average plot size for a skyscraper in our data set is just over 25,000 square feet (about 160 feet²). If we assume 160 feet of frontage for a skyscraper and multiply this by the land values per foot, we get the following land value estimates for a skyscraper lot in each area of interest: \$1,155,000 south of City Hall, \$148,300 between City Hall and 14th Street, and \$376,000 north of 14th Street. Next

Dep. Var.: Ln(Total Cost)				
	(1)	(2)	(3)	(4)
Bedrock Depth	-0.0125 (2.32)*	-0.0121 (3.67)**	-0.0124 (3.59)**	
Bedrock×Downtown				-0.0117 (3.61)**
Height	0.0278 (2.91)**	0.0257 (3.40)**	0.0282 (4.23)**	0.0300 (4.63)**
BR Depth×Height	0.0010 (1.31)			
BR Depth×Skyscraper			0.0124 (2.53)*	0.0130 (2.62)*
BR Depth×Height×Skyscraper		0.0006 (2.33)*		
ln(Building Volume)	0.8597 (17.86)**	0.8579 (18.36)**	0.8564 (18.4)**	0.8380 (17.15)**
Brick Costs _{t-2}	0.9841 (3.57)**	0.9837 (3.62)**	1.0051 (3.87)**	1.077 (4.09)**
Constant	-0.3282 (0.39)	-0.2734 (0.39)	-0.3015 (0.44)	-0.1786 (0.26)
R^2	0.925	0.928	0.928	0.931
\bar{R}^2	0.9166	0.9206	0.9212	0.9231

Table 3: 53 observations. Robust t-statistics below coefficients. *Stat. sig. at 95% level; **Stat. sig. at 99% level.

consider the average depth to bedrock in each of these three regions: 22 meters south of City Hall, 26 meters between City Hall and 14th Street, and 7 meters north of 14th Street.

If one additional meter of bedrock increased costs by about \$9,000 (as reported above), then constructing a skyscraper on the average lot in the bedrock valley was only \$36,000 more expensive (since the bedrock is four meters deeper on average) compared to south of City Hall. But the lot is less expensive by more than \$1,000,000 in the bedrock valley vis a vis south of City Hall. Thus even taking into account the additional costs of deeper bedrock, the total cost of constructing a skyscraper in the financial district is far more expensive once land values are included. A developer would save substantial sums of money by buying a lot in the bedrock valley at a much lower price and paying the additional costs of digging to the bedrock. Note that this would be true even if one had to pay additional bedrock costs of the maximum depth of bedrock in our data 46 meters (46 meters x \$9,000 = \$414,000; still well below the difference in lot acquisition).

In addition, building a skyscraper north of 14th street would save 19 meters of digging to bedrock compared to the bedrock valley for a savings of $19 \times \$9,000 = \$171,000$. Again,

the savings in terms of bedrock costs are smaller than the difference in the value of land between the two areas.

Even though deep bedrock had the potential to increase the costs of construction, these costs were small compared to differences in the land acquisition costs. Thus the idea that the costs of digging to bedrock prohibited the construction of skyscrapers in the bedrock valley is unjustified. Because of lower land prices, skyscrapers could have been built in the bedrock valley at total costs less than they were built in other areas of Manhattan. The fact that builders were willing to build on these other lots suggests that other explanations are more plausible for the lack of skyscrapers in the bedrock valley, namely, agglomeration externalities, and other economic and demographic factors which we explore next.

4.3 The Effect of Depth to Bedrock on Skyscraper Location

Because we are interested in whether the bedrock or other variables influenced the spatial distribution of tall buildings, we perform a probit analysis, which estimates the probability of a skyscraper (versus non-skyscraper) being built at a particular location as a function of several variables, including the distance from the city center (specified as the distance in kilometers from the corner of Wall Street and Broadway), the depth to bedrock, the land price (from the 1909 Land Value maps), population density for each sanitation district (in 1890), manufacturing worker density for each Assembly District (in 1906), the percent of each sanitation district's residents that are white with two native parents, the percent black and the percent foreign, the number of hectares of park space (and cemetery space) and the number of elevated railway transit stops within a half mile radius of each building (in 1890). Table 4 gives the descriptive statistics of these variables; Table 5 gives the results of various specifications.

Generally, as can be seen from Table 5 the coefficients have the expected signs. The likelihood of a skyscraper being built decreases with the depth to bedrock (though is not significantly different from zero, and is not robust across specifications), the distance to the city center of Wall Street and Broadway, and in the density of manufacturing workers in the area. The probability of a skyscraper increases in the number of transit stops and with higher land values. The probability of a skyscraper being built is positively related to the

Variable	Mean	Std. Dev.	Min.	Max.
Skyscrapers	0.43			
Building height (stories)	15.03	10.5	2	55
Avg. bedrock depth (meters)	17.07	12.0	-1.19	47.01
SD Area (hectares)	32.2	8.80	10.5	47.3
SD Pop. Density excluding Parks/Cems.	394.1	332.2	30.2	1386.3
SD Park and cemetery space (hectares)	0.898	2.16	0.00	9.7
SD % Pop. white with both parents native	21.8	13.3	3.36	50.63
SD % Population foreign	43.1	8.12	22.0	63.8
SD % Population black	2.66	3.16	0.026	18.4
AD Area (hectares)	148.9	78.0	39.7	466.6
AD Factory worker density (per hectare), 1906	205.4	185.1	3.68	751.9
Avg. Land values (\$ per foot of frontage), 1909	3,122	3,879	285	16,900
# El Stops within 1/2 mile radius	6.53	3.05	0	13

Table 4: Descriptive statistics. # obs. is 173. All data from 1890, except where otherwise noted. Sources: see Appendix. Note: SD, AD means are weighted based on # of buildings in these areas.

percent of native whites in the neighborhood. Also, the amount of park space is positively related to the probability of a skyscraper being built in that neighborhood.

In addition, to parse out possible bedrock effects, in Table 5, equations (2) and (6), show the results of regressions where the bedrock variable is split into two variables: the depth of bedrock interacted with a dummy variable if the bedrock is below sea level and the depth of bedrock interacted with a dummy variable if the bedrock is above sea level. Presumably, if the bedrock is below sea level digging down to it would be more difficult since it would be more likely to contain wet soil or quicksand. From these regressions, however, there is no effect from the bedrock that is below sea level, while we see a positive effect from the depth to bedrock above sea level indicating that deep bedrock is conducive to building a skyscraper. The reason for this counter-intuitive result is most likely due to the fact that the bedrock above sea level is also very close to the surface, or perhaps above the surface in some cases; and the closer it is, the more likely the bedrock becomes a nuisance because it has to be removed via blasting in order to lay a foundation. This concurs with our total cost regressions which show a negative cost effect for bedrock when a non-skyscraper is being built.

Land prices are most likely endogenous, but we include them in equation (5) to investigate their possible effects. The results must be interpreted with caution. As we can see, land

	(1)	(2)	(3)	(4)	(5)	(6)
BR Depth	-0.005 (2.53)*		-0.0004 (0.342)	$1.3e - 07$ (0.03)	-0.0007 (1.97)*	
BR Depth \times ($<$ Sea Lvl)		0.0004 (0.16)				-0.0002 (0.56)
BR Depth \times ($>$ Sea Lvl)		0.035 (2.87)**				0.003 (2.11)*
Pop. Density per SD			-0.00005 (2.17)*	$-1.2e - 06$ (3.36)**	0.00001 (0.82)	-0.00005 (2.08)*
% SD Res. White Native			0.0016 (3.93)**		0.0006 (1.35)	0.001 (3.31)**
% SD Residents Black				0.00004 (2.96)**		
% SD Residents Foreign				-0.00002 (2.26)*		
AD Worker Density, 1905			-0.00015 (4.14)**	$-2.8e - 06$ (3.59)**	-0.00008 (2.47)*	-0.0001 (3.26)**
# El Stops			0.005 (3.54)**	0.003 (2.85)**	0.001 (2.94)**	0.004 (2.67)**
Park and Cemetary Space			0.004 (3.68)**	0.00008 (4.72)**	0.004 (2.51)*	0.003 (3.30)**
Distance to Wall & BWay			-0.011 (3.02)**	-0.0001 (2.47)*	-0.007 (2.39)*	-0.012 (3.76)**
ln(Land Values), 1909					0.025 (4.15)**	
psuedo-R ²	0.025	0.071	0.593	0.612	0.744	0.619
psuedo-Log Likelihood	-78.5	-74.8	-32.8	-31.2	-20.7	-30.7

Table 5: Probit: Dep. Var: Skyscraper=1; no skyscraper=0. Marginal effects are reported. z-statistics below marginal effects. *Stat. sig. at 95% level; **Stat. sig. at 99% level. The regression was run with weights that were the inverse of the building height, to account for the over-sampling of skyscrapers in the data set.

prices are perhaps the most important factor in the location of skyscrapers. Also there may be some concern that our measure of factory workers in each assembly district is endogenous for some years. However, most factories in these districts were established before 1890 and therefore strongly correlate with past decisions about land use. Thus the presence of factory workers is likely to be exogenous to the presence of skyscrapers constructed after 1890.

To investigate the magnitude of the effects, we also present the elasticities of the independent variables with respect to the probability of a skyscraper being built at a specific location for specifications (3), (5), and (6). We find that there are several almost equally important factors in the likelihood of building a skyscraper. The most important factors are the land prices, density of manufacturing workers, the access to public transportation, the percent of white native residents and the distance to the financial district center at Wall Street and Broadway. But, the depth to bedrock has one of the smallest magnitudes of the

	(3)	(5)	(6)
BR Depth	-1.00 (0.90)	-2.54 (1.79)	
BR Depth x Below Sea Level			-0.574 (0.55)
BR Depth x Above Sea Level			0.796 (2.10)*
Pop. Density per SD	-3.31 (1.84)	-2.04 (1.35)	-3.77 (1.71)
% SD Residents Native White	4.02 (3.09)**	2.04 (1.35)	3.47 (3.01)**
AD Worker Density, 1905	-4.12 (3.11)**	-3.15 (2.21)*	-4.16 (2.50)*
# El Stops	3.82 (3.31)**	4.45 (2.20)*	3.00 (2.54)*
Park and Cemetary Space	0.254 (3.13)**	0.177 (1.48)	0.241 (2.78)**
Distance to Wall St and Broadway	-4.84 (2.45)*	-4.20 (2.20)*	-6.22 (2.96)**
ln(Land Values), 1909		32.5 (3.31)**	

Table 6: Elasticities of coefficients from probit regressions, given in Table 5. Absolute value of z-statistics below estimates. *Stat. sig. at 95% level; **Stat. sig. at 99% level.

factors. Again, the results do not indicate that the depth to bedrock is a “smoking gun” that solely determined the landscape of skyscrapers in Manhattan as the folklore suggests.

4.3.1 Isolating the Effect of Bedrock on Skyscraper Location

We now perform two counterfactual exercises in order to isolate the effect of bedrock on skyscraper location. In the first, we examine the predicted skyline if bedrock is held constant across the city. In the second, we examine the predicted skyline if bedrock is the sole determining factor for skyscraper location.

In the first exercise, we remove the bedrock variable from the regression and then rerun the regression to get predicted values (we use equation 3 from Table 5). We show the results of this exercise in Figure 9. As can be seen in the figure, there is still expected to be an absence of skyscrapers in the middle latitudes of the city (the previously described bedrock valley) even if we remove the effect of bedrock from the regression.

We display the change in probability between the estimated model and the depth to bedrock held constant model in Figure 10, i.e., \hat{p} (“full” reg. w/o B.R.) $- \hat{p}$ (“full” reg.). Again, the full regression is eq. (3), from Table 5. The first thing to notice is that the

change in probabilities is generally very small. The largest change is 11% in absolute value. However, if bedrock were not a factor, we would predict a small shift of skyscrapers from very far downtown to the area around City Hall. This suggests that bedrock depths may have influenced the placement of skyscrapers within the downtown business district; bedrock may have shifted skyscrapers from the northern part of the financial district to the southern part. However, and more importantly, there is virtually no change in the probabilities where the bedrock is the deepest; those are the districts with large foreign populations and with a high degree of manufacturing concentration. If bedrock was a strong determinant of skyscraper completions we would expect much larger changes in the predicted probability in the deep bedrock areas.

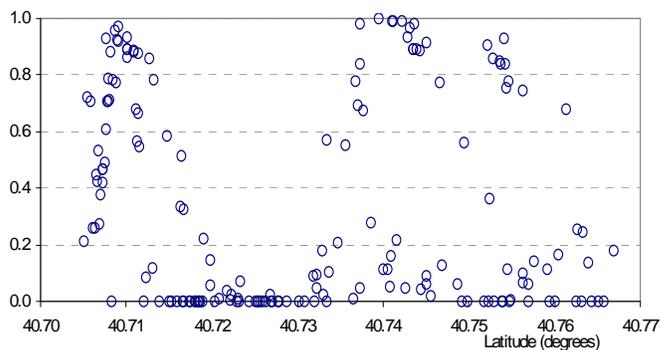


Figure 9: Predicted probability of a skyscraper as a function of latitude, holding bedrock depths constant.

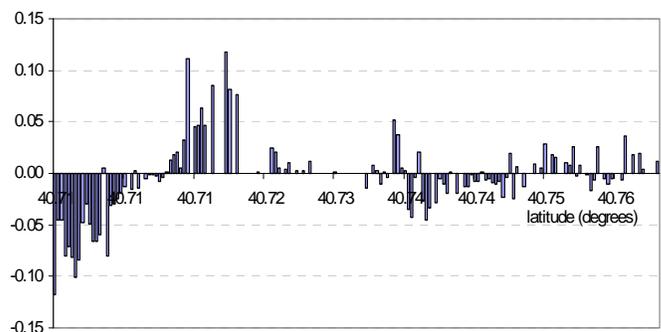


Figure 10: Difference between predicted values with bedrock depth variation versus predicted values with constant bedrock depth ($\hat{p}_{NoBR} - \hat{p}_{BR}$).

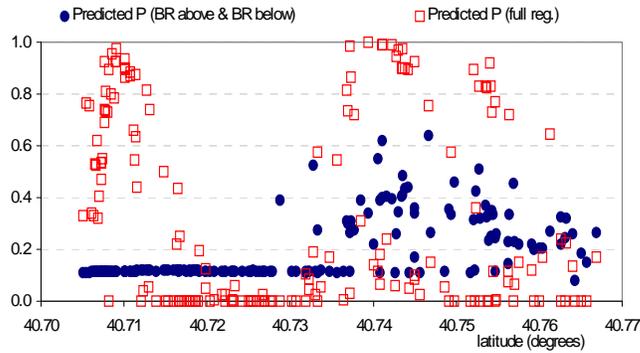


Figure 11: Predicted values for a full regression (Eq. 3, Table 5) versus predicted values for regression with just two bedrock/sea level interaction terms (Equation 2, Table 5).

For the second exercise, we contrast the predicted values of the “full”probit (Equation 3, Table 5) to the predicted values from the probit results of Equation 2, Table 5, which only has two variables: the depth of bedrock interacted with below and above sea level dummies. Equation 2 should be thought of as the “bedrock only model” of skyscraper location. Figure 11 shows a scatter plot of the predicted values from these two estimations. The squares are the predicted values of the “full” probit (Equation 3, Table 5) and the circles are the predicted values from the probit results of the bedrock only estimation (Equation 2, Table 5). As shown in the figure, a bedrock only model would predict essentially no skyscrapers below latitude 40.73 (roughly 14th Street), i.e., no skyscrapers in the bedrock valley *and* no skyscrapers in the financial district south of City Hall. That is to say, for all buildings where bedrock is below the surface, because the estimated coefficient is so small, we see essentially no bedrock effect whatsoever. On the other hand, where bedrock is above sea level we see more accurate predicted values. To summarize, even if bedrock was the sole determining factor for the skyline, the skyline would have developed much differently than it did. There would have been only one skyscraper district north of 14th street; the high skyline in the financial district would not have existed. This also suggests that there was no “tipping point” effect in the development of the midtown business district.

5 Conclusion

This paper has investigated the degree to which Manhattan’s geology has affected the spatial distribution of its skyscrapers. We focus on the first generation of skyscrapers from 1890 to 1915, prior to the implementation of zoning regulations. The objective of this work has been to estimate the degree to which the depth to bedrock on the island channeled skyscraper development to areas where bedrock depths were relatively close to the surface—south of City Hall and north of 14th Street.

We have collected two types of data sets to investigate this question. First we look at how these depths have affected construction costs for several large commercial buildings completed between 1899 and 1915. We find that bedrock depths only had a positive effect on costs for buildings greater than 20 stories, but the costs did not add more than 7% to the total construction costs *and were far smaller than land acquisition costs*.

Next we investigate the probability of a skyscraper being built at any given location south of 59th Street as a function of bedrock depths and several other economic variables, including access to public transportation, land values, population density, manufacturing worker density and the distance to a pre-established center of commerce (the financial district). We find that the economic and demographic factors—agglomeration and transportation effects as well as population densities—far outweigh the effect of bedrock depths on the location of skyscrapers. In short, our results support the theory that the polycentric nature of Manhattans skyline is a result of a spatial equilibrium readjustment rather than from geological considerations. That is, the evidence suggests that builders “jumped” over manufacturing and tenement districts, in order to create a new business district that was near white collar “suburban” residents, who were moving northward on Manhattan island throughout the 19th century.

One area for further investigation is the historical location of the slum and manufacturing districts that the skyscraper developers chose to avoid. As mentioned above, these districts are highly correlated with deep bedrock in Manhattan. Areas with bedrock nearer to the surface tend to have better drainage and are less swampy as a result, potentially making them less desirable residential and white collar locations. Thus, while we find strong evidence that

bedrock played no direct role in the location of skyscrapers in late 19th and early 20th century New York, there may have been some indirect geological influence from earlier centuries. In addition, further work can explore how New York City's spatial demographics were changing over the 19th and early-20th; this would shed light on residential patterns of different types of workers and skills.

A Appendix: Data Sources and Preparation

Skyscrapers: The skyscrapers are all buildings listed as 80 meters or taller and completed between 1890 and 1915 on www.skyscraperpage.com and/or www.emporis.com (as of June 2008). These websites generally provided the number of floors, and height in feet or meters. www.skyscraperpage.com generally provides addresses. Missing addresses were found via searches on www.google.com. The number of floors was also checked against *Atlas of New York City, Borough of Manhattan* (1921). Information about location and whether they were a headquarters or not comes from historical articles about each building in the *New York Times*.

Non-skyscrapers: First we randomly chose 100 city blocks south of 59th Street (each block has a city tax block id #, which ranges from approximately 1 to 1500 below 59th Street.) One observation was deleted because it was not below 59th Street. This gave us 99 randomly chosen city blocks. The block and lot numbers were obtained from the NYC Map Portal (<http://gis.nyc.gov/doitt/mp/Portal.do>). The block numbers for the non-skyscraper group were randomly generated and the lots are randomly chosen once the block was identified.

Elevation, Longitude and Latitude: Google maps-based software tool from Zonum Solutions - DigiPoint2. Elevation is relative to sea level.

Depth to Bedrock: Bedrock depths relative to sea level were obtained from two sources (1) “Rock Data Map Of Manhattan” provided by Dr. Klaus Jacob of the Lamont Observatory and (2) “Bedrock And Engineering Geological Maps Of New York County,” from the US Geological Survey. The first map provides bedrock data for specific locations based on borings. For the skyscrapers group it provides data for the exact building lot for the most of the observations. In case of a missing data point on the specific block, an arithmetic average of the surrounding data points has been used. The second map provides information in a form of contours of the bedrock surface, with contour intervals of 20 feet. Again averages were taken as necessary. Depth to bedrock in the paper is determined by subtracting the depth to bedrock relative to sea level from the elevation relative to sea level.

Land Values (1909): “Tentative Land Value Maps of the City of New York” (1909). Land values are given per linear foot of frontage. The land values in Figure 2 are calculated as follows. For each building in the data set, average land values are calculated for the block on which the building resides. Next the buildings are sorted from south to north. A moving average (of 5) is calculated by averaging the land values of the two buildings south of it, the land value of the building itself, and the two north of it.

Assembly District Manufacturing Density (1906): from Pratt (1911), Table 15.

Sanitation District Data (1890) from *Vital Statistics of New York and Brooklyn Covering a Period of Six Year Ending May 31, 1890*. Census Bureau.

Number of Elevated Railroad Stops with a half mile radius (1890). Elevated railroad map of New York, Map #4 from Landers (2000).

Construction Cost Data: Total cost, building volume and project developer name data are from the cost job book from the Fuller Construction Company. The data is archived at the Skyscraper Museum. Building addresses were located via historical articles in the *NY Times* or from building permit information from www.metrohistory.com. Building heights were from either www.skyscraperpage.com or the *Atlas of the Borough of Manhattan* (1921).

Real Brick Costs: New York City Brick Cost Index is from the *Historical Statistics of the United States*. The brick costs were then divided by the value of the GDP deflator. Costs were normalized so that the year 1896 had a value of 1.0.

New York City Population North of 40th Street: New York census and ward data come from <http://www.demographia.com/db-nyc-ward1800.htm>

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