

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

Jason Barr[†]
Rutgers University, Newark
jmbarr@rutgers.edu

Troy Tassier
Fordham University
tassier@fordham.edu

Rossen Trendafilov
Fordham University
trendafilov@fordham.edu

July 30, 2010

Abstract

Skyscrapers in Manhattan must 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 bedrock is close to the surface in these locations, with a bedrock “valley” deep below the surface 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. We find that bedrock depths had very little influence on the creation of separate business districts; rather its poly-centric development was due to residential and manufacturing patterns, and public transportation hubs. We do find evidence, however, that bedrock depths influenced the placement of skyscrapers within business districts.

Key words: skyscrapers, geology, bedrock, urban agglomeration

JEL Classifications: D24, N62, R14, R33

*We thank Gideon S. 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.

[†]Corresponding author.

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

In the late-19th century, a set of technological innovations allowed for the construction of skyscrapers. Relatively light but high-strength steel beams obviated the use of heavy and 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.¹ Ideally, a skyscraper should be anchored to the bedrock to prevent (possibly) uneven settling.

In lower Manhattan, where the demand for New York's skyscrapers first existed, access to the bedrock was often limited or difficult because of its depth below the surface, the highly varied nature of the subsoil, the presence of subterranean rivers, and the limited knowledge of the underground terrain in general (*New York Times*, 1907; *Building and Record*, 1912).² In some areas, the subsoil contained quicksand, other areas had dry sand and clay, and boulders were randomly distributed throughout the subsoil. Engineers could perform test borings, but because both the subsoil conditions were highly variable and the depth to the bedrock was also highly uneven, these borings would often produce incomplete information and problems would arise during the actual foundation preparation work.

Builders faced considerable economic and physical constraints in this regard. While high land values in lower Manhattan created the incentive to build tall as a way of "making the land pay" (Gilbert, 1900, p. 643), engineers had to first solve these foundation problems. Builders could not simply dig their way to bedrock because wet soil might flow out from beneath surrounding buildings causing those buildings to sink, while filling the construction sight with the mud (*New York Times*, 1897; Semsch, 1908).

The very first skyscraper developers solved this problem by using wood pilings pounded into the ground (Landau and Condit, 1996). As long as skyscrapers were less than about 20 stories (85 meters) and the subsoil was not wet or varied, this was

¹Disregard for geology can have big consequences. For example, important structures in Mexico City 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 (though, ironically this seems to have been a net benefit to humankind due to its appeal as an architectural curiosity). In Chicago deep and uneven building settlement was a major concern; for some early tall buildings, settlement of a foot or more was not uncommon (Peck, 1948).

²The Sanitary and Topographical Map of the City and Island of New York prepared under the direction of Egbert L. Viele (1865) remains an important guide to builders about the locations of Manhattan's underground waterways. (Kurutz, 2006)

a feasible solution (see Kidder, 1909). But the economic and promotional benefits of skyscrapers soon created the demand for even taller buildings, which made pilings an inadequate solution. At that point, engineers had to dig down to the bedrock to anchor the buildings; the solution to reach bedrock was the pneumatic caisson. However, even this method was not easy, as they often sank or “ran away” in the wet subsoil (*Building and Record*, 1912), and the danger of fire or explosions within the caisson were ever present (*New York Times*, 1904).

A 1912 article entitled “Recent Problems in Pneumatic Foundation Setting” in the *Record and Guide* which chronicles many of the difficulties encountered in skyscraper foundation work writes, “Builders sometimes ask why foundation work costs so much in New York. The answer is: The risk is so great no matter how well trained the units of a foundation company’s working organization may be, mistakes are sure to happen at times. No matter how carefully the site may have been bored, boulders or quicksand are liable to appear....All perilous work is expensive, because men of robust physique and of sufficient bravery hourly to risk death are hard to find” (p. 933).

Thus the ease with which developers were able to reach bedrock to anchor skyscrapers had the potential to greatly impact the cost of skyscraper construction and the placement of skyscrapers within the city. Across the island as a whole, access to bedrock varies greatly. It has been argued that this access affected the pattern of skyscrapers we see today.

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 because either digging to bedrock or creating new and elaborate foundation technologies were too costly relative to other locations within the city where bedrock was near the surface.

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).³

Though there are a few people who have provided dissenting opinions on the matter (such as Landau and Condit (1996) and Marshall (2007)), this story has become a New York legend and is deeply embedded in the historiography of the city. However, it has never been empirically tested. We study the effect of depth to bedrock on the cost and spatial distribution of the earliest group of skyscrapers in Manhattan, 1890-1915, using

³Evidently, Schubert’s words sparked the widespread belief that bedrock depths have determined the skyline. We thank Gideon Sorkin for providing the source of this belief.

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 empirically measured the effect of bedrock on the location of buildings in the Manhattan skyline. More broadly our work aims at providing some evidence as to why New York has two separate and distinct highrise districts, rather than one long continuous one.

In order to investigate the role of bedrock 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 significantly increase construction costs for these projects; but the costs associated with deeper bedrock were small relative to the overall construction costs of a skyscraper, and relative to the land values of building lots across the city.

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 all 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 suggests that the poly-centric 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 at acceptable cost. That stated, we do find evidence that the depths to bedrock did affect the location of skyscrapers within the different business districts. In summary, it appears that the effect of bedrock was strong enough to influence the local placement of skyscrapers within a business district, but not strong enough to determine the business districts themselves.

1.1 Related Literature

Though our work is the first to explore the effect of geology on the Manhattan skyline, other works have explored how geology may affect the returns from worker density (Rosenthal and Strange; 2008; 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 had 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, at least in Manhattan for the period that we study.

However, geology can affect urban spatial structure in other ways. Burchfield, et al. (2006) demonstrate how geological features, such as mountains or aquifers, can enhance or diminish urban sprawl. Thus it still remains an open question how geology can effect the spatial distribution economic activity. The above papers provide evidence that geology can matter, but the more important question relates to how these geological features affect the relative cost and benefits of land use. Our work shows that in the case of skyscrapers in New York, despite the large costs they imposed in absolute value terms, their relative costs were low compared to the benefits of overcoming geological constraints.

The evidence presented here suggests that the poly-centric nature of Manhattan emerged out of a natural economic process of subcenter formation due to the construction of elevated railroads and the northward movement of the population along the island of Manhattan. While Fujita and Ogawa (1982) and Helsley and Sullivan (1991), for example, present models of 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 wide-spread use of the automobile (Glaeser and Kahn, 2004). The evidence here suggests, however, that poly-centric urban development is a much earlier phenomena, emerging in the late-19th century in New York (which concords with Jackson’s (1987) findings).⁴

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.⁵ The following year Joseph Pulitzer’s

⁴As such, midtown Manhattan perhaps represents one of America’s earliest “edge cities” (Marshall, 2007; Garreau, 1991).

⁵The 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.

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

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

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. 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.⁶

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 skyscrapers, which ended in 1915.⁷ Table 1 provides some descriptive statistics about the skyscrapers in our data set. From 1890 to 1915 we have found that there were 74 skyscraper completions. The height of these earliest skyscrapers ranged 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, which 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.

2.1 The Location of Economic Activity in Manhattan

During the late-19th century, New York developed three “centers” as defined by land values and building heights. Figure 2 further illustrates the poly-centric nature of Manhattan in the early 20th century.⁸ The first center is that of lower Manhattan, with high land values and tall buildings between Wall Street and City Hall. Another center

⁶We can describe the relationship between stories and height via the OLS-derived equation: $\widehat{floors} = 0.173 + 0.235 \text{ meters}$, $R^2 = 0.89$, # obs.=74; robust standard errors below estimates. Source: See Appendix.

⁷In 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.

⁸Average 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.

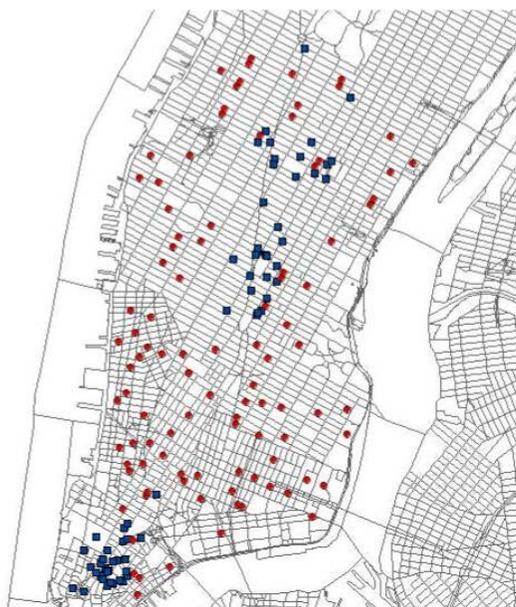


Figure 1: Skyscrapers and non-skyscrapers in Manhattan, 1915. Skyscrapers are blue squares and other buildings are circles. Sources: see Appendix.

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 is 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 of latitude 40.736° to 59th Street (Central Park) average land values were \$2,354.

Why did the business district not continue north of city hall and why did there emerge two smaller districts north of 14th street? Was it bedrock, as the folklore suggests, or did other factors, such as agglomeration and transportation costs or negative externalities caused by slums play a role? One can tell a story that supports either case (see Marshall, 2007). On one hand bedrock depths may have presented an obstacle. On the other hand, the area between 40.719° and 40.735° had a high concentration of tenement housing and factories, and was relatively under-served by public transportation. In

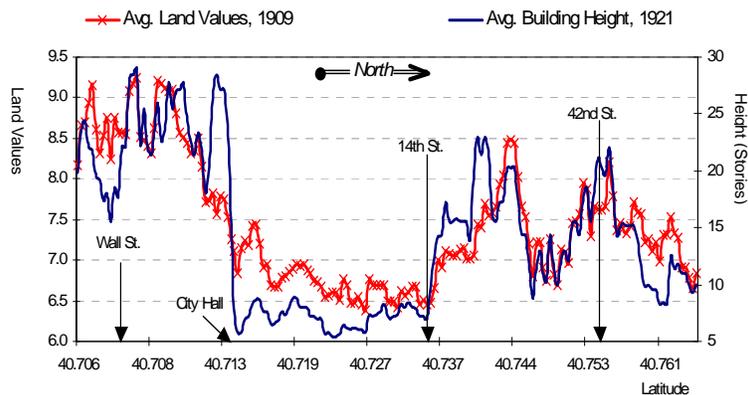


Figure 2: Natural log of average land values in 1909 and average building heights in 1921 versus degrees latitude in Manhattan. Sources: see Appendix.

addition, in 1871, New York City mandated that the NY Central Railroad complete its Manhattan terminus at 42nd Street, well above the area of dense economic activity, so as to reduce the amount of pollution and congestion in lower Manhattan. As Manhattan grew, this area became a natural focal point for economic activity. In addition, New York's population was steadily moving northward. Generally the wealthy and upper middle class households were on the vanguard of this northward movement as they fled encroachment by commercial activity in the more southern districts of the city. The first elevated railroads were constructed in the early 1870s, and thus lowered the cost of commuting to and from the northern areas of the city.

As Figure 3 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 business 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 residential spatial equilibrium.

Furthermore, Figure 4 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*.⁹ This correlation between foreign born residents and bedrock depth is most likely a coincidence,

⁹In 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.

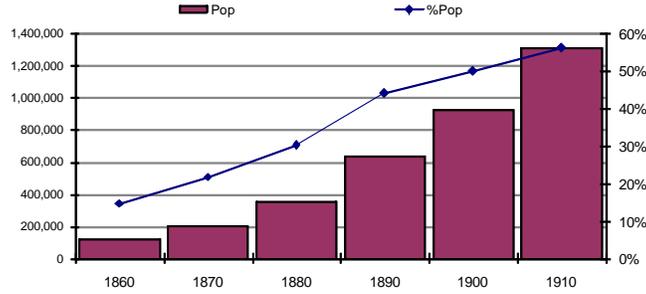


Figure 3: Manhattan population and percent of population living above 40th Street. Source: see Appendix.

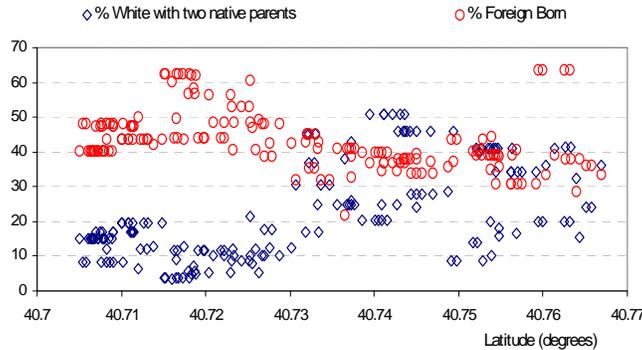


Figure 4: Percent foreign born and native white residents in the various sanitation districts in Manhattan. Sources: see Appendix.

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.¹⁰ In theory, the developers of skyscrapers may have had a disincentive to place tall buildings in these poorer neighborhoods.

Note, however, that the aim of this work is to explore the role of geology in the formation of the skyline, controlling for other economic factors. We do not directly explore the dynamics that gave rise to the growth of midtown as a separate commercial and office district. We leave this for future work. However, based on the evidence presented in this paper, we hypothesize that the northward movement of the upper and

¹⁰There 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 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.

middle class population promoted the incentives for businesses to move to be closer to the population.¹¹ This also created transportation hubs in midtown, which further promoted business growth in this area. Presumably the clustering of business then generated agglomeration benefits, which further bid up land values and created the incentives for skyscrapers to emerge.

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).¹²

Figure 5 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 5 also indicates the location of skyscrapers throughout Manhattan south of Central Park. The triangles are locations of the 74 skyscrapers 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.

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 5 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 constructed on bedrock that was 40 meters below the

¹¹For example, in 1890 the *New York Herald* moved its headquarters from across from City Hall (“Newspaper Row”) to Sixth Avenue and 35th Street. The *Record and Guide* (1890) reported, “The idea of moving the office up town is to be more centrally situated for local news” (p.-). In 1904, the *New York Times* also left Newspaper Row and moved to Broadway and 42nd Street for a similar reason. Note that during the 1870s, the Madison Square Park neighborhood also developed into a vibrant restaurant and theatre district, which eventually moved north to Times Square after the turn of the century (Postal, 2001).

¹²Note that Rosenthal and Strange (2008) present geological maps that indicate the presence of sedimentary bedrock in Manhattan. This appears to be an error as the vast majority of the bedrock surface is made up of so-called Manhattan schist, which is metamorphosed sedimentary rock (Tamaro, et al., 2000).

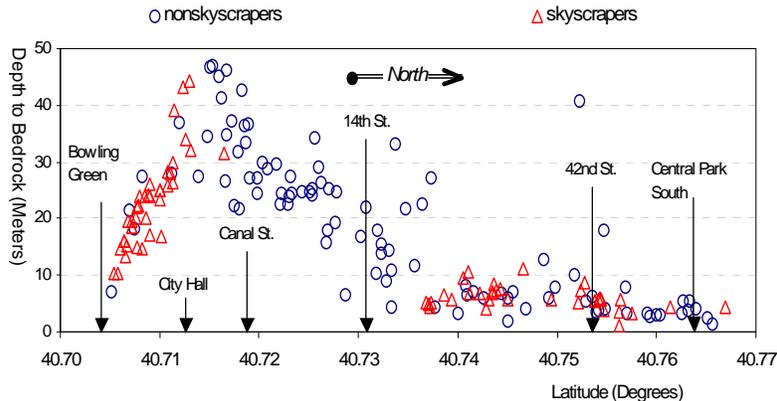


Figure 5: Scatterplot: Depths to bedrock for Manhattan, south of Central Park. Depth is measured relative to the surface. Sources: See appendix.

surface.¹³ 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 5. 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 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 model that will allow us to parse out the effects of depth to bedrock and other economic effects 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,

¹³Note that several of the skyscrapers built near City Hall rested on piles; however, these buildings were among the very earliest skyscrapers and were thus generally less than 20 stories.

to keep the model simple, we investigate a static model. As mentioned above, we leave the study of the dynamic process for future work.

The model below has two aims. First, it presents a motivation for the regressions provided below; and second, the model suggests that if the provision of skyscrapers was based on a true tradeoff between agglomeration benefits and large construction costs due to foundation preparation, then the pattern of the skyline would be different than if this tradeoff did not exist.

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.¹⁴ $A(j)$ 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 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 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

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

¹⁴The 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.

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 are also a function of distance from the center. Assume that $c_h(\cdot) > 0$, $c_{hh}(\cdot) > 0$, $c_j(\cdot) \geq 0$. 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 (1964) and Mills (1972), 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.

3.2.2 Bedrock Cost Effects

Let's 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.¹⁵ 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

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

¹⁵We 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 include 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.

3.2.3 Bedrock Depth Function

Assume that bedrock depth follows the shape given in Figure 5. 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.

Figure 6 shows how the relative marginal benefits and costs of anchoring 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 $r - g'(j)$. 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 the very lower part of Manhattan (from Wall Street south) we would expect to see skyscrapers since the rents are extremely high and the bedrock is not too far from the surface. 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 of $r - g'(\bar{h})$. If the difference 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

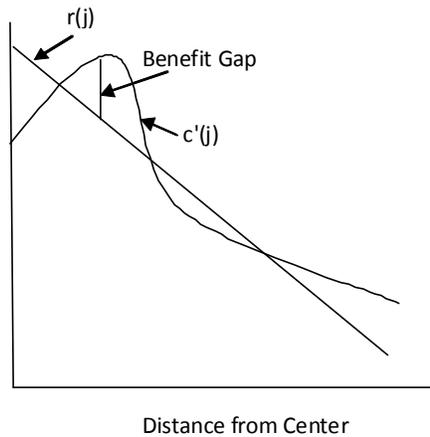


Figure 6: Costs and benefits of skyscrapers as a function of distance.

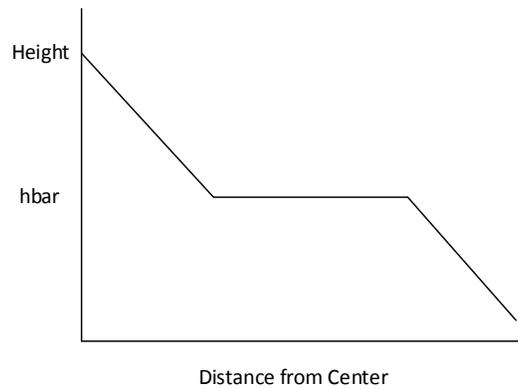


Figure 7: Equilibrium height as a function of the distance from the center.

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 7 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. 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. We explore these factors more in the empirical section below.

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 construction costs for 53 large 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.¹⁶ 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.

¹⁶Elevation, longitude and latitude are found via the Google-based software tool DigiPoint2 (<http://www.zonums.com/gmaps/digipoint2.html>). Elevation is relative to sea level.

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> 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 on the bedrock surface, based on the same datum as topographic contours, with contour intervals of 20 feet. For the statistical analysis that follows, *depth to bedrock* is taken as an average of the depth from the first map and the second map.¹⁷

In addition we have collected data for several variables that may also affect the probability of skyscraper construction at a location. We 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 Table 4 for the average sizes of the districts).

From Pratt (1911), we have AD data for manufacturing worker density. The Cen-

¹⁷The 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.

sus 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 count 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).¹⁸ 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 collected information on the land values from "Tentative Land Value Maps of the City of New York" (1909). Land values are given per foot of street frontage. Note that "land values" are only the value of the land; they exclude the value of improvements and buildings on the land. For each location in the data set, average land values are calculated for the block on which the location resides.

Note that there 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 values for a period prior to initial skyscraper construction, such as 1890, but this data were not available. In the end, we have decided to use land values as a right hand side variable in one of the specifications for the following reason. First, the emergence of three business districts, as shown in Figure 2, began in the second half of the 19th century, with the construction of the elevated railroads and the northward

¹⁸Note 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.

movement of the population. As such, the land values in 1909 most likely reflect land value patterns that were in place before the development of skyscrapers.

In addition, however, we are less concerned about the estimated coefficient for the land value variable, but rather we are interested in including it as possible control variable, to see how its inclusion affects the estimate of the bedrock depth variable. As will be discussed in more detail below, its inclusion provides evidence that, controlling for land values, bedrock depths did have some influence on the placement of skyscrapers. That is to say, the evidence suggests that, *holding land values constant (e.g., within lower Manhattan)*, builders were sensitive to the expense of anchoring the building to the bedrock.

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 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 bedrock does increase costs as expected. In equation (1), a sum of depth to bedrock and the interaction of depth to bedrock and height yields an increase in construction costs due to bedrock 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

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.

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).¹⁹

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 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

¹⁹Our findings concord well with in Kidder (1909), who reported that in regard to the Manhattan Life Insurance Building (1893), the world’s tallest building at the time, the cost of sinking caissons to the bedrock was “only 8 or 9 per cent of the estimated cost of the building” (p. 75).

	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.

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. We do note, however, that these construction costs associated with

bedrock may have been large enough to influence the location choice of builders within a business district. In other words, if two lots were available in the same business district (say the downtown financial district) and had other similar qualities, the cost effect of deep bedrock at one and not the other may have been a deciding factor. We investigate this in subsection 4.4

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).²⁰

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 at the location (though is not significantly different from 0), 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 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,

²⁰We have also run the regressions using building height; they produce similar results. We prefer the probit regressions because we are interested in the likelihood of observing a tall building, without regard to how tall the building may be.

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 cemetary 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 .5 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.

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 build a foundation. This concords with our total cost regressions which show a negative cost effect for bedrock when a non-skyscraper is being built.

As discussed above, land prices are most likely endogenous, but we include them in one specification, equation (5), to investigate their possible effects. Because of the possible endogeneity, those results must be interpreted with caution. As we can see, land prices are perhaps the most important factor in the location of skyscrapers. However, more importantly when we include the land value in the equation we see that the coefficient for the bedrock variable is now statistically significant. This suggests that within regions of the city, controlling for land values, builders did have some sensitivity to the additional costs associated with bedrock depths. We provide further evidence of this, with our counterfactual exercises provided below (and which do not include land values).

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.

	(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.

4.4 Local Bedrock Effects

We now perform a counterfactual exercise in order to isolate the effect of bedrock on skyscraper location. We examine the predicted skyline if bedrock is held constant across the city. To do so 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 8. 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 9, i.e., \hat{p} (“full” regression without bedrock) $- \hat{p}$ (“full” regression). 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. This provides evidence that, in general, if bedrock were a strong determinant of the skyline, we would expect to see much larger changes in the predicted

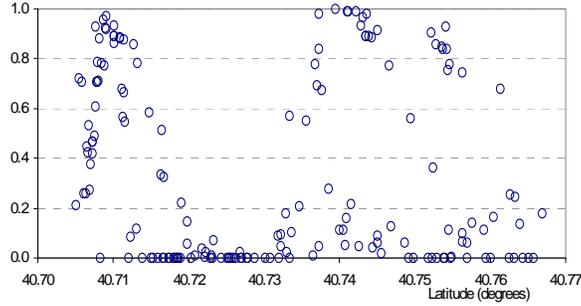


Figure 8: Predicted probability of a skyscraper as a function of latitude, holding bedrock depths constant.

probabilities north of City Hall and below 14th street.

Interestingly, however, we see evidence that builders, to some degree, were sensitive to the bedrock depths. The positive probabilities in the northern part of lower Manhattan indicate that if bedrock depths were not an issue we would have likely seen more skyscrapers in the area around City Hall and fewer in the area around Wall Street, which is just under a half mile away. 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.

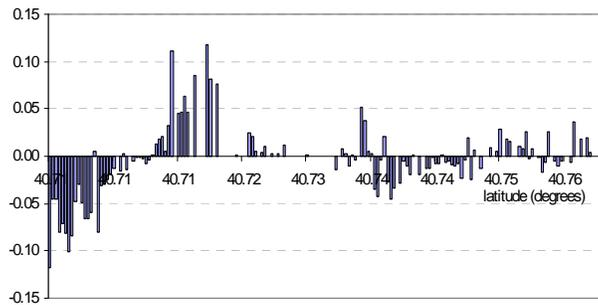


Figure 9: Difference between predicted values with bedrock depth variation versus predicted values with constant bedrock depth ($\hat{p}_{NoBR} - \hat{p}_{BR}$).

Overall, the results of this section suggest that any effect of bedrock was local rather than global in nature. The bedrock effect may have been important enough to figuratively move a skyscraper *within* a business district; but it was not strong enough to move a skyscraper *between* business districts. Notice that this finding emerges in two situations, in the counterfactual exercise and in the regression where we include land values.

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 the effect of bedrock depths on skyscraper completions. 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.

Though the cost of anchoring buildings were small in comparison with land values, we do find evidence that within the lower Manhattan business district, builders were sensitive to the costs. Our counterfactual exercises demonstrate that though bedrock depths didn’t have much of an impact on the skyline across the island in general, it seems to have caused builders to shift their skyscrapers away from City Hall and more toward Wall Street, where in general, access to the bedrock was closer to the surface.

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, and this would help shed light on the dynamic process by which midtown Manhattan emerged as a “sub-center,” relatively far from lower Manhattan.

A Appendix: Data Sources and Preparation

Skyscrapers: The skyscrapers are all of the buildings that were listed as 80 meters or taller and completed between 1890 and 1915 on *www.skyscraperpage.com* and/or *www.emporis.com*. These websites generally provided the number of floors, and the height. *www.skyscraperpage.com* generally provides addresses. Missing addresses were found via searches on *www.Google.com*. The number of floors was additionally checked against *Atlas of New York City, Borough of Manhattan* (1921) for substantial differences.

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 using a 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,” created by the US Geological Survey. The first map provides specific 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 on the bedrock surface, based on the same datum as topographic contours, with contour interval 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 then located via historical articles in the NY

Times or from building permit information from www.metrohistory.com. Then building heights were taken 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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