Fracking, Drilling, and Asset Pricing: Estimating the Economic Benefits of the Shale Revolution

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Abstract

We quantify the effect of a significant technological innovation, shale oil development, on asset prices. We use stock price changes on major shale news announcement days to link aggregate stock price changes to shale development activity. Using these announcement days, we exploit industry cross-sectional variation in price changes to construct a shale mimicking portfolio. We show that this portfolio can help explain aggregate stock market returns, but only during the time period of shale oil development. Based on the effect of this mimicking portfolio on aggregate stock market returns, we find that $2.6 trillion of the increase in aggregate U.S. equity market capitalization since 2009 can be attributed to shale oil.

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1 Introduction

Asset pricing theory is typically agnostic about the nature of technology shocks that underpin the variation in asset values.[1] At the same time, much of the debate in empirical research centers on the relative role of news about future cash flows in explaining variation in aggregate asset prices, as opposed to news about discount rates (e.g., Bansal and Yaron (2004), Campbell and Vuolteenaho (2004), Hansen, Heaton and Li (2008), Cochrane (2011), Greenwald, Lettau and Ludvigson (2014)). Over the five years following the Great Recession (2009 through 2014) the U.S. equity market capitalization roughly doubled, despite fairly anemic rates of growth in the real economy, suggesting falling discount rates as the main driver of rising valuations. However, over the same time period U.S. oil production increased dramatically, from less than 5 Mb/d (million of barrels per day) in 2010 to over 8 Mb/d in 2014, with total U.S. oil production forecast to nearly double by 2015 relative to the pre-crisis levels. Almost all of this increase can be attributed to a breakthrough technological innovation that allows oil to be extracted from shale rock formations that were previously thought to be too costly to access. This innovation, which involves the combination of hydraulic fracturing ("fracking") and horizontal drilling, in the matter of a few years has fundamentally changed the global energy supply-demand balance. Its success was also largely unexpected, as evidenced by the published forecasts of the Energy Information agency (EIA). Given the importance of oil to the U.S. economy, how much of the recent rise in the equity market can be attributed to the unexpected development of U.S. shale oil? Might this suggest a greater role for cash-flow news in explaining asset price fluctuations?[2]

Identifying the effect of shale oil technological innovations from asset prices is challenging. Asset prices are affected by a variety of economic factors, and isolating the effect of a technology shock from discount rate shocks and other confounding factors is difficult. To mitigate this issue, and isolate clean measures of the effect of shale technology innovations on the broader economy we focus on asset price changes on dates when significant shale an-

[1] Recent work by Kogan, Papanikolaou, Seru and Stoffman (2012) linking news on patented technologies to equity returns is a notable and important exception.

[2] Our work here also fits into a long literature attempting to quantify the economic impact of oil shocks. Examples include Hamilton (1983), Sadorsky (1999), Hamilton (2003), Barsky and Kilian (2004), Kilian (2009), Kilian and Park (2009), Bodenstein, Guerrieri and Kilian (2012), and numerous others

nouncements are made. We use these events to undertake three empirical exercises designed to measure the effect of shale oil technological innovations on the economy.

To assess whether aggregate market returns are linked to important shale events, we first focus on asset price changes on the earnings announcement days of shale firms. We find that unexpected positive earnings news for shale producers leads to significant abnormal stock returns for shale firms. We then find that these abnormal shale firm returns have a significant positive effect on aggregate market returns. Specifically, for a 1% increase in the stock price of an index of shale firms, there is a 0.19% increase in the aggregate market on these days, after instrumenting for the shale returns with revenue surprises of the main shale oil firms.

We then measure how different industries are affected by examining the cross-section of industry returns on the day of the most significant shale discovery announcement during our time period. We find that there is significant dispersion linked to exposure to shale. Specifically, a one standard deviation increase in shale exposure for an industry leads to a 5.1% higher average annual return than the average industry during the shale period.

Our initial tests provide evidence that shale news does affect overall market returns as well as the cross-section of returns. However, while these strategies enable us to identify a link between shale oil technological innovations and the market as a whole, the small number of these shocks does not allow for a direct estimate of the total benefit from shale oil development. This is because the shocks on these particular days represent a fraction of the total change in market expectations over the period.

In order to estimate the total benefit from shale oil over time, we construct a shale mimicking portfolio based on the returns of different industries on the announcement date of a major shale discovery. Firms with high announcement returns receive a greater weight in this portfolio; firms with lower returns receive less weight. The intuition behind this empirical design is that there is no single asset we can use to cleanly measure innovations in shale development. However, the mimicking portfolio weights that are constructed using the slopes of the cross-sectional regressions allow us to synthetically create such an asset, building on the classic approach of Fama and MacBeth (1973). These weights are based on responses of industries' stock returns to an exogenous unexpected positive innovation in

shale oil production. We use this portfolio as an asset-price proxy for the value of shale oil development, and assess the explanatory power of this portfolio for market returns over different time periods.

We find that exposure to the shale mimicking portfolio has strong explanatory power for aggregate stock market returns from 2012 to 2014 period in which market exposure to the shale index is high. In total, we find that shale oil development is responsible for $2.6 trillion of the increase in stock market value during this time period. We find that our shale exposure proxy has no explanatory power in earlier time periods when shale oil production was virtually nonexistent.

A potential concern with our methodology is that while the discovery announcement we use to derive our portfolio weights can be considered exogenous, there may have been other reasons why stock prices changed on the key announcement date we use. For example, if the overall market increased for other reasons, we may just be picking up high beta stocks as opposed to high shale exposure stocks in our portfolio. We control directly for a number of these alternative factors. First, we include two different estimates for the effects of beta on aggregate stock market returns in our main regression, using beta estimates from both the pre-crisis and crisis time periods (as a robustness check, we also control for industry market betas on the FOMC announcement days, following Savor and Wilson (2014)). Second, we also control for the effect of oil price changes, by constructing a portfolio using announcement day returns on the day of a key OPEC announcement in November 2014 that drove down oil prices significantly. This approach allows us to isolate industries that are positively (or negatively) exposed to shale oil news for reasons other than oil demand. In essence, we are controlling for the response to the oil price itself with the OPEC announcement, which makes our estimated value of shale somewhat conservative in the sense that it ignores any potential role of shale in the recent decline in oil prices.

Indeed, our estimates are likely to represent the lower bound on the contribution of the shale revolution on the U.S. economy, because we explicitly control for price effects.[3] How might the magnitudes we have found compare to the magnitude of the price effect?

[3]Another possibility is that increased shale production might decrease uncertainty about long-run oil prices. We find some evidence for high shale returns leading to lower oil price volatility. See Appendix **??**.

To put this comparison in context we undertake a simple back-of-the-envelope calculation. Total U.S. consumption of crude oil and petroleum products is approximately 18 Mb/d. Assuming that the advent of shale has led to a price reduction of approximately \$20 per barrel, consistent with the long term expectations from WTI Oil futures of around $\$60 - \$70$ per barrel (depending on the magnitude of the risk premia), this translates into \$131.4 billion per year in savings for oil consumers (including both household and corporate sectors). Projecting these cost savings in perpetuity (admittedly a strong assumption) and discounting them at a rather conservative rate of 10% per annum yields approximately \$1.31 trillion in savings (lowering the discount rate to 5% increases this number to \$2.62 trillion). While this simple calculation is subject to many caveats, it suggests that both the impact of the shale oil technology through the supply side of the economy, as identified in our prior empirical tests, and the impact of changes in oil prices on the demand side are economically meaningful, and are of similar magnitude.

This paper proceeds as follows. First we develop a simple reduced-form asset pricing model with an explicit role for oil demand and production in Section 2. We then describe the data construction and our empirical approach in Section 3. Section 4 presents the results of our empirical analysis. Section 5 concludes.

2 Model

In this section we develop a simple toy model of oil production and demand that motivates the use of asset prices to extract technology shocks.

2.1 Demand for Oil

A representative firm produces consumption goods via a Cobb-Douglas production technology

$$Y_{t+1} = A_{t+1} O_{t+1}^{1-\alpha} K_t^{\alpha},$$

where A_{t+1} is an aggregate productivity shock, O_{t+1} is oil, which plays the role of an intermediate good, and K_t is capital, where the time subscript refers to the fact that capital is chosen

one period ahead (i.e. before the productivity shock is realized). Capital depreciates fully after the period's production is complete. The firm acts competitively, therefore maximizing profits implies that oil prices must satisfy

$$P_t^O = (1-\alpha)A_t O_t^{-\alpha} K_t^{\alpha}$$

given the aggregate supply of oil O_t (we assume this production technology is the only source of domestic demand for oil).

2.2 Oil Supply

Total oil supply is a sum of supply generated by two oil (sub)sectors:

$$O_t = S_t^{Shale} + S_t^{Other}$$

The two sectors are:

1. shale oil, S_t^{Shale}
2. All other oil production (OPEC, Large Integrated Oil Producers, International Oil Production, etc., net of foreign demand) , S_t^{Other}

There is a continuum of competitive price-taking firms in each sector, each sharing a common, sector-specific productivity shock Z_t^i and using competitively supplied factor input L_i ('leases') at a price w_i.

Oil Company Production is given by

$$S_t^i = Z_t^i L_i^{\nu}, 0 < \nu < 1$$

Oil Company Profits

$$\Pi_t^i = P_t^O S_t^i - w_i L_i, \text{ which implies}$$

$$\Pi_t^i = P_t^O S_t^i (1-\nu)$$

Assuming marginal cost of deploying one lease w_i is fixed, we have $\nu P_t^O Z_t^i L_i^{\nu-1} = w_i$ so that sector output is equal

$$S_t^i = Z_t^i L_i^\nu = \left(Z_t^i\right)^{\frac{1}{1-\nu}} \left(\frac{w_i}{\nu P_t^O}\right)^{\frac{\nu}{\nu-1}}$$

and

$$\Pi_t^i = \left(P_t^O Z_t^i\right)^{\frac{1}{1-\nu}} (1-\nu) \left(\frac{w_i}{\nu}\right)^{\frac{\nu}{\nu-1}}.$$

The intuition behind this production function is that while the costs of drilling are roughly the same across locations, some of the drilled wells are much more productive than others and therefore are profitable to operate at lower levels of oil prices, while less productive leases are utilized only when prices are sufficiently high.

We assume that the sectors differ in their productivity Z_t^i as well as marginal cost of production w_i, which jointly determine the relative importance of each sector in total oil supply. While in general different oil sectors may differ in the degree of decreasing returns, this assumption simplifies exposition without driving any of the implications.

Assume for simplicity that one unit of capital must be invested at the beginning of the period to operate the technology, with full depreciation by the end of the period. Then returns on firms in sector i equal profits: $R_{t+1}^i = \Pi_{t+1}^i$.

We assume that all of the productivity shocks, A_t, S_t^{Shale}, and S^{Other}, together with innovations to an exogenously given stochastic discount factor M_t, are jointly lognormally distributed.

2.3 Asset Pricing

The value of capital invested in the aggregate production sector is just the present value of next period's profits:

$$V_t^i = \alpha E_t \left[M_{t+1} A_{t+1} O_{t+1}^{1-\alpha} K_t^\alpha\right]$$

assuming no depreciation between periods ($V_t^i = K_t^i$) implies that the returns to an average firm are

$$R_{t+1}^a = \frac{\alpha A_{t+1} O_{t+1}^{1-\alpha} K_t^\alpha}{V_t^i} = \frac{A_{t+1} O_{t+1}^{1-\alpha} K_t^\alpha}{E_t \left[M_{t+1} A_{t+1} O_{t+1}^{1-\alpha} K_t^\alpha\right]} = A_{t+1} O_{t+1}^{1-\alpha} K_t^{\alpha-1}$$

or, in logs,

$$\begin{aligned} r^a_{t+1} &= \Delta a_{t+1} + o_{t+1} + p_{t+1} - g_A - (1-\alpha) Eo_{t+1} + \alpha k_t + r_t - \frac{1}{2} Var\left[\log\left(M_{t+1} A_{t+1} O^{1-\alpha}_{t+1} K^{\alpha}_t\right)\right] \\ &= (E_{t+1} - E_t) a_{t+1} + (1-\alpha)(E_{t+1} - E_t) o_{t+1} + r_t - \frac{1}{2}\sigma^2_m + rp^a + \frac{1}{2}\sigma^2_a \\ &= (E_{t+1} - E_t) o_{t+1} + (E_{t+1} - E_t) p_{t+1} + r_t + rp^a - \frac{1}{2}\sigma^2_a, \end{aligned}$$

where the aggregate market equity risk premium

$$rp^a = -Cov\left(m_{t+1}, \Delta o_{t+1}\right) - Cov\left(m_{t+1}, \Delta p_{t+1}\right)$$

is assumed constant for simplicity, as is the corresponding return volatility

$$\sigma^2_a = Var\left(\Delta o_{t+1} + \Delta p_{t+1}\right)$$

and the risk-free rate is $r_t = E_t m_{t+1} - \frac{1}{2}\sigma^2_m$.

Similarly, excess returns to oil producers in sector i are given by

$$r^i_{t+1} - r_t + \frac{1}{2}\sigma^2_a = \frac{1}{1-\nu}(E_{t+1} - E_t) z^i_{t+1} + \frac{1}{1-\nu}(E_{t+1} - E_t) p_{t+1} + rp^i_t, \tag{1}$$

where the risk premium rp^i is determined by the conditional covariances of the shocks with the SDF innovations.

We approximate innovations to the log of total supply as

$$\begin{aligned} (E_{t+1} - E_t) o_{t+1} &\approx \xi^{Shale}(E_{t+1} - E_t) s^{Shale}_{t+1} + \left(1 - \xi^{Shale}\right)(E_{t+1} - E_t) s^{Other}_{t+1} \\ &= \frac{1}{1-\nu}\xi^{Shale}(E_{t+1} - E_t) z^{Shale}_{t+1} \\ &\quad + \frac{1}{1-\nu}\left(1 - \xi^{Shale}\right)(E_{t+1} - E_t) z^{Other}_{t+1} - \frac{\nu}{1-\nu}(E_{t+1} - E_t) p_{t+1} \end{aligned}$$

where $\xi^{Shale} = E\left[\frac{S^{Shale}_t}{O_t}\right]$, and we assume that Σ is a constant variance-covariance matrix of S^{Shale}_t and S^{Other}_t so that the convexity adjustment $\frac{1}{2}\left(\xi^{Shale}, 1 - \xi^{Shale}\right)\Sigma\left(\xi^{Shale}, 1 - \xi^{Shale}\right)'$ drops out.

Then aggregate market return innovations can be approximated as

$$\begin{aligned}(E_{t+1}-E_t)\, r^a_{t+1} &\approx \frac{1}{1-\nu}\xi^{Shale}\,(E_{t+1}-E_t)\, z^{Shale}_{t+1} \\ &+ \frac{1}{1-\nu}(1-\xi^{Shale})\,(E_{t+1}-E_t)\, z^{Other}_{t+1} + \frac{1-2\nu}{1-\nu}\,(E_{t+1}-E_t)\, p_{t+1}\end{aligned} \tag{2}$$

Therefore, since the market return innovation in equation (2) is a linear combination of the sector-specific oil productivity shocks and innovations to oil prices, the long-run average share of shale oil in total oil supply, ξ^{Shale} can be identified by regressing the market excess return on the shale sector return, controlling for the other sector returns (given by (1)) as well as oil price innovations.

3 Data and Identification

Data for this project come from several sources. All data for oil production and forecasts are from the Energy Information Assocation (EIA). WTI futures returns are constructed using data from Bloomberg. Stock market data is from CRSP and Datastream (details of industry portfolio construction are in the appendix). Reported revenue and analyst projections of revenue are from Thomson Reuters' IBES database.

3.1 The Shale Revolution: a Primer

Shale oil and natural gas reserves were long thought to be uneconomic to develop. For example, as recently as the late 1990s only 1% of U.S. natural gas production came from shale. Then in the early 2000s Mitchell Energy began experimenting with new techniques for drilling shale, and found that by combining horizontal drilling with hydraulic fracturing ("fracking"), natural gas from shale could be economically produced. The unlocking of shale has led to a dramatic increase in production of natural gas, which ultimately led to lower prices of natural gas in the U.S. and, consequently, electricity. With low natural gas prices and high oil prices in 2009, firms began to experiment with using shale technology to extract oil, as oil and gas are often trapped in similar geologic formations. Figure 1 displays the recent trends in oil production. Several firms were successful in adopting shale technology in

oil basins, including the Permian, the Bakken formation, and the Eagle Ford shale. As Panel A shows, with the adoption of shale technology production in these basins has increased significantly.

There are three features of the shale oil boom that make it especially interesting from an asset pricing perspective. The first is that the rise in production was unexpected, and can therefore be interpreted as a true "Technology Shock". Panel B of Figure 1 shows U.S. crude oil production from 2005 to 2014, along with monthly forecasts of future oil production from the EIA's monthly publication of Short Term Energy Outlook. Consistent with Panel A, starting in 2012 U.S. Crude Production rises dramatically. This rise in production was unanticipated by forecasts, which consistently undershoot production for the first year of the Shale Boom, before adjusting towards the end of the period.

The second important feature of the boom is its magnitude. While clearly increased productivity is a benefit for shale oil producers, its importance for the rest of the economy hinges on the fact that this production increase is significant relative to total world supply. Panel C of Figure 1 illustrates that the increase in U.S. oil production driven by shale deposits amounts to roughly 5% of total world oil production. While this may not seem large, given the highly inelastic nature of oil demand it has a potential to have a large long-run impact on price levels. Typical estimates of long-run demand elasticity (see for instance Kilian and Murphy (2014)) are near -0.25, suggesting that a 5% increase in world supply may yield up to a 20% drop in price. While the price does not drop dramatically over the sample we consider, this period coincides with unrest in the Middle East and consequently volatile supply from the region. The recent increases in Libyan production combined with the greatly increased U.S. production have combined to depress global prices by roughly 20% in the three months since the end of our sample. Without U.S. oil production increases, it is very likely that the recent reductions in Middle East supply would have translated into significantly higher prices than those observed.

The final feature that makes this shock somewhat unique is that it originated in a small number of easily identifiable firms which we designate as the "Shale Oil Index." These are firms with a significant amount of production derived from shale oil. Panel D illustrates the cumulative returns of this "Shale Oil Index" to several stock price indices. The returns to the

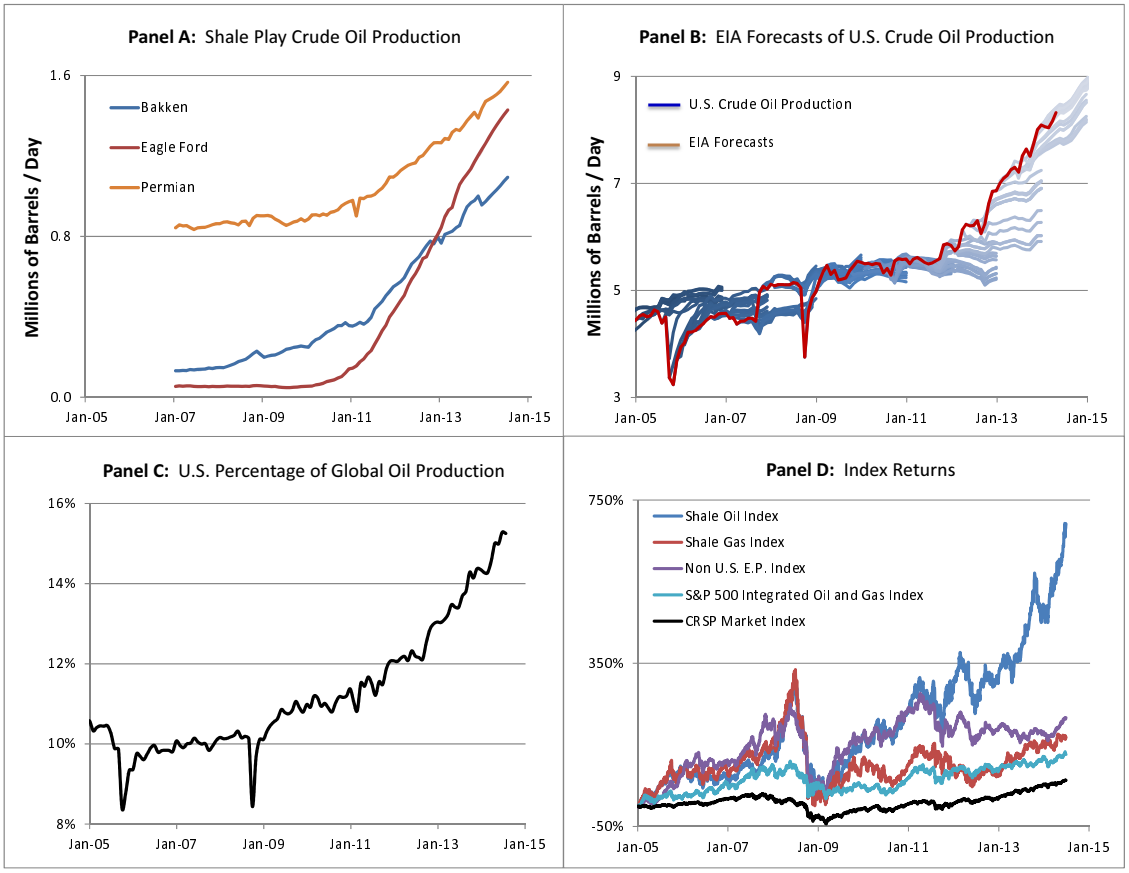
"Shale Oil Index" are plotted with several other energy producer stock indices. The first is the"Shale Gas Index", described in Section 3, the second is a "Non U.S. E&P Index", which consists of E&P firms outside of the United States. The third is an index of the four large integrated oil and gas producers on the S&P 500. The cumulative returns to the aggregate CRSP market index are also included for comparison. As Panel D shows, the shale oil firms exhibit no abnormal returns relative to other industry producers prior to the sharp rise in production. However, following that rise, they experience a period of extraordinary growth, rising roughly 200% in a two year time. These stock returns are useful for understanding when asset prices began reflecting shale oil expectations. However, using a "Shale Oil Index" to precisely measure aggregate stock market effects is problematic, as discount rate shocks, and other shocks likely affect both the Shale Oil Index and aggregate stock prices. For this reason, we focus our identification using asset price changes in and around shale news announcements.

3.2 Identification Approach: Shale News and Stock Returns

While the toy model in section 2 shows that asset prices contain information about the technological shocks affecting oil production (as well as demand), identifying these shocks empirically. It may be impossible to perfectly control for oil price innovations and, more generally for other shocks that simultaneously drive returns to both shale oil firms and other firms in the economy, such as changing discount rates (e.g. through time varying aggregate uncertainty or preference shocks).

Our approach to overcoming this challenge involves using stock returns around news announcements pertaining to oil supply, specifically shale-oil and non-shale oil. The idea behind this identification strategy is that news announcements that are specific to shale, and oil more broadly, are plausibly exogenous to other aspects of the macroeconomy, and in particular to discount rates. We implement this strategy in three slightly different but related ways. First, we instrument for the time series of shale firm stock returns using revenue surprises around earnings announcements of the major shale firms. Second, we consider the cross-section of industry returns around two major shale announcements and a significant OPEC announcement and examine the performance of this cross-section over

Figure 1: U.S. Oil Production and Stock Returns



various time periods related to shale production. Finally, in order to quantify the total economic impact of shale oil we use information in the time-series and cross-section of industry returns to estimate overall market value attributable to increases in production. We do this by constructing a portfolio in the cross-section of industries which attempts to mimic impacts to shale production. These methods are similar to those which are standard in the asset pricing literature for quantifying risk-premium or *expected* returns, but instead we use them here to quantify *realized* returns.

4 Empirical evidence

4.1 Shale Oil Earnings Announcements and Aggregate Stock Returns

In order to address the issue of causality, we would like to identify exogenous shocks to shale oil firm values that can act as an instrument for returns to the Shale Index. An ideal instrument would be an announcement, or series of announcements, which provide information about shale oil production without providing material information about other important economic shocks (e.g., Savor and Wilson (2014) show that announcement dates capture the bulk of priced shocks to firm cash flows). Unfortunately, while there are announcements made by government agencies regarding oil production, they do not appear to have a material impact on the returns to oil firms, suggesting that they are not a source of new information. Instead we look at information provided by the shale oil companies' themselves as part of their regular earnings announcements, which should be private prior to the announcements as it is material to the value of the companies.

For this exercise we focus on the last two years of the sample, during which the R^2 of the market return on the Shale Shock is high and we see the largest increase in shale oil production. Though we have many companies in the Shale Index, the information released by different companies over a short time period is likely highly correlated, and therefore may become rapidly redundant. To this end, we focus on the two largest companies (in terms of shale oil assets) in the index, EOG Resources (EOG) and Pioneer Resources (PXD). To

construct a measure of new information in the earnings reports, we focus on a measure of unanticipated revenue surprise, which is simply the log of the ratio of actual reported revenue to the average analyst projected revenue in the Thomson Reuters' IBES database.

We construct 15 observations, which represent announcements related to Q2 2012 to Q1 2014, with the exception of Pioneer's 2014 Q1, which is not in the IBES database. Since the earnings reports are released after market close on the announcement day, we match the revenue surprise measure to returns over the next trading day. The standard method for this analysis is a two stage least squares (2SLS) regression of R^{MKT} on $R^{ShaleOil}$, using the measure of revenue surprise as instrument for returns to the shale oil index. However, due to the well-known poor statistical properties of this procedure (especially acute in our very small sample), it may be preferable to focus on the reduced form specification of the IV regression, as suggested by Chernozhukov and Hansen (2008). Table 1 shows the results for both procedures. The OLS regressions of returns to the shale index, as well as returns to the aggregate market index, against the revenue surprise from the two firms' announcements, can be interpreted as the first stage and the reduced form specifications, respectively. Both variables show a clear positive relation with the revenue surprise of these shale firms. Even with only 15 observations, the relationship between both return variables and the revenue surprise variable is significant at the 5% level, and in fact at 1% level for the shale index return. The reduced form regression has a high R-squared of 19% for market returns on shale firms' revenue surprise. Consistent with the reduced form results, the 2SLS regression of the market excess return on the shale index return instrumented with the shale firms' surprise also recovers a strong, statistically significant relation.

As a confirmation that this relation between shale oil revenue surprise and the aggregate market return on these days is not being driven by other information revealed in the announcements, as a placebo test we repeat the analysis using the same 15 days' returns against the average revenue surprise across all firms reporting on these days. We find that there is no relation between these announcements and either shale oil returns or aggregate market returns (both the regression coefficients and the R-squared are essentially zero in all of the specifications), suggesting that information revealed in shale oil announcements is important for aggregate market returns.

Table 1: Stock Market Returns on Shale Announcement Days

	PXD and EOG Revenue Surprises			**Market Avg. Revenue Surprises**		
Method:	OLS	OLS	2SLS	OLS	OLS	2SLS
	$R^{ShaleOil}$	R^{Mkt}	R^{Mkt}	$R^{ShaleOil}$	R^{Mkt}	R^{Mkt}
Surprise	0.213***	0.040**		0.102	-0.043	
	(0.046)	(0.017)		(0.347)	(0.123)	
$R^{ShaleOil}$			0.186**			-0.418
			(0.074)			(3.089)
Constant	0.005	0.002	0.001	0.015**	0.003	0.010
	(0.005)	(0.002)	(0.002)	(0.006)	(0.002)	(0.046)
Observations	15	15	15	15	15	15
R-squared	0.550	0.190	0.551	0.003	0.006	0.001

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table shows results of regressions of both Shale Industry and Aggregate Market returns on 15 earnings announcements for EOG Resources (EOG) and Pioneer Resources (PXD) from second quarter 2012 to third quarter 2014. For each earnings announcement a revenue surprise measure is constructed using IBES estimates and realized revenue announcements. In the first two columns this revenue surprise is then used as the independent variable in regressions of the corresponding daily return to the Shale Oil Index $R^{ShaleOil}$, and the aggregrate R^{Mkt}. In the third column, the surprise is used as an instrument for $R^{ShaleOil}$ in a 2SLS regression with R^{Mkt} as the dependent variable. The last three columns repeat this analysis using the average revenue surprises from all other firms on those days as a placebo test.

4.2 Shale Exposure across Industries

The time series of revenue surprises and market returns suggest a link between shale discoveries and the stock market. In this section and in what follows we exploit heterogeneity in industry exposure to shale innovations to quantify the impact of shale production on the stock market.

We use NAICS code descriptions to construct industry portfolios of all CRSP stocks.[4] We treat stocks of oil and gas producing companies, differently, using the S&P Integrated Oil and Gas Index as our non-shale oil industry portfolio, the Shale Oil Index, and the Shale Gas Index, while all the other oil producers not included in these indices populate the "Other Oil" portfolio.

While this allows us to create a measure of exposure to shale news, revenue surprises are an imperfect proxy for news about shale oil prospects, since revenue or earnings are not necessarily the most important news about the viability of new technologies, and could also be driven by demand shocks.

Hydraulic fracturing and horizontal drilling provide the basic building blocks for shale development. However, companies need to apply this technology and then calibrate these techniques to particular oil and gas reservoirs (e.g., see Covert (2014)). Often it is the case that the economics of shale in a given reservoir are unknown. Therefore when successful shale efforts are announced, significant asset revaluations occur. In many cases, a single positive well result for a reservoir can indicate the potential for hundreds of follow-on wells, which can have billions of dollars of NPV for a given company. The announcements of these positive well results represent a unique opportunity to assess how other-non-shale industries respond to unexpected announcements of significant improvements in shale supply.

The largest of these announcements in the sample is the announcement of Pioneer Natural Resources DL Hutt C #1H well in the Wolfcamp A reservoir. On July 31, 2013 after market close, Pioneer Natural Resources announced the successful test of the DL Hutt C #1H, which began production at 1,712 Barrels of Oil Equivalent per Day (BOEPD) of natural gas and crude oil, with 72% crude oil content. This was the first successful well test of the

[4] Alternatively, one could use the standard Fama-French industries available from Ken French's website. However, their industry classifications based on SIC codes are too coarse to generate enough variation in exposure to oil.

Wolfcamp A, and represented a significant improvement of shale potential across the entire Spaberry/Wolfcamp field, the world's second largest behind only the Ghawar Field in Saudi Arabia. Pioneer's stock price increased 12.2% on this announcement, adding $2.7 Billion to the firm's enterprise value. This announcement is also the largest revenue surprise in our set, and occurs after the Shale boom was well underway.[5] We use the industry portfolio return on this single announcement day as a proxy for industry's exposure to increases in shale productivity.

Industries' sensitivity to shale news can come through several economic channels. To the extent that increase in fracking/drilling activity increases demand for output of industries that supply the positive news about shale sector productivity are good news for these industries - we can refer to this as the "supply-chain effect." To the extent that increasing income of households involved in the shale oil production, directly or indirectly, and the overall improves the health of the local economies, it might benefit consumer-oriented industries that experience increasing demand for their goods - we can refer to this as the "income effect."[6] Finally, to the extent that good news about shale oil supply can depress oil prices, it may benefit a variety of industries whose output consists of goods that are complements with oil (e.g. cars) or whose expenditure shares increase through the effect on the consumers' budget constraints - this can be called the "price effect." This latter effect is quite distinct from the others in that its magnitude can be affected by non-shale oil supply shocks, in the direction that is opposite of the supply-chain and income effects.

It is therefore important to control for such price effects separately. In fact, the data provides the perfect event for identifying the impact of non-shale supply shocks on oil prices. On November 28, 2014, the OPEC released the outcome of 166th Meeting of the OPEC Conference in Vienna that occurred on the preceding day. The key result of the meeting was the decision that member countries would not cut their oil supply in response to increased supply from non-OPEC sources and falling prices. On the announcement day oil prices

[5]The second largest revenue surprise in the set, the May 6, 2013 earnings announcement by EOG which contained substantial news about exploratory results in both the Eagleford and Bakken shale fields leading to a roughly 10% increase in EOG's stock price.

[6]Gilje (2011) documents the impact of windfall oil revenues on the local economies, while Cascio and Narayan (2015) focus on the increasing wages of low skilled workers and its consequences for educational attainment.

dropped by over 10%, and the shale index fell by roughly 8%, while the aggregate U.S. market return was essentially zero. Abnormal return on this announcement gives us a measure of exposure to an exogenous supply shock to oil prices, unrelated to technological innovation in the shale sector.

4.3 Evidence from the Cross-section of Realized Stock Returns

In order to estimate the impact of shale (and oil) news on the cross section of industries we run standard Fama-MacBeth regressions of weekly excess returns of the industry portfolios on characteristics, where the latter include the shale announcement return and the OPEC announcement return of each industry. The announcement returns are standardized to have the standard deviation equal to one. We also control for the lagged market betas of each of the industries estimated before and during the financial crisis. We do not control for contemporaneous betas as those may be endogenous to the shale shock, as industries' relative important in the market portfolio changes.

Table 2 presents the results of these regressions across four subperiods: Pre-Crisis (01/2003 - 07/2008), Crisis (07/2008 - 06/2009), Post-Crisis (06/2009 - 03/2012), and the Shale Oil Period (03/2012 - 03/2015). Panel A presents the results using the full cross-section of industries, where as in Panel B the three key industries related to oil and gas (Shale Oil, Shale Gas, S&P Integrated producers) are excluded. Thus, all of the cross-sectional slope coefficients are averaged over subperiods in order to understand the role of oil shock sensitivities on industry returns during the period when shale oil was – and was not – a major source of innovation.

The first result that oil shocks are an important driver of stock returns. The effect identified through the OPEC announcement return is strongly statistically significantly negative during the pre-crisis period of rising oil prices. The average Fama-MacBeth slope coefficient of -0.155 suggests that a one standard deviation increase in an industry's sensitivity to the OPEC shock translates into a 15.5 basis point per week (or, about 8 percent per year) lower return on average over this period than an average industry. During both the crisis and the post-crisis periods the coefficient is not statistically significant, as both oil prices and stock returns fall dramatically during the crisis and then recover. Finally, during the shale

period the OPEC announcement coefficient is strongly and significantly positive at 0.131 (or 0.148 if oil firms are excluded). This is a clear manifestation of the fact that the falling oil prices during this period (both due to shale and the OPEC announcement, as well as other supply shocks and possible non-U.S. demand shocks) have lifted stock prices of firms that most benefit from low oil prices - the same firms whose valuations suffered during the period of rising oil costs before the crisis.

What is the role of shale? Unlike the OPEC announcement, the shale announcement sensitivity is a significant (and positive) driver of returns only during the last period, when shale production became a significant economic force. When the shale announcement return is the only characteristic its effect is marginally significant, with a coefficient of 0.048, in the full sample, but strongly significant, with a coefficient of 0.098, when the shale oil, shale gas, and integrated oil and gas sectors are excluded. This suggests that the decline in oil prices driven by forces outside of the U.S. (e.g., global demand or OPEC supply) depressed valuations of U.S. shale and non-shale oil firms to a substantial degree. Indeed, when we control for the OPEC announcement return the shale coefficient becomes strongly significant in both sample, with the similar magnitudes (0.71 and 0.08). Controlling for the OPEC sensitivity raises the shale slope because it allows us to disentangle two opposing effects oil prices have on U.S. firms, in their relation to the shale industry. While the "supply chain," "income," and "price" effects may all be positive for shale, only the direct "price effect" is positive for the OPEC shock, since it lowers oil prices without helping U.S. production. In fact the effect is negative for the firms that benefit from shale for non-price reasons, since it hurts U.S. shale oil production and therefore limits the extent of positive spillovers.

Overall, the effect of a one standard deviation increase in its sensitivity to the shale oil discovery announcement increases an industry stock return over the shale period by about 3 to 4 percent per annum, but has no statistically discernible effect on stock returns in any other time period. Controlling for the pre-crisis and crisis period stock market betas does not have any effect, suggesting that the shale announcement return is not picking up industries with (persistently) high (and low) market betas. Note that average returns over the short subsamples that drive the Fama-MacBeth coefficients we estimate need not represent *expected* returns. The effect of shale is likely driven by a series of positive surprises - technological

shocks that have a first order effect on current and future cash flows of a range of industries but may or may not change their exposure to systematic risk and expected returns.

4.4 Constructing the Oil Factor Portfolios

While the previous analysis relies primarily on the cross-sectional variation in average returns on industries across time periods, the same identification strategy can be used to extract information about the time-series behavior of returns within each of the subsamples, and therefore shed additional light on the nature of the oil shocks that we recover. This information is contained in the time-series of the cross-sectional slopes of the Fama-MacBeth regressions. It is well known (going back to Fama (1976)) that the coefficients of the individual cross-sectional regressions of returns on characteristics can be interpreted as portfolio returns, since these slopes are given by

$$\lambda_t = W_t' R_{t+1}^x,$$

where R_{t+1}^x is the vector of excess returns on the test assets and the matrix of portfolio weights is given by

$$W_t = X_t \left(X_t' X_t\right)^{-1}$$

with matrix X_t containing all of the characteristics on the right-hand side of the Fama-Macbeth regression, with the first column containing ones (for the cross-sectional intercept). Since $W_t' X_t = I$ the first column of W_t gives weights of a unit investment portfolio and all others correspond to zero investment portfolios that have a weighted average value of one for a given characteristic and zero for all the other characteristics. Back, Kapadia and Ostdiek (2013) refer to these as "characteristic pure play portfolios" since they are maximally diversified in the sense of minimizing the sum of squared weights across test assets, while isolating the effect of a given characteristic on the cross-section of returns by controlling for other characteristics (including betas).

Here, we start by treating the returns of industry portfolios on the shale discovery announcement day (and similarly OPEC announcement day) as the characteristic (that remains constant over time) and use this approach to construct a trading strategy that essentially goes long industries exhibiting a positive response to the shale announcement and short in-

Table 2: Fama-Macbeth Regression of Industry Returns on Announcement Day Return

Panel A: All Industries

	Pre-Crisis (01/2003 - 07/2008)			Crisis (07/2008 - 06/2009)			Post-Crisis (06/2009 - 03/2012)			Shale Oil Period (03/2012 - 03/2015)		
OPEC Announc. Ret.	-0.155***		-0.167***	0.140		0.124	-0.002		-0.004	0.131***		0.144***
	(0.056)		(0.055)	(0.292)		(0.300)	(0.064)		(0.060)	(0.047)		(0.045)
Shale Discovery Ret.		0.001	-0.025		-0.044	-0.011		0.043	0.044		0.048*	0.071**
		(0.018)	(0.020)		(0.094)	(0.100)		(0.028)	(0.028)		(0.027)	(0.028)
Pre-Crisis Beta			0.060			-0.066			0.024			-0.035
			(0.042)			(0.138)			(0.049)			(0.035)
Crisis Beta			-0.004			-0.071			-0.016			-0.005
			(0.029)			(0.335)			(0.064)			(0.033)
Constant	0.262**	0.320**	0.071	-0.356	-0.343	0.120	0.417*	0.352	0.303**	0.337**	0.212	0.383***
	(0.122)	(0.124)	(0.088)	(0.843)	(0.816)	(0.558)	(0.252)	(0.254)	(0.141)	(0.144)	(0.142)	(0.123)
Observations	21,804	21,804	21,804	3,634	3,634	3,634	10,981	10,981	10,981	12,245	12,245	12,245
Number of Weeks	276	276	276	46	46	46	139	139	139	155	155	155

Panel B: All Industries Excluding Shale Oil, Shale Gas, and S&P Integrated Oil and Gas

	Pre-Crisis (01/2003 - 07/2008)			Crisis (07/2008 - 06/2009)			Post-Crisis (06/2009 - 03/2012)			Shale Oil Period (03/2012 - 03/2015)		
OPEC Announc. Ret.	-0.156***		-0.160***	0.137		0.123	0.001		-0.010	0.148***		0.142***
	(0.055)		(0.052)	(0.288)		(0.276)	(0.066)		(0.058)	(0.048)		(0.044)
Shale Discovery Ret.		-0.067**	-0.049*		0.003	-0.001		0.057	0.057		0.098***	0.080**
		(0.033)	(0.027)		(0.184)	(0.148)		(0.040)	(0.036)		(0.034)	(0.033)
Pre-Crisis Beta			0.069			-0.073			0.017			-0.041
			(0.042)			(0.146)			(0.048)			(0.034)
Crisis Beta			-0.014			-0.062			-0.008			0.003
			(0.030)			(0.341)			(0.064)			(0.033)
Constant	0.261**	0.406***	0.100	-0.357	-0.401	0.106	0.419*	0.334	0.289**	0.338**	0.149	0.371***
	(0.122)	(0.130)	(0.090)	(0.844)	(0.887)	(0.562)	(0.252)	(0.265)	(0.140)	(0.145)	(0.150)	(0.121)
Observations	20,976	20,976	20,976	3,496	3,496	3,496	10,564	10,564	10,564	11,780	11,780	11,780
Number of weeks	276	276	276	46	46	46	139	139	139	155	155	155

Fama-Macbeth Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

This table shows results from Fama-Macbeth Regressions on the cross-section of 79 weekly industry returns over different subsamples. The explanatory variables are the industry return on the PXD Announcement Day (8/01/2013), the Opec Announcement Day (11/28/2014), as well as market betas calculated for both the pre-crisis and crisis periods. In Panel A all 79 industries are used, while in Panel B, three oil specific industries are excluded (Shale Gas, Shale Oil, and S&P Integrated Oil & Gas Producers). Betas and announcement day returns are adjusted to have unit standard deviation. Returns are weekly.

dustries with negative return responses. In addition to the shale and OPEC announcement returns, we can use the pre-crisis and crisis market beta estimates as characteristics as well, constructing portfolios that capture the (potential) market rewards for exposure to beta risk. Thus, we are essentially using individual slopes that produce the Fama-MacBeth coefficients reported in the Table 2 above.

The individual values of the announcement returns and market betas, as well as the resulting portfolio weights are reported in Table 6. We exclude the three oil and gas indices from the portfolio construction since we want to extract information about other industries sensitive to shale. Note that since all of the characteristic pure play portfolios are zero cost, the weights add up to one even though the characteristics do not. Thus, in particular, the industries that receive a negative weight in the Shale Discovery portfolio do not necessarily experience a negative return on the day of the Pioneer announcement, but could simply have a weaker than average positive response (since the market return on the day was positive). That said, most of the extreme return responses - and portfolio weights - are quite intuitive. Industries that receive the largest positive weights in the Shale Discovery are Oil and Gas Drilling (that act as subcontractors for both shale and non-shale oil producers), Business Services and Engineering Services (that are also heavily involved in shale exploration and production, directly or indirectly). Railroads are also naturally sensitive to shale as the boom in oil production in the areas of the U.S. that are far from the available refining capacity or pipelines saw a dramatic rise in the shipment of oil across the country. The most negative weights such as for Coal and Gold Mining are also intuitive, at least for coal, which is a major substitute for oil in heating, etc. Consumer-oriented industries, such as Clothes, receive positive weights because they have large shale announcement shocks likely due to the importance of gasoline prices in consumer budgets, as corroborated by strong positive OPEC announcement effects of such industries. For industries like Ground Transportation there is also a clear effect of the complementarity with oil. Some industries that have strong shale announcement responses receive relatively low weights in the Shale Discovery mimicking portfolio due to the effect of controls. For example, Passenger Airlines have a well-above average Shale announcement return of 1.9 percent but receive essentially a zero weight in the portfolio because their response to the OPEC announcement is even stronger, 5.64 percent,

which is natural given the key role of fuel prices for airline profits. This industry also has a historical market beta well above one, potentially further reducing its weight in the shale portfolio. Note that the OPEC announcement returns line up very closely with the OPEC announcement returns, loading up most on industries that benefit from low oil prices, and going short industries that benefit the most from U.S. domestic oil production, such as Oil and Gas Drilling, Mining Equipment, Oil Pipelines, and Railroads.

4.5 Exploring the Time-series

Figure 2 plots the cumulative time series of mimicking portfolio returns – i.e., the slopes of the cross-section of industry returns regressed on the "characteristics" – the two sets of announcement returns and two sets of betas, along with the cumulative total U.S. stock market return over the sample period. The time-series behavior of these returns features very intuitive patterns. The OPEC Announcement portfolio, which goes long industries that benefit from low oil prices and short industries that benefit from high prices performs very poorly over the pre-crisis period. As oil prices rise, it loses about 20%, rebounding somewhat during the financial crisis and then stabilizing until essentially the end of 2014, when it rises sharply as oil prices fall. The Shale Discovery portfolio follows a similar, but less steep, path of decline, but begins to rise much earlier, around the middle of 2011 and beginning of 2012, consistent with our identification of the beginning of the "shale oil period". The Pre-crisis Beta and Crisis Beta portfolios track the stock market return closely up until the beginning of the "shale period," during which neither one of them exhibits the steep rise of the market portfolio itself.

What is the nature of shocks driving the time series of returns on these portfolios? As a validation exercise, we examine their correlation with the major oil-related variables that were explicitly excluded from their construction: the oil price and the returns to the three oil and gas indices. These results are reported in Table 3. Panel A shows results from regressing the weekly WTI oil price changes on the OPEC Announcements portfolio, the Shale Discovery portfolio, the two market beta-based portfolio and the aggregate stock market return itself. The OPEC Announcement return is extremely strongly negatively correlated with oil prices, as expected, since it is capturing the returns to firms benefitting from low oil prices and hurt

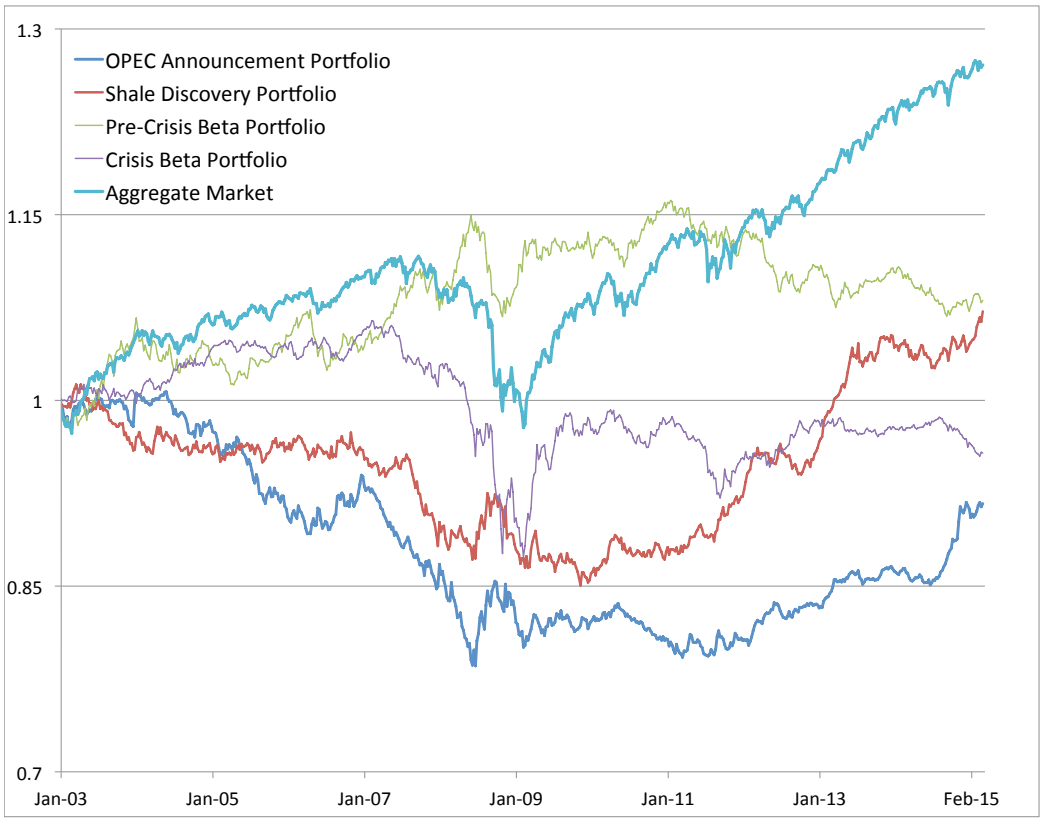
by high oil prices. This result is robust across all time periods, with coefficients between -3 and -5.5 in magnitude. This means that a one percentage point return on the OPEC portfolio corresponds to a three to five percent fall in the oil price. The effects of the total market return variables are not consistent over time and across specifications.

The coefficient of the Shale Discovery portfolio is positive and statistically significant only in the recent shale oil period, with a positive shale return of 1% corresponding to around a 3 percentage point rise in the oil price. This positive coefficient suggests that the Shale Discovery portfolio is primarily driven by industries that benefit from the positive spillovers generated by the shale oil production, more so than by firms benefitting from a potential effect of shale on the oil price. This validates our use of the OPEC announcement as a control for non-U.S. oil supply that drives much of the variation in the oil prices. Indeed, the R^2 of these regressions are between 40 and 60 percent, with most of the explanatory power coming from the OPEC Announcement returns.

Panel B presents results from regressing the S&P Integrated Oil & Gas Index returns on the same variables. The evidence here is similar, as the OPEC Announcement portfolio is picking up the variation in the oil prices, which drive much of the fluctuations in the oil firm returns. The Shale Discovery portfolio is positively correlated with the integrated producers' returns during both the crisis and the shale periods, but not after controlling for the market return, when the effect becomes negative (and marginally significant in the recent period). Panel C presents similar evidence for the Shale Gas index, suggesting that while shale oil and gas might benefit from the same forces that increase global oil prices, there is not particularly strong direct connection between the two.

Finally, Panel D shows the same regressions for the Shale Oil Index. Here the effect of the Shale Discovery portfolio is markedly different, even thought the OPEC announcement effect is very similar to those above. The two shale variables are extremely strongly correlated during the shale period, with coefficeints between 2.5 and 4, approximately (the smaller coefficient when controlling for the market return). During the other time periods the correlation is much weaker and not robustly significant, as expected. This suggests that, even though the Shale Discovery portfolio return explicitly does not include any shale oil firms, it loads strongly on industries that benefit from the shale revolution through their production chain

Figure 2: Cumulative Returns on Mimicking Portfolios



links or other possible spillovers.

4.6 Explaining the Stock Market Performance

Ultimately, we would like to understand the role of the technological innovations in the shale oil sector on the U.S. stock market as a whole. A natural way to do this is via performance attribution, which, in our case, amounts to regressing the market return on the same portfolios we used to correlate with the oil price and oil and gas indices above. Table 4 presents the results. In the periods prior and during the financial crisis. The (insignificantly or marginally significant) positive exposure of the market to the shale portfolio means that the market return in the presence of an essentially zero return to the shale mimicking portfolio suggests that the latter has no explanatory power for the market. Meanwhile, the sign of the market

Table 3: Explaining Oil Prices and Index Returns with Characteristic Portfolio Returns

Panel A: Oil Price Changes

	Pre-Crisis		Crisis		Post-Crisis		Shale Oil Period	
OPEC Announc. Portfolio	-3.421***	-3.362***	-5.583***	-5.469***	-3.217***	-3.126***	-4.368***	-4.281***
	(0.292)	(0.283)	(1.213)	(1.321)	(0.524)	(0.469)	(0.583)	(0.580)
Shale Discovery Portfolio	0.281	0.337	3.286*	3.191	-0.382	-0.846	2.355***	1.951***
	(0.526)	(0.508)	(1.804)	(1.902)	(0.656)	(0.637)	(0.546)	(0.588)
Pre-Crisis Beta Portfolio	-1.029**	-0.079	-2.952**	-2.918**	0.292	-1.520**	0.234	-0.250
	(0.410)	(0.546)	(1.187)	(1.188)	(0.588)	(0.718)	(0.480)	(0.597)
Crisis Beta Portfolio	0.446	0.983*	2.258***	1.961*	1.919***	0.219	1.761***	1.241*
	(0.496)	(0.525)	(0.457)	(1.052)	(0.340)	(0.461)	(0.491)	(0.637)
Market Return		-0.419*		0.150		0.832***		0.266
		(0.241)		(0.524)		(0.175)		(0.187)
Weeks	276	276	46	46	139	139	155	155
R-squared	0.428	0.440	0.543	0.544	0.507	0.584	0.456	0.465

Panel B: S&P Integrated Oil & Gas Index Returns

	Pre-Crisis		Crisis		Post-Crisis		Shale Oil Period	
OPEC Announc. Portfolio	-1.922***	-2.077***	-1.773***	-1.127***	-1.476***	-1.335***	-1.706***	-1.354***
	(0.160)	(0.106)	(0.506)	(0.389)	(0.322)	(0.180)	(0.362)	(0.234)
Shale Discovery Portfolio	0.227	0.080	-0.836	-1.373**	0.765	0.049	1.393***	-0.235
	(0.317)	(0.246)	(0.789)	(0.632)	(0.509)	(0.280)	(0.425)	(0.234)
Pre-Crisis Beta Portfolio	1.470***	-1.026***	-1.523*	-1.327**	1.384***	-1.417***	0.725**	-1.228***
	(0.184)	(0.241)	(0.807)	(0.511)	(0.405)	(0.291)	(0.322)	(0.215)
Crisis Beta Portfolio	1.729***	0.318	1.526***	-0.155	1.956***	-0.670***	1.703***	-0.393*
	(0.306)	(0.219)	(0.269)	(0.462)	(0.340)	(0.209)	(0.365)	(0.205)
Market Return		1.102***		0.852***		1.286***		1.071***
		(0.077)		(0.254)		(0.063)		(0.056)
Weeks	276	276	46	46	139	139	155	155
R-squared	0.538	0.753	0.597	0.712	0.536	0.862	0.342	0.761

Panel C: Shale Gas Index Returns

	Pre-Crisis		Crisis		Post-Crisis		Shale Oil Period	
OPEC Announc. Portfolio	-3.520***	-3.664***	-6.263***	-4.996***	-2.796***	-2.651***	-3.111***	-2.818***
	(0.195)	(0.192)	(0.911)	(0.687)	(0.603)	(0.532)	(0.614)	(0.569)
Shale Discovery Portfolio	0.394	0.258	2.700*	1.646	-0.090	-0.824	2.321***	0.965
	(0.421)	(0.399)	(1.466)	(1.120)	(0.896)	(0.761)	(0.604)	(0.613)
Pre-Crisis Beta Portfolio	1.987***	-0.329	-1.445	-1.061	0.694	-2.173***	0.327	-1.298**
	(0.260)	(0.389)	(1.100)	(0.740)	(0.655)	(0.751)	(0.525)	(0.536)
Crisis Beta Portfolio	2.228***	0.919**	3.819***	0.519	4.020***	1.331**	3.357***	1.613***
	(0.366)	(0.393)	(0.475)	(0.902)	(0.507)	(0.667)	(0.591)	(0.598)
Market Return		1.022***		1.672***		1.316***		0.892***
		(0.127)		(0.393)		(0.209)		(0.175)
Weeks	276	276	46	46	139	139	155	155
R-squared	0.635	0.711	0.769	0.858	0.550	0.663	0.386	0.487

Panel D: Shale Oil Index Returns

	Pre-Crisis		Crisis		Post-Crisis		Shale Oil Period	
OPEC Announc. Portfolio	-3.478***	-3.621***	-5.283***	-4.261***	-3.088***	-2.975***	-3.863***	-3.487***
	(0.198)	(0.198)	(0.672)	(0.543)	(0.488)	(0.426)	(0.493)	(0.356)
Shale Discovery Portfolio	0.802*	0.668*	2.349**	1.499*	0.652	0.080	4.185***	2.449***
	(0.412)	(0.383)	(1.127)	(0.795)	(0.707)	(0.592)	(0.612)	(0.556)
Pre-Crisis Beta Portfolio	1.557***	-0.729**	-2.086**	-1.776***	1.226**	-1.012*	1.903***	-0.179
	(0.203)	(0.329)	(0.865)	(0.565)	(0.524)	(0.609)	(0.508)	(0.499)
Crisis Beta Portfolio	1.949***	0.657**	2.981***	0.319	3.347***	1.248***	3.414***	1.179**
	(0.339)	(0.329)	(0.336)	(0.650)	(0.374)	(0.442)	(0.597)	(0.542)
Market Return		1.009***		1.349***		1.027***		1.142***
		(0.117)		(0.273)		(0.150)		(0.125)
Weeks	276	276	46	46	139	139	155	155
R-squared	0.622	0.706	0.774	0.868	0.647	0.737	0.560	0.711

Standard Errors in Parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Explaining Market Returns with Characteristic Portfolio Returns

	Pre-Crisis		Crisis		Post-Crisis		Shale Oil Period	
Shale Discovery Portfolio		0.13		0.63		0.56*		1.52***
		(0.22)		(0.59)		(0.33)		(0.33)
OPEC Announc. Portfolio	0.18*	0.14	-0.49*	-0.76**	0.03	-0.11	-0.05	-0.33
	(0.10)	(0.10)	(0.26)	(0.37)	(0.18)	(0.20)	(0.25)	(0.23)
Pre-Crisis Beta Portfolio	2.26***	2.27***	-0.26	-0.23	2.16***	2.18***	1.67***	1.82***
	(0.12)	(0.12)	(0.53)	(0.53)	(0.23)	(0.24)	(0.31)	(0.25)
Crisis Beta Portfolio	1.26***	1.28***	1.96***	1.97***	2.04***	2.04***	1.77***	1.96***
	(0.21)	(0.23)	(0.20)	(0.19)	(0.20)	(0.20)	(0.33)	(0.30)
Constant	0.03	0.03	-0.28	-0.24	0.36***	0.33**	0.40***	0.32***
	(0.07)	(0.07)	(0.35)	(0.35)	(0.12)	(0.13)	(0.12)	(0.11)
Observations	276	276	46	46	139	139	155	155
R-squared	0.61	0.61	0.79	0.79	0.71	0.72	0.32	0.43

Standard Errors in Parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table shows time series regressions of aggregate stock market returns on characteristic portfolio returns in four subperiods. The characteristic portfolio returns are constructed as the weekly slope coefficients in a Fama-Macbeth regression of the cross-section of industry returns on the OPEC Announcement Return, the Shale Discovery Return, and industry market betas calculated in both the pre-crisis and crisis periods. The three oil indices are not included in the original cross-sectional regressions.

exposure to the OPEC Announcement portfolio flips sign, as rising oil prices during the boom years give way to the collapsing oil the crisis (and industries benefitting from this not falling as much as the market overall). The beta mimicking portfolios are generally very highly correlated with the market return across subsamples (except during the crisis, when the explanatory power of pre-market betas falls).

The far more striking results occur in the shale period. In this period, both the market return and the shale portfolio earned highly robust positive returns. However, when the market return is regressed upon the return to the shale portfolio, this beta of the market on shale is much higher (roughly 1.5) and extremely statistically significant. Moreover, adding the Shale Discovery to the regression containing the OPEC and beta controls increases the R^2 from 0.32 to 0.43, suggesting that during this period news about shale oil are responsible for about 11% of the variation in the aggregate stock market. In the other periods the contribution of shale to the market variance is essentially zero.

4.7 Economic Magnitudes

We can use the coefficients in Table 4 to estimate the overall value effect of shale oil development. We know from the Fama-Macbeth regressions in Table 2 that the average shale discovery portfolio return is 7.1 basis points per week during the shale oil period. Therefore, over the 150 week shale oil period, the total cumulative return is 7.1 basis points $\times$ 150 = 10.65%. We then multiply this return by the coefficient from the shale discovery portfolio in Table 3 to get 10.65% $\times$ 1.52 = 16.19%. Therefore, the overall value effect of shale, implied by asset prices is 16.19% of the U.S. total equity market capirtalization as of the beginning of the shale period. The total market value at the beginning of the shale period was \$16 trillion, therefore the total value effect derived from our methodology is 16.19% $\times$ \$16 trillion = \$2.6 trillion.

How plausible is this figure? As a back of the envelope check on this, we can compare this figure to the estimated value of the capital expenditures being spent on shale over time. According to the Oil & Gas Journal, capital spending by the Oil and Gas Industry in the U.S. was estimated to be \$338 billion in 2014. The Baker Hughes rig count implies that roughly 78% of this activity is associated with shale oil development. Despite the recent downturn in prices, the EIA expects shale oil development to persist for many years. Assuming a 15 year life on this development and a 10% annual discount rate, suggests that the present value of cash flows associated with shale oil development is \$2 trillion. However, the 15 year life assumption above is based on existing shale oil production relative to proved reserves, as outlined by the EIA. The extent to which new discoveries are made, or reserves increase, the higher the expected life of the development will be and the greater the value of the resource. Given this back of the envelope calculation, the \$2.6 trillion implied by asset prices using our methodology seems plausible.

As discussed earlier, this result likely understates the true impact of shale production on the U.S. economy due to the fact that decreases in oil prices or long-run oil price uncertainty, which are both consequences of the increased production, are also likely to have a positive effect but are largely excluded from our analysis. Still, it suggests that the reprieve from the high uncertainty regarding the long-run oil supply has had a significant effect on stock market returns in the last 5 years.

4.8 Robustness: FOMC Announcements

One concern in interpreting the regressions of the total stock market return on the Shale Discovery portfolio return is that it may be simply picking up the changing market beta of the shale mimicking portfolio itself. While this change is likely driven by the fact that shale oil became a more important part of the U.S. economy, we would like to avoid spuriously attributing market-wide shocks originating elsewhere in the economy to shale simply due to the increased covariation between the two.

In order to address this concern we include an additional control variable that helps identify shocks that are exogenous to shale news. Savor and Wilson (2014) show that market beta is a good predictor of expected returns on stocks during days of the announcements by the Federal Open Market Committee, which are the days when the bulk of the equity risk premium is realized. Given the potential importance of monetary policy (and the Quantitative Easing program) during the shale period these FOMC announcement days are ideal for identifying non-shale shocks to U.S. stocks. We repeat our main tests, the Fama-MacBeth regressions of industry returns on the shale and OPEC announcements, including as an additional control industry betas estimated over the 12 FOMC announcement days in our sample.

Table 5 presents the results in Panel A. It is clear that the estimated impact of the shale announcement returns is completely unaffected by the control, as all of the coefficients are essentially the same and the FOMC beta has no significant impact on the cross-section of industry returns. Nevertheless, we construct a new set of mimicking portfolios using the slopes from this regression, and repeat our analysis of the time-series performance of the total stock market. Panel B of the table shows that the FOMC beta portfolio is indeed quite strongly correlated with the market return over the shale period, with the beta equal essentially to one, as expected. However, it only helps strengthen the effect of the Shale portfolio on the market return, raising the coefficient to 1.68. This shows that the covariation between the shale innovations that we identify using the Shale Discovery portfolio and the aggregate stock returns is not likely to be driven by variables that are altogether outside the shale oil sector, thus validating our approach.

Table 5: Robustness Check: Effect of Shale Year FOMC days on Returns and Market Beta

Panel A: Fama-Macbeth Regressions of Industry Returns

	Industry Average Returns			
	Pre-Crisis	Crisis	Post-Crisis	Shale Years
Shale Discovery Returns	-0.049*	0.006	0.053	0.082**
	(0.027)	(0.151)	(0.036)	(0.032)
OPEC Announc. Returns	-0.160***	0.143	-0.019	0.149***
	(0.055)	(0.294)	(0.061)	(0.046)
Pre-Crisis Beta	0.069*	-0.067	0.014	-0.039
	(0.042)	(0.143)	(0.047)	(0.034)
Crisis Beta	-0.014	-0.077	-0.001	-0.002
	(0.029)	(0.340)	(0.063)	(0.031)
FOMC Announc. Beta	-0.002	0.178	-0.083	0.055
	(0.080)	(0.380)	(0.104)	(0.099)
Constant	0.102	-0.061	0.367**	0.319**
	(0.114)	(0.609)	(0.186)	(0.137)
Observations	20,976	3,496	10,564	11,780
Number of Weeks	276	46	139	155

Panel B: Explaining Aggregate Market with Characteristic Portfolios

	Aggregate Market Returns			
	Pre-Crisis	Crisis	Post-Crisis	Shale Years
Shale Discovery Portfolio	0.14	0.70	0.54	1.68***
	(0.23)	(0.81)	(0.33)	(0.32)
OPEC Announc. Portfolio	0.14	-0.80	-0.02	-0.40*
	(0.10)	(0.51)	(0.21)	(0.23)
Pre-crisis Beta Portfolio	2.27***	-0.21	2.11***	1.93***
	(0.12)	(0.54)	(0.22)	(0.25)
Crisis Beta Portfolio	1.27***	1.97***	2.17***	1.66***
	(0.23)	(0.19)	(0.21)	(0.32)
FOMC Ann. Beta Portfolio	0.10	0.96	-0.63*	1.05***
	(0.23)	(0.76)	(0.37)	(0.34)
Constant	0.03	-0.24	0.31**	0.31***
	(0.07)	(0.36)	(0.12)	(0.11)
Weeks	276	46	139	155
R-squared	0.61	0.80	0.73	0.45

Standard Errors in Parentheses

*** p<0.01, ** p<0.05, * p<0.1

Panel A shows the results of Fama-Macbeth regressions of average returns on the same variables as in table 1 but also including the industry market beta calculated using returns on the 12 FOMC announcement days in the Shale Year period. Panel B repeats the regressions of Table 3 but using the FOMC Beta characteristic portfolio as an additional control.

5 Conclusion

In a matter of a few years the technological innovations associated with fracking have revolutionized the U.S. oil market. The long run impact of this technology is uncertain, however. The continued ability of shale companies to reduce costs of extraction is actively debated, as are the amounts of the recoverable hydrocarbons trapped in shale rock. Its importance for future economic growth also depends on the economy's long-run response to oil supply shocks, which is difficult to estimate. We use information contained in asset prices to evaluate the contribution of shale oil to the U.S. economy, to the extent that it is captured in the aggregate stock market capitalization. We find that technological shocks to shale supply capture a substantial fraction of total stock market fluctuations, suggesting that shale oil is an important contributor to the future U.S. economic growth.

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Table 6: Industry Announcement Returns, Betas, and Characteristic Portfolio Weights

	Announcement Returns and Market Betas				Characteristic Portfolio Weights			
	Shale Discovery Return	OPEC Announc. Return	Pre-Crisis Beta	Crisis Beta	Shale Discovery Return	OPEC Announc. Return	Pre-Crisis Beta	Crisis Beta
Shale Oil Producers	6.95	-10.36	0.81	1.48				
S&P Integrated Oil & Gas	-0.04	-5.38	0.82	0.79				
Shale Gas Producers	3.60	-6.89	0.93	1.88				
Oil and Gas Drilling	2.66	-9.04	0.90	1.43	3.71	-5.16	-0.64	-0.36
Business Services	3.03	0.05	1.10	1.09	3.54	-0.15	0.19	-0.59
Engineering Services	2.96	-2.70	1.43	1.46	3.44	-2.04	2.25	-1.13
Copper Production	2.74	-2.03	1.24	0.93	3.12	-2.36	2.64	-3.26
Clothes	2.74	1.29	1.10	1.26	2.65	1.31	-0.87	1.10
Railroads	2.32	-5.13	1.07	1.08	2.52	-3.59	1.33	-2.25
Guns and Weaponry	2.55	-0.28	1.25	1.07	2.40	-0.70	1.75	-1.73
Ground Transportation	2.51	2.06	0.95	0.88	2.23	1.35	-0.75	-0.22
Boxes and Containers	2.43	0.35	1.05	0.98	2.15	0.13	0.19	-0.80
Wholesale	2.35	-0.59	1.13	1.01	2.04	-0.66	0.99	-1.42
Construction Products	2.18	-3.78	1.14	1.33	1.90	-2.12	0.64	-0.52
Industrial Equipment	2.24	-2.39	1.31	1.14	1.87	-2.08	2.52	-2.33
Concrete and Cement Producers	2.39	-3.26	1.33	2.37	1.82	0.42	-2.20	5.49
Paper Products	2.36	0.45	1.21	1.54	1.69	1.27	-0.78	2.05
Stone Quarrying	2.22	-0.36	1.24	1.28	1.55	-0.03	0.77	-0.16
Car Manufacturing and Sales	2.12	0.20	1.29	1.43	1.17	0.65	0.47	0.73
Marine Transport	2.06	-0.27	1.19	1.48	1.11	0.74	-0.48	1.53
Gas Pipelines	1.64	-4.40	0.57	0.91	1.10	-1.91	-2.46	0.09
Mining Equipment	1.69	-7.31	0.95	1.72	1.08	-2.94	-1.73	2.10
Optical Equipment	2.14	2.10	1.44	1.33	0.95	1.36	1.71	-0.14
Game and Toy Manufacturing	2.05	1.69	1.22	1.32	0.90	1.66	-0.08	1.00
Tobacco	1.70	1.18	0.47	0.40	0.81	1.00	-2.57	-0.76
News Media	1.88	0.96	0.78	1.28	0.78	2.30	-3.57	3.23
Shipbuilding	1.77	0.50	0.89	0.86	0.69	0.59	-0.71	-0.44
Insurance	1.82	0.05	0.87	1.35	0.67	1.60	-2.81	2.82
Water Utility	1.67	-1.12	0.98	0.79	0.65	-1.01	0.85	-2.12
Radar and Sensor Systems	1.69	-0.16	0.96	0.80	0.59	-0.21	0.32	-1.52
Game and Toy Stores	1.81	1.23	0.97	1.14	0.56	1.60	-1.33	1.16
Oil Pipelines	1.36	-5.22	0.52	0.98	0.51	-2.08	-2.96	0.62
Design Firms	1.76	0.27	1.30	0.94	0.50	-0.50	2.67	-2.57
Furniture Production	1.78	-0.26	1.08	1.45	0.49	1.09	-1.34	2.10
Aircraft Production	1.70	-0.11	1.09	1.07	0.45	0.16	0.38	-0.53
Power Generation Equipment	1.73	-1.74	1.63	1.45	0.34	-1.52	3.98	-1.94

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	Announcement Returns and Market Betas				Characteristic Portfolio Weights			
	Shale Discovery	OPEC Announc.			Shale Discovery	OPEC Announc.		
	Return	Return	Pre-Crisis Beta	Crisis Beta	Return	Return	Pre-Crisis Beta	Crisis Beta
Research and Development	1.56	0.52	0.89	0.61	0.30	0.00	0.37	-2.13
Scientific Instruments	1.63	-0.02	1.21	0.92	0.27	-0.45	1.99	-2.18
Other Oil Firms	1.20	-8.69	0.84	1.45	0.25	-4.19	-1.16	0.50
Retail Banking	1.66	-0.29	1.11	1.37	0.24	0.78	-0.65	1.32
Media Entertainment	1.71	1.00	1.07	1.35	0.23	1.75	-1.23	1.88
Plastics	1.41	-2.58	1.11	0.89	0.13	-2.03	1.90	-2.66
Defense and Military	1.65	1.16	1.05	1.23	0.13	1.63	-0.96	1.29
Financials	1.78	0.20	1.54	1.77	0.12	1.00	1.25	1.57
Office Equipment	1.59	0.01	1.11	1.19	0.10	0.55	0.03	0.23
Passenger Airlines	1.91	5.64	1.42	1.22	0.05	3.74	1.14	0.52
Restaurants	1.48	1.02	0.99	0.79	-0.05	0.59	0.37	-1.33
Natural Gas Production	1.28	-2.85	0.75	1.01	-0.07	-0.90	-1.63	0.26
Home Products	1.34	1.06	0.53	0.51	-0.10	1.19	-2.49	-0.33
Hotels	1.70	0.92	1.15	2.05	-0.10	3.34	-3.46	6.12
Liquor Producers	1.40	1.83	0.68	0.66	-0.16	1.71	-2.00	0.01
Food Production	1.25	0.87	0.56	0.55	-0.33	1.10	-2.31	-0.33
Waste Management	1.14	-0.61	0.83	0.58	-0.53	-0.58	0.29	-2.28
Commercial Banking	1.36	-0.33	1.04	1.80	-0.60	2.17	-2.99	4.65
IT Services	1.13	-0.02	1.21	0.91	-0.90	-0.32	2.12	-2.20
Petroleum Refining	0.78	-6.85	0.86	1.30	-0.91	-3.15	-0.82	0.17
Communications	1.13	0.53	1.11	0.89	-0.91	0.31	1.16	-1.48
Medical Equipment	0.99	0.46	0.76	0.71	-1.02	0.78	-1.14	-0.55
Electrical Equipment	1.10	-0.44	1.31	1.19	-1.07	-0.14	1.90	-1.06
Personal Services	0.96	0.64	0.74	0.77	-1.13	1.14	-1.61	0.07
Telephone Communications	1.11	0.63	1.45	0.98	-1.16	-0.29	3.71	-2.92
Commercial Equipment	1.05	0.33	1.40	0.93	-1.23	-0.50	3.62	-3.08
Retail Sales	0.96	1.44	1.00	0.84	-1.37	1.20	0.17	-0.76
Agriculture and Farming	0.82	-0.79	0.72	1.02	-1.39	0.84	-2.37	1.30
Electricity Production	0.82	0.95	0.67	0.72	-1.46	1.47	-2.07	0.29
Home Construction	0.93	-1.61	1.44	1.47	-1.49	-0.55	2.21	-0.41
Rubber Products	1.03	0.34	1.49	1.73	-1.64	1.38	1.06	1.77
Pharmaceuticals	0.67	0.49	0.66	0.51	-1.67	0.66	-1.16	-1.20
Software	0.76	0.44	1.07	0.80	-1.73	0.24	1.26	-1.82
Aluminum Refining	0.78	-2.86	1.40	2.02	-1.91	0.16	-0.11	3.14
Other Metal Mining	0.68	-3.85	1.51	1.85	-2.00	-1.26	1.81	0.98
Real Estate Trusts	0.53	-0.37	0.80	1.07	-2.19	1.18	-1.99	1.40
Gas Stations	0.29	-0.25	0.82	0.51	-2.53	-0.20	0.54	-2.45
Farm Equipment	0.42	-0.77	1.28	1.44	-2.74	0.60	0.77	0.80
Lumber	0.32	0.40	1.19	1.45	-3.08	1.73	-0.30	1.82

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	Announcement Returns and Market Betas				Characteristic Portfolio Weights			
	Shale Discovery	OPEC Announc.			Shale Discovery	OPEC Announc.		
	Return	Return	Pre-Crisis Beta	Crisis Beta	Return	Return	Pre-Crisis Beta	Crisis Beta
Chemical Producers	0.07	-1.35	1.10	1.00	-3.23	-0.36	1.17	-1.18
Steel Production and Refining	0.12	-2.24	1.47	1.64	-3.41	-0.36	2.02	0.48
Coal Mining	-0.51	-3.69	1.34	1.69	-4.71	-0.71	1.12	1.16
Gold Mining	-0.99	-7.66	0.86	1.19	-4.97	-3.43	0.07	-0.63