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The shine of precious metals around the global financial crisis

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We analyze the price behaviour of the main precious metals – gold, silver, platinum and palladium – before, during and in the aftermath of the 2007-08 financial crisis. Using the mildly explosive/multiple bubbles technology developed by Phillips, Shi and Yu (2015, *International Economic Review* 56(4), 1043-1133), we find significant, short periods of mildly explosive behaviour in the spot and futures prices of all four metals. Fewer periods are detected using exchange-rate adjusted prices, and almost none when deflated prices are used. We assess whether these findings are indicative of bubble behaviour. Convenience yield is shown to have little efficacy in this regard, while other fundamentals proxy variables and position data offer only very limited evidence against prices having been anything other than fundamentals-driven. Possible exceptions are in gold in the run-up to the highpoint of the financial crisis, and in silver and palladium around the launch of specific financial products. Some froth, however, is reported and discussed for each metal.

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1. Introduction

This paper examines the price behaviour of the precious metals gold, silver, platinum and palladium before, during and in the aftermath of the 2007-08 financial crisis. Our interest stems firstly from the empirical observation that there was a sustained pre-crisis run-up in the prices of precious metals and other commodities prior to a sharp, downward adjustment in the midst of the crisis in 2008. The post-crisis data indicate that all four metals eventually enjoyed price run-ups that superseded pre-crisis levels, and experienced some sharp, downward adjustments at various points. In our analysis of precious metals prices, we therefore test for departures in trend that offer evidence of periods of exuberance and collapse, possibly on multiple occasions during the sample period. In particular, we examine whether any of the metals prices exhibited bubble behaviour, by which we mean changes beyond the fundamental variables that economic theory suggests underlie them. This issue is important from a policy perspective; for if prices are seen to diverge from fundamental values, this may indicate speculative behaviour on the part of economic agents. Within the class of commodities, it is especially relevant for precious metals because of their perceived role as investment assets.

We focus particularly on the behaviour of precious metals around the financial crisis. In the aftermath of the crisis, policymakers have sought to limit the speculative activities of economic agents, seeing these as being contributory to (past and potential future) financial crises. The *2010 Dodd-Frank Wall Street Reform and Consumer Protection Act* introduced in the United States, which allows the regulator to limit position sizes in certain U.S. commodity futures markets, is the canonical example in this regard. If this policy-based intervention were based on incorrectly perceived speculation when the market is truly efficient, it may produce misleading price signals that are welfare reducing through a maligning effect on the allocative efficiency of the market. It is therefore important that the issue of identifying fundamentals-based price behaviour and non-fundamentals-based speculation is put on a proper evidential basis through statistical testing, such as is provided by this paper.

Our analysis of precious metals prices is more extensive than simply an assessment of whether prices during the sampling period were determined by fundamentals or speculation. More broadly, we seek to provide a comprehensive description and explanation of the key time series properties of the precious metals complex around the financial crisis. Towards this end, we apply the mildly explosive/bubbles detection technology recently proposed by Phillips, Shi and Yu (2015a&b: PSYa&b), which offers a basis upon which to test for departures in trend in the direction of mildly explosive alternatives, in a way that is robust to multiple and/or periodically collapsing bubbles of the type discussed by Evans (1991). The technology also offers a statistically consistent basis upon which to date the origination and collapse of bubbles. Here, we are interested in whether the precious metals complex as a whole, or any of gold, silver, platinum or palladium in particular, exhibited any of the type of price exuberant behaviour documented in other commodity markets in the run-up to the financial crisis.[1] We are also interested in whether there was any marked or exceptional behaviour during and in the aftermath of the crisis when economic policymaking was non-standard, given the various special properties such as "store of value", "safe haven status" or "hedge against inflation" that are typically ascribed to the precious metals to varying degrees.

The PSY procedure identifies mildly explosive periods in the sample that indicate departures from trend, which are then assessed using proxy variables thought to represent economic fundamentals for bubble behaviour (by which we mean behaviour that indicates departure from "fundamental value"). In the pioneering paper, Phillips, Wu and Yu (2011, PWY) used dividend yield as the natural fundamental proxy variable for the NASDAQ stock price index. Specifically, the ratio of the NASDAQ index and dividend yield on the basis of monthly data was used to test whether there was a non-fundamentals-based departure from trend in the form of explosivity in NASDAQ stock prices. As Figuerola-Ferretti et al. (2015) explain, this procedure is impractical to apply to commodities because the ratio of commodity prices and the natural counterpart to dividend yield – convenience yield – becomes uninformative when the convenience yield approaches zero, which it can do for perfectly natural reasons. We demonstrate that this same problem affects precious metals, where the measured convenience yield can be low or even negatively valued, making the ratio between the commodity price and measured convenience yield uninterpretable.

A second reason for our needing a broader approach towards fundamentals than in PWY (2011) is that we here focus on higher frequency (weekly) data, which enables

[1] See, e.g., applications to agricultural commodities by Etienne et al. (2014, 2015) and to non-ferrous metals by Figuerola-Ferretti et al. (2015).

us to test for potentially relevant, shorter periods of mild explosivity in prices than monthly data would permit, but this comes at a cost because many natural fundamentals proxy variables such as industrial production, which might permit a distinction between gold and silver, are usually collected at the monthly frequency at best.[2] Accordingly, the interpretation of our results, while always evidence-based, is to some extent pieced together using a variety of sources. These include, however, position data that allow for a direct test for speculative behaviour in each of the four precious metals. Here, we have preferred to employ as candidate proxy variables the fundamentals that have been specifically proposed in the precious metals literature, such as gold lease rates, convenience yield and bar hoarding, along with some reference to the macroeconomic and financial environment, rather than to employ a more data-based approach, such as Batten et al. (2010) proposed for gold, which assessed a large number of potential proxy variables in a data-based manner. This type of data-based approach is more feasible for monthly data and is currently the subject of work by the authors that is complementary to this paper.

The advent of the PWY/PSY technology has finally addressed the statistical problems in bubbles testing that were identified by Evans (1991) in the seminal tests proposed by Diba and Grossman (1984, 1988) based on the standard application of unit root and co-integration tests, that were applied to gold *inter alia*. This has brought efficacy to recent empirical work on bubbles testing. In the context of precious metals, Homm and Breitung (2012) applied the prototype PWY (2011) test to real gold prices over a sample between January 1985 and November 2010 and found no evidence for a mildly explosive region at any significance level. They also applied an alternative, Chow-type test which was significant at the 10% level for both weekly and monthly data. In preliminary work for UNCTAD, Gilbert (2010) used the same prototype PWY test during a different sampling period – just the 2006-08 crisis – and reported no mildly explosive episodes in gold and silver, his representatives of the previous metals complex. And again using same test, but over a different sample period, Baur and Glover (2015) found evidence for mild explosivity in nominal monthly prices in gold in the decade from around 2002 that was punctuated by the

[2] The results we obtained using monthly data were qualitatively the same as for weekly data but there was evidence to suggest the algorithm to detect mildly explosive periods was less accurate. Results are available from the authors on request. Research on the behavior of the PSY test applied to the *same series* sampled at *different frequencies* is currently being undertaken by the second author.

financial crisis. Harvey et al. (2016) used the PWY test to identify numbers of mildly explosive episodes in gold, silver and platinum in a paper focussed on making the test robust to changes in volatility during the sample period, but without date-stamping explosive periods. Their robust tests based on weekly data find at least one mildly explosive region in all three metals at the 10% significance level but only in silver at the 5% level.

Two recent papers have applied an early version of the PSY procedure to gold.[3] Zhao et al. (2015) considered a sample period from January 1973 – March 2014 using nominal monthly spot prices and identified five mildly explosive periods in gold, including the periods October 2007-August 2008 and September 2009-April 2013. Long et al. (2016) considered the period April 1, 1968 – August 6, 2013 using biweekly nominal spot prices obtained by averaging daily data, and identified five similar mildly explosive periods, including November 2007-July 2008 and April 2010-February 2012. None of the above papers, whether based on the PWY or PSY procedures, test for departures in prices from fundamental values.[4]

Other tests for mildly explosive/bubble behaviour involving precious metals, but not using the PWY/PSY methodology, include Bialkowski et al. (2015) who used a regime-switching model alongside various proposed measures of fundamental value. Although their results were sensitive to the choice of fundamental, they registered recent association between the gold price and the European sovereign debt crisis. Lucey and O'Connor (2013) also used a regime-switching approach but considered lease rates – the interest that can be earned by lending the physical metal at various maturities – as the measure of fundamental value. They reported some evidence for bubbles, but only when the variance was constant across regimes. Barone-Adesi et al. (2014) also used lease rates to assess speculative behaviour in gold. In a notable earlier paper, Bertus and Stanhouse (2001) constructed a supply-demand model for

[3] Both papers used the procedure outlined in Phillips et al. (2012), which differs from the final version which offers a rule based on size and power considerations for selecting the smallest sample width fraction, r_0, upon which the key statistics used in the paper depend.

[4] Baur and Glover (2015) argue that mildly explosive periods can be equated with speculation and propose their own framework for defining bubbles based on heterogeneous agents. Figuerola-Ferretti et al. (2015) offered a context, however, in which inelastic mine supply combined with fluctuating demand saw departures in non-ferrous metals prices from the random walk with drift model that could be explained by a standard stock-to-use-ratio fundamental. We prefer, therefore, to follow the PSY approach to bubbles, in terms of their representing departure from fundamental value. The PSY procedure encompasses rational bubbles, intrinsic bubbles, herd behavior and time-varying discount factor fundamentals. See Footnote 5, p. 1045 in PSY (2015a).

gold based on dynamic factor analysis and, using quarterly data, found little evidence for long bubbles using conventional significance levels. If the stringency of the testing is relaxed, they documented some support for shorter bubbles around significant periods such as the worldwide stock market crash on Black Monday (19th October 1987). Emekter et al. (2012) found that 11 of 28 commodities, including gold and platinum, but not silver and palladium, showed evidence of bubbles using a duration dependence test and the interest-adjusted basis as a proxy for convenience yield.[5]

This paper contributes to the extant literature in several ways. Firstly, we offer a balanced treatment of the properties and underpinnings of the precious metals complex before, during and in the aftermath of the Global Financial Crisis, in what we believe is the most comprehensive such study to date. Looking at the four main metals furnishes us with a wider lens through which we can examine the financial crisis than can be achieved by looking at, say, just gold alone. Secondly, we use the PSY (2015a&b) test procedure to examine the mild explosivity/bubbles properties of the precious metals complex during the crisis. Statistically, this procedure supersedes both the original PWY (2011) procedure and the improved, sequential version proposed by PSY (2015a) in its robustness to testing for multiple and/or periodically-collapsing bubbles. And thirdly, we offer an evidence-based assessment of whether prices departed from fundamental values in the spirit of the PSY approach. Our work is distinguished from the two recent applications of the PSY test by Zhao et al. (2015) and Long et al. (2016) through the detail of its focus on the financial crisis; its consideration of both spot and futures prices; its treatment of the precious metals complex as a whole; its evidence-based approach in assessing fundamentals and speculation; and in the robustness of its analysis to a potentially changing dollar *numeraire*.

The paper is organized as follows. Section 2 introduces the four main precious metals and describes their raw time series properties during the sample period. Section 3 briefly discusses the supply and demand constituents of the precious metals. Section 4 summarizes the PSY bubbles-testing methodology including the wild bootstrap procedure justified for the PWY test by Harvey et al. (2016). In Section 5, the PSY test is applied to raw spot and futures nominal price series for each metal, and series

[5] The interest-adjusted basis is derived from the difference between the current spot price and the contemporaneous futures price, net of interest.

deflated by the currency value of the Special Drawing Rights (SDR) basket and by the U.S. Producer Price Index (PPI). In Section 6, we offer some interpretation and analysis based on fundamentals proxy variables and Commitments of Traders (CoT) position data published by the U.S. Commodity Futures Trading Commission (CFTC). Section 7 concludes.

2. Precious metals prices since 2000

We consider spot and front-month (one-month) weekly COMEX prices from the beginning of the last decade until the end of 2013 for the four major precious metals: gold, silver, platinum, and palladium.[6] The appropriateness of considering the front-month contract stems from its being the most liquid futures contract. Precious metals are by tradition traded in U.S. dollars per troy ounce (oz). Because the dollar as *numeraire* is itself changing, it is possible that inflation and other monetary variables have real effects, as could the value of the dollar exchange rate. This consideration is likely to be more important for precious metals, which to various degrees play the role of investment assets, than it is for, say, agricultural commodities. For robustness, we therefore also consider the spot and futures prices deflated by the currency value of the SDR basket, and by the U.S. PPI.[7] Our primary data source is the Bloomberg International database.

We shall informally divide the sample into three periods of interest, notionally corresponding to periods before, during and after the crisis. In the pre-crisis period, many commodity prices began showing significant rises from as early as around mid-2003, then sharper rises and possibly some exuberance, especially from late 2007 and

[6] The COMEX exchange in New York currently operates as a designated contract market of the CME Group, the world's largest and most diverse options and futures market place. Precious metals are predominantly traded on the London Bullion Market (gold and silver), the London Platinum and Palladium Market, and COMEX. The former two are the metals' main physical markets where a bidding process generates daily reference prices for each metal. Fund activity is mainly concentrated on COMEX. We shall, however, use both spot and futures COMEX prices to avoid any potential non-synchronous trading issues, given that we later discuss convenience yield which is a function of both spot and futures prices at a given point in time.

[7] The currency value of the SDR is determined using a basket of major currencies (the U.S. dollar, the Euro, Japanese Yen and pound sterling) based on market exchange rates. Adjusting nominal world price series by the SDR currency value or the PPI index confers some robustness on our approach but it is not definitive: prices can rise in one currency and fall in another, and using a U.S. price index is merely one approach, albeit the usual one, to deflate world prices denominated in dollars. For wont of a better alternative, Deaton and Laroque (1996) in their celebrated paper deflated commodity prices by the U.S. Consumer Price Index and the literature has followed their lead. Here, however, we have deflated by the U.S. PPI index so that our results can be directly compared with those by Figuerola-Ferretti et al. (2015a) in their study of non-ferrous metals prices, where it was natural to use an index constructed at the wholesale/producer stage.

into 2008. Indeed, it was during the early part of this period, around or even just before the nascent growth in U.S. subprime mortgage lending (whose later accelerated growth and collapse many investigators believe played a precipitant role in the crisis) that the then Federal Reserve Chairman Ben Bernanke publicly asked the question that has motivated much post-crisis research:

> "Can the Federal Reserve (or any central bank) reliably identify 'bubbles' in the prices of some assets, such as equities and real estate? And, if it can, what if anything should it do about them?"[8]

One important question we address, therefore, is whether, and to what extent, precious metals were prone to bubble-like behaviour in the run-up to the financial crisis. We test for possible departures in trend in each metal in the direction of mild explosivity and then assess through the lens of the financial crisis whether there is evidence that points towards any such departures being fundamentals-based or speculatively driven. Our aim is therefore more specific than a study of the financial crisis *per se* and, given that the precise dates of its active phase are open to interpretation we will limit ourselves to assessing our findings against a timeline of events we now describe.

The key events in the 2007-08 financial crisis are likely to have stemmed from the U.S. housing crisis that was deepening in early 2007. In late-February, the Federal Home Loan Mortgage Corporation, Freddie Mac, announced it would no longer purchase the most risky subprime mortgage loans. In June, The Bear Stearns Companies, Inc., a New York-based investment bank and securities trading and brokerage firm, pledged a collateralized loan to bail out one of its hedge funds. Three weeks later, Bear Stearns disclosed two of its subprime hedge funds had lost nearly all their value given the decline in the market for subprime mortgages. They were liquidated on July 31, sparking action against Bear Stearns and contagion effects that would go on to affect credit markets and the real economy.

We are particularly interested in the timeline of 2008, where there was an initial run-up in all four precious metals prices and generally across the commodities sector as the financial crisis developed. In January and February, there was also a notable South African power crisis that affected platinum and palladium mine production. In March, the U.S. Federal Reserve agreed to guarantee $30bn of Bear Stearns assets in connection with the government-sponsored sale of the investment bank to JP Morgan Chase & Co., a multinational banking and financial services holding company that is

[8] http://www.federalreserve.gov/Boarddocs/Speeches/2002/20021015/default.htm

the largest bank in the U.S. In the background, the dollar had been depreciating and the oil price rising, and in mid-July the dollar hit a record low against the Euro around the same time as the oil price hit a record high. Precious metals prices began declining in the second quarter. We shall therefore assess whether there are fundamentals that give an indication as to why prices *fell* at the most acute stage of the crisis, given that this price behaviour would appear to contradict the safe-haven status usually accorded to precious metals. In early-September, the U.S. government took control of Freddie Mac and its sister mortgage finance company, the Federal National Mortgage Association, Fannie Mae, to aid the distressed housing market. On September 15, the day many investigators including Phillips and Yu (2011) dated as the key point of the crisis, Lehman Brothers Holdings Inc., a global financial services firm, filed for bankruptcy amid a collapse in the junk bond market. This was the largest investment bank to fail in the U.S. for nearly twenty years, and sparked off contagion effects. A small spike is seen in the gold price during September, but not a rally, and again gold and other precious metals remained subdued. We will report evidence that supports the conjecture that the fall in investment demand in precious metals, and in gold in particular, arose from positions being unwound to facilitate margin calls in more traditional financial assets. In late-September, the U.S. government rejected a $700bn Wall Street financial rescue package causing a severe stock market dip, but managed to pass a revised version of this package, called the Troubled Asset Relief Program (TARP), on October 3. Precious metals showed some recovery in the aftermath of its imposition, and rallied into the following year, even although from December 2008, the U.S. economy became officially in recession.

In the aftermath of the 2007-08 period, we focus more widely on worldwide events that may have influenced precious metals prices. In March, the U.S. Federal Open Market Committee (FOMC) decided to increase substantially the Federal Reserve's balance sheet by purchasing (an additional) £750bn of mortgage-backed securities and announcing the purchase of $300bn of longer-term U.S. Treasury securities over the following six months. In April, China revealed a 454-tonne increase in its gold reserves. In August, in the context of rising gold prices, the IMF approved the sale of 403.3 tonnes gold; and in October, India bought 200 tonnes from them. In 2010, concerns began to mount over financial instability in Europe, with sovereign debt playing a key role in Portugal, Ireland, Italy, and especially Greece and Spain. Bialkowski et al. (2015) found association between the gold price and the European sovereign debt crisis when the latter acted as a fundamental, although as noted above, their results were sensitive to the choice of fundamental. We are also interested to see whether there was any departure in trend in precious metals complex as a whole around this time and, if so, whether this associates with the timeline of the European sovereign debt crisis during its peak period between February and June. Other important events in 2010 included, in early-November, the FOMC announcing a second round of quantitative easing (QE2), this time buying $600bn of U.S. Treasury securities by the end of the second quarter of 2011.

The main events in 2011 pertaining to precious metals included the Greek government's passing austerity cuts in June, bringing some stability to the Eurozone; the credit ratings agency Standard and Poor's downgrade of U.S. sovereign debt in August; and, after earlier disagreements, the FOMC announcement in September of "Operation Twist" involving the purchase of $400bn of U.S. securities with long maturities and the sale of securities with maturities of less than 3 years, in a bid to extend the average maturity of the Federal Reserve's own portfolio. This programme was a precursor of the eventually-agreed third quantitative easing programme (QE3). We shall see that gold and silver prices in 2011 to some extent were correlated with the macroeconomic environment, but there were also relevant demand-side considerations, especially for silver. No departures from trend in any precious metal were detected after 2011.

The key properties of the raw spot price series across the main markets during the sample period are as follows.[9]

[Figure 1A around here]

2.1. Gold

In 2000, the gold price averaged around $280/oz, fell around 3% in 2001 and then rose just under 15% in 2002. In 2003, gold began what would become a sustained rise in prices up to the financial crisis, and ended the year at a high of over $400. After a solid year in 2004, gold began to rise more spectacularly towards the end of 2005, breaching the $500 mark and the price then rose sharply, reaching around $725 – a 26-year nominal high – in mid-May 2006, before a correction. The gains in silver in the second quarter of 2006 were even more spectacular. In 2007, the gold price advanced strongly, in November reaching around $840, just below its all-time

[9] Source material for the following subsections, beyond the data themselves, include the annual GFMS *Gold Surveys*, The Silver Institute's *World Silver Surveys* and Johnson Matthey's *Platinum Reports*.

nominal high of $850 in January 1980, before falling back slightly. The general, sustained rise in gold continued, however, and in March 2008, in the run-up to the financial crisis, gold posted a (London) nominal high of $1,011.25 just before the collapse of Bear Stearns. Another price spike was seen in July (around the time the oil price hit a record high). The general picture in later 2008, however, saw the gold price come under sustained pressure as the financial crisis unfolded, spiking again just briefly after the collapse of Lehman Brothers, before falling to nearly $700 in October. Prices then gained again in December such that, overall, the average annual price rose in 2008 for what was the seventh consecutive year. It rose again in 2009 (from a relatively low base) by nearly a quarter, with a fourth-quarter rally taking the price to a new nominal record high of over $1,200. In 2010, prices again rallied after a subdued first quarter but gains were much less than for silver and copper (in the context of recovering post-crisis industrial base). 2011 saw the annual average price increasing for a tenth consecutive year and, by just below 30%, was largest proportionate increase since 2006. Prices rose steadily from February to June, then rapidly in July and August, reaching a high in early September of nearly $1,900 before falling back to an extent, during a time when monetary issues were very much in consideration. Silver showed a similar price pattern, with its rise in the first three quarters even sharper than gold's. In 2012, the gold price rallied until late February, declined until mid-May, traded within a narrow band until August, and rallied in August and September. The period was characterized by protracted U.S. congressional wrangling over the budget deficit. 2013 finally witnessed the end to the twelve-year bull-run in gold prices, with the annual average price falling by over 15%. Two violent drops in the first half of 2013 pushed the spot price below $1,200 on separate occasions.

2.2. Silver

Silver's price rose steadily from 2003 until 2008. In 2004 and 2005, its proportionate increase was the largest of the main precious metals; and in 2006, it hit a 25-year high, the average annual price increasing by over 50% year-on-year. An important element of 2006 was the introduction of exchange traded funds (ETFs) in silver in early April.[10] In 2007, prices again performed strongly, the annual average

[10] ETFs are investment funds that are traded on an exchange by participants who are authorized by agreement with the particular ETF distributors. They generally hold assets such as stocks, commodities

rising over 15% to a 27-year high of $13.38/oz. In 2008 - the year the financial crisis came to a head – the spot price had initially risen to a (London) high of $20.92 in March but then dropped to a low of under $9 in October, a pattern that, at least on the surface, was followed by the other precious metals and some other commodities. In spite of the spot price drop, the annual average price in 2008 was still the highest it had been in nominal terms since the 1980's. It declined, however, for the first time in eight years in 2009, though only by around 2%. This figure, however, was largely a result of the highs reached in early 2008 and the slow start in 2009, and masks the rally from a low in mid-January of around $10.50 to a 17-month (London) high of $19.18 in early December 2009. Silver also recorded a large intra-year gain in 2010 and a rally from September 2010 took the price to a 30-year high on December 30th in London of $30.70. Gold, in contrast, managed a weaker (though still substantial) around 25% rise in its average annual price in 2010. In 2011, the rise in silver was dramatic: the London silver fix on April 28th posted a high of $48.70, just shy of the all-time nominal high of $49.95 seen in January 1980. Silver outperformed all precious metals in 2011 in a rising precious metals market: palladium posted a near 40% gain; gold was up just under 30%, although platinum's rise, of only just over 5%, was more modest. In 2012, silver retreated from the highs reached during 2011. This decline contrasted with gold, which rose by over 5% to reach a fresh nominal high.

2.3. Platinum

In January 2001, platinum reached its highest level for almost 14 years at around $645/oz but fell back during the year to reach a low of just over $400 in October before rallying for the remainder of the year. In 2002, successive rallies led to the price increasing by around $150 to the $600 mark. This rise intensified in 2003 with the price reaching a high of just under $850 in December. Platinum rose in early 2004 but then traded sideways, before resuming its rise in the second half of 2005 to a 25-year (London) high of $1,012 in December. Similar patterns were seen in other metals markets, with gold, copper, zinc and aluminium all rising to multi-year peaks. The platinum price was volatile during some months in 2006, especially May and November, alternating with periods of relative calm, before climbing early in 2007. It remained at such levels until September when its price rose sharply higher, reaching a

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or bonds, and can be bought or sold at the end of each day for their net asset value but can trade above or below this value throughout the day.

new record of $1,544 in December. Over the year, it gained around 35% on its 2006 value. Platinum prices in 2008, the year of the financial crisis, moved dramatically, continuing their 2007 advance from an opening fix of $1,530 to an all-time high of $2,276 in March and then fell heavily in the second-half of the year to end at around $900, a level not seen since 2005. Platinum performed strongly again in 2009, rising over 50% from its opening fix to end near its peak of around $1,500 in December. In 2010, it gained over 15%, the rise from September reflecting a gold-led rise in prices across the whole precious metals complex. Until the following September, it largely traded between $1,700 and $1,900 before beginning a decline that saw it lose more than a fifth of its value in 2011 overall. In 2012, after opening at just over $1,400, it again reached over $1,700 by late February, but soon returned to around its opening level and was relatively subdued for the rest of the year, save for a brief rise back to $1,700 in early October (coinciding with labour disruption in South Africa). The price rose to this level again in February 2013 before falling back with gold around June, recovering slightly later in the year.

2.4. Palladium

Palladium prices rose appreciably in the second half of the 1990's, reaching a record (London) fix of $1,094/oz at the beginning of the sample period, in January 2000. The price slumped to $315 in October before beginning to rally again, although prices remained weak in 2002. Palladium, in contrast to platinum, remained subdued in 2003 and 2004. It broadly followed the direction of the other precious metals in 2005, trading within a narrow range for most of the year, followed by a strong rally at the end. It outperformed platinum in 2006 and kept pace with it in the first half of 2007. In the year of the financial crisis 2008, palladium prices were volatile, like the prices of the other precious metals, beginning the year at $370 and in line with gold and platinum prices climbed to $588 in March, its highest point since 2001, before falling to end the year at around half of its value at the beginning. In 2009, palladium was buoyant around the time of gold's rise to record levels and over the year more than doubled in price to achieve a final fix of just over $400. Palladium was the star performer of the precious metals complex in 2010, doubling again in price between the year's opening and closing fixes. It followed the price of gold on an upward trend for most of the year, and appreciated considerably against platinum. It traded at ten-year highs for several months in 2011 but shed about 20% of its value over the course of the year. It traded in a relatively narrow range in 2012, beginning at just over \$650, rising to over \$720 in February before ending the year at just under \$700. It was initially firmer in 2011 before dropping in April. Over the final six months of the year, platinum traded in a range between \$680 and \$760.

While our main interest is in the spot and front-month futures nominal prices, which represent actual market outcomes, we also report exchange-rate adjusted prices and inflation-adjusted prices, which add to our evidence base in a way that aids the robust interpretation of our results. Figure 1B graphs front-month futures nominal prices, Figure 1C front-month SDR-prices and Figure 1D front-month U.S.-PPI deflated prices during the 2000-2013 sample period.

[Figures 1B–1D around here]

The standard application of PWY/PSY-type tests is predicated on an assumption of constant volatility across regimes. Harvey et al. (2016) showed that the PWY test may over-declare mildly explosive periods in the presence of non-stationary volatility. To assess informally whether this might be a feature of our data, we plot the first differenced series for each metal.

[Figures 2A-2D around here]

The graphs offer some evidence that volatility in prices increased in the aftermath of the financial crisis, especially in gold, silver and platinum. Alongside our standard test results, we therefore report some results using (higher) data-based critical values based on applying the wild bootstrap, whose validity and efficacy Harvey et al. (2016) demonstrate in the context of the PWY test. Given the similarity in structure between the PWY and PSY tests, Harvey et al. argued that the validity of applying the wild bootstrap is likely to carry over to the PSY test, but this has still to be demonstrated. Like Etienne et al. (2014, 2015), we therefore apply the wild bootstrap of the PSY test without formal justification.

3. The PSY mildly explosive/bubble-testing methodology

The PSY (2015a&b) methodology represents the development of a statistically rigorous procedure based on a test for temporary regime shifts of exuberance and collapse that are embedded in a time series evolving as a stochastic trend. Built upon the theoretical contribution by Phillips and Magdalinos (2007a&b), the test is based on a notion of a mildly explosive process that facilitates constructing appropriate distribution theory in autoregressive (AR) models whose AR parameter is locally above unity. The sequential nature of the test makes it robust to periodically collapsing bubbles (see especially PWY, 2011).

The procedure is based on three steps:

- testing the null hypothesis that there are no mildly explosive periods in the sample against the alternative that there is at least one such period;
- if the test rejects, date-stamping the mildly explosive period(s) in the sample;
- setting the results in the context of a rational asset pricing model and using fundamentals proxy variables to assess whether or not detected periods of mild explosivity are consistent with departures from the metal's fundamental value

Starting from a fraction r_1 and ending at a fraction r_2 of the total sample, with window size $r_w = r_2 - r_1$, we fit, as in conventional (left-sided) augmented Dickey-Fuller (ADF) tests, the regression model

$$\Delta x_t = \alpha_{r_1,r_2} + \beta_{r_1,r_2} x_{t-1} + \sum_{i=1}^{k} \psi^i_{r_1,r_2} \Delta x_{t-i} + \varepsilon_t , \qquad (1)$$

where k is the lag order chosen on sub-samples using the BIC (information criterion), and $\varepsilon_t \sim$ i.i.d. $(0, \sigma^2_{r_1,r_2})$. The number of observations in the regression is $T_w = \lfloor T r_w \rfloor$ and we denote the ADF-statistic (t-ratio) of the coefficient of x_{t-1} based on this regression by $ADF_{r_1}^{r_2}$.

PSY (2015a&b) introduce two statistics, the backward sup ADF (BSADF) statistic and the generalized sup ADF (GSADF) test. They are defined as:

$$BSADF_{r_2}(r_0) = \sup_{r_1 \in [0, r_2 - r_0]} \{ADF_{r_1}^{r_2}\} . \qquad (2)$$

$$GSADF(r_0) = \sup_{r_2 \in [r_0, 1]} \{BSADF_{r_2}(r_0)\} , \qquad (3)$$

where the endpoint of the sample is fixed at r_2 and the window size is allowed to expand from an initial fraction r_0 of the total sample to r_2. PSY (2015a) propose r_0 be chosen to minimize size distortion, according to the rule $r_0 = 0.01 + 1.8/\sqrt{T}$, where T is the sample size.[11] This procedure defines a particular BSADF statistic. The GSADF statistic is then constructed through repeated implementation of the BSADF procedure for each $r_2 \in [r_0, 1]$. Critical values are obtained by simulation.

[11] Based on earlier versions of the tests, the results by Zhao et al. (2015) and Long et al. (2016) are based on a different initial fraction.

PSY (2015a&b) provide limiting distribution theory and small sample simulation evidence.

The null test of no mildly explosive periods is based on the GSADF statistic. Date-stamping mildly explosive periods is achieved through the BSADF statistic: the origination and termination points of a first bubble, $r_{1,e}$ and $r_{1,f}$, are estimated, subject to a minimum duration condition, by

$$\hat{r}_{1,e} = \inf_{r_2 \in [r_0, 1]} \left\{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \right\}, \tag{4}$$

$$\hat{r}_{1,f} = \inf_{r_2 \in [\hat{r}_e + \delta \log(T)/T,\, 1]} \left\{ r_2 : BSADF_{r_2}(r_0) > scv_{r_2}^{\beta_T} \right\}, \tag{5}$$

where $scv_{r_2}^{\beta_T}$ is the $100(1-\beta_T)\%$ right-sided critical value of the BSADF statistic based on $\lfloor T r_2 \rfloor$ observations and δ is a tuning parameter that can be chosen, in principle, on basis of sampling frequency. A tuning parameter of unity implies a minimum duration condition of log(T) observations. A mildly explosive period is declared if and when the BSADF statistic has been above its critical value for at least $\lfloor T \hat{r}_{1,e} \rfloor + \lfloor \log(T) \rfloor$ observations. Conditional on a first mildly explosive period having been found and estimated to have terminated at $\hat{r}_{1,f}$, the procedure is then repeated in search of a second and possibly subsequent periods. PSY (2015b) show that, subject to rate conditions, the sequential procedure provides consistent estimates of the origination and termination dates of one, two and three (and, in principle, more) bubbles.

The data generation process (DGP) under the alternative hypothesis exhibits K bubble episodes in the sample period, represented in terms of sample fraction intervals $B_i = [\tau_{i,e}, \tau_{i,f}]$ (i = 1, 2 , . . . , K), within periods of prevailing martingale-type behavior in the intervals $N_0 = [1, \tau_{1,e}]$, $N_j = [\tau_{j-1,f}, \tau_{j,e}]$ (j = 1, 2 , . . . , K – 1) and $N_K = [\tau_{K,f}, T]$, as follows:

$$x_t = (x_{t-1} + \varepsilon_t)\, 1(t \in N_0) + (\delta_T\, x_{t-1} + \varepsilon_t)\, 1(t \in B_i)$$
$$+ \sum_{i=1}^{K} \left(\sum_{l=\tau+1}^{t} \varepsilon_l + x_{\tau_{i,f}}^{*} \right) 1(t \in N_i) \qquad (t = 1, \ldots, T) \tag{6}$$

$$\delta_T = 1 + c/T^{\alpha}, \quad c > 0, \quad \alpha \in (0,1). \tag{7}$$

Bubble implosion is modelled, for each i, by $x_{\tau_{i,f}}^{*} = x_{\tau_{i,e}} + x_i^{*}$, where $x_i^{*} = O_p(1)$. This entails an abrupt collapse to the value of the last pre-bubble observation plus an $O_p(1)$

perturbation, representing a re-intialization of the process from which it resumes its trend. In developing work, Phillips and Shi (2014) and Harvey et al. (2016) have modelled bubble implosion in a way that is less abrupt than PSY (2015a), using a specification proposed by Harvey et al. (2015).

Harvey et al. (2016) demonstrate that the PWY test is over-sized when its assumption of constant volatility is maintained when the true processes exhibit permanent volatility shifts. As noted, Figures 2A-2D suggest this is the case for precious metals prices given the apparent rise in volatility after the highpoint of the financial crisis. Their proposed alternative, wild-bootstrap implementation of the PWY test by design embodies the structure of the volatility in the actual data. Applied in the context of the PSY test, this entails (cf. Etienne et al. 2014, p. 135):

1. For each data set, estimating the model (1) under the null hypothesis of no mildly explosive period, i.e. with the restriction $\beta_{r_1,r_2} = 0$ imposed. Denote the residuals by $\hat{\varepsilon}_t$ and the estimated coefficients by $\hat{\beta}_{r_1,r_2}$.
2. Generating wild bootstrap residuals $\hat{\varepsilon}_t{}^*$ such that $\hat{\varepsilon}_t{}^* = \hat{\varepsilon}_t \, \eta_t$, where η_t is (standardly in context) a sequence of independent N(0, 1) random variables.
3. Generating recursive bootstrap samples $x_t{}^*$ using
$$x_t{}^* = x_{t-1}{}^* + \sum_{i=1}^{k} \hat{\psi}_{r_1,r_2}^{i} \, \Delta x_{t-i}{}^* + \hat{\varepsilon}_t{}^* \quad (t = 1, \ldots, T).$$
4. Calculating BSADF values on the bootstrap sample using (1) for every endpoint for some minimum window size.
5. Repeating steps 1-4 a number of times to build up an approximation to the distribution of the BSADF statistic. We use 5,000 replications, the same number as PSY(2015a) used in the standard case (even although the current procedure is far more computationally costly).

Harvey et al. do not proceed to the second stage of date-stamping mildly explosive episodes but it is notable that higher, bootstrap-adjusted critical values can lead to a reduction in the number of explosive periods compared with the standard implementation of the test because the test becomes more stringent, or an increase in number of such periods if an identified long bubble in the standard implementation splits up into two or more shorter ones.

The third and final element of the PSY procedure assesses whether the detected mildly explosive periods are bubbles. The test procedure can be interpreted as a test for (rational) bubbles under the standard rational asset pricing equation

$$P_t = \sum_{i=0}^{\infty} \left(\frac{1}{1+r_f} \right)^i E_t (D_{t+i} + U_{t+i}) + B_t , \tag{8}$$

where P_t is the (present-value) price of an asset, D_t is the payoff received from the asset, U_t represents unobservable fundamentals, and r_f is the (positive) risk-free interest rate (see PSY, 2015a, Section 2). The quantity $(P_t - B_t)$ is called the market fundamental, and the bubble component, B_t, is assumed to satisfy the property

$$E_t (B_{t-1}) = (1 + r_f) B_t , \tag{9}$$

which is explosive, given $r_f > 0$. In Section 5, fundamental proxy variables are used to assess whether the degree of non-stationarity in P_t is greater than the degree of non-stationarity in the fundamental; if so, the mildly explosive period is declared by the PSY procedure to be a bubble.

Our use of weekly data in our application of the PSY test to precious metals potentially impacts upon on the efficacy of the test; for while PSY (2015a&b) set the tuning parameter to unity in a context where only one sampling frequency was considered, their main empirical applications involved mainly monthly data. As is common in commodity and financial market applications, we use higher-frequency (weekly) data, not least to enable us to test for bubbles that in context are plausibly shorter than would be detectable using monthly data. This might suggest that, if unity really were the appropriate value for the tuning parameter for monthly data, we should use a higher value for weekly data. The optimal choice of tuning parameter (on the basis of sampling frequency) is currently the subject of ongoing work by the second author; here we simply follow Figuerola-Ferretti et al. (2015) and confer some robustness on our approach by reporting results using higher values of the tuning parameter alongside unity.

To maintain compatibility with the rational bubbles model, we follow PWY and PSY in analyzing price changes and not price returns, and only date-stamp positive bubbles. Price returns would entail using the logarithms of prices instead of the levels, and in such a context an explosive process would be reflected in a non-zero intercept, not in the autoregressive coefficient.

4. Test Results

The GSADF statistic tests in the direction of at least one episode of mildly explosive behaviour in the sample. Tables 1A-1C give eight GSADF statistics corresponding to the spot and front-month futures price series for each of the precious metals. Table 1A reports results for nominal prices, Table 1B for SDR-adjusted prices and Table 1C for U.S. PPI-deflated prices. Critical values are generated for the given sample size and rule-based value of r_0, and for the standard application of the PSY test are the same across each metal. Because the wild bootstrap adjusts critical values on the basis of the data, the critical values for the volatility-adjusted application of the test are metal specific.

[Tables 1A-1D around here]

In every case, the GSADF statistic rejects the hypothesis of no mildly explosive periods in 2000-2013 for all the precious metals (gold, silver, platinum and palladium) at the 1% significance level. With such corroboratory evidence for mildly explosive periods, we then move to the second, date-stamping stage of the PSY procedure using the BSADF statistic, noting that because of the imposition of a minimum duration condition, it is possible that no explosive period is actually dated here. In Tables 2A-2C, we list the number of mildly explosive periods for the spot and one-month futures nominal prices and the two adjusted series for each metal, at the 1%, 5% and 10% significance levels. Table 2D displays the same for front-month futures nominal prices for each metal, with critical values adjusted by the application of the wild bootstrap. As noted above, lower significance levels (cf. higher bootstrap-adjusted critical values) may lead to fewer bubbles being declared because the test becomes more stringent than in the standard case, but potentially more bubbles may be declared because long bubbles may split into shorter bubbles. For this reason, in what follows we place more weight on the mildly explosive episodes that are actually date-stamped by the PSY procedure.

[Tables 2A-2D around here]

In the first block of each table, we have reported all the excesses of the BSADF statistic over its critical value *without imposing a minimum duration condition*. This information is useful in a context where we are using different values of the tuning parameter to measure the amount of "froth" that imposing a minimum duration condition dispenses with. Following Yiu et al. (2013) and others, we also report the incidence of both explosive and implosive periods even given the abrupt collapse embodied in the specification (9) because, although outside the scope of this paper, the PSY procedure can have some efficacy under different models of bubble implosion (see Phillips and Shi, 2014). In all four cases, a large number of mildly explosive periods are identified. When we move to the second block in each table, we see the results given by the standard application of the PSY test, with tuning parameter set to unity, give smaller numbers of detected explosive periods. Here, important differences emerge among the four metals.

[Tables 3A-3D around here]

The spot and front-month futures nominal prices show a small number of short (two or three month) mildly explosive episodes in all four metals. Indeed, looking at Table 3A, which date-stamps the mildly explosive periods on the basis of the BSADF sequences, we see there is a period in gold in the second quarter of 2006, in the run-up to the financial crisis in 2008 and in two periods in 2011; in silver during the same period in 2006 as in gold, in 2011 again as in gold, but not in the immediate run-up to the crisis; and in platinum briefly in 2006, and, as in gold, in the run-up to the crisis. Palladium showed mild explosivity in two periods after the crisis, in the spot price only. In the SDR-adjusted prices, similar results are found for gold, silver and palladium, but no mildly explosive episodes are reported for platinum. The mildly explosive periods in gold spot prices are slightly shorter around 2007-08 than were identified by Zhao et al. (2015) and Long et al. (2016) on the basis of the earlier version of the PSY test and, more significantly, a later period (or two adjacent shorter periods for nominal prices) of price exuberance is declared here only in 2011. Inspection of the raw weekly gold spot price series in Figure 1A indicates that there were dips in the price in 2011 that led to the termination of the declared mildly explosive period. It is also possible, however, that our shorter data span means that the responsiveness of the PSY test to a run-up in prices following a collapse is more sluggish than for longer data spans and that the efficacy of the date-stamping procedure here needs to be better informed by a more detailed study of PSY test properties.

For the deflated prices, the situation is significantly different. Here, much more froth has been removed against the case where no minimum duration condition is imposed, and only one explosive period is detected in the spot and front-month futures prices in only silver and palladium. A conclusion of there being few or no bubbles is reinforced by the results using nominal prices with bootstrap-adjusted critical values where mildly explosive periods are detected under the standard duration condition only in silver in 2004 and platinum in early 2008.

[Figures 3A-3D around here]

Figures 3A-3D plot the BSADF test statistic sequences and the associated 5% critical value sequence for the one-month futures nominal prices. The figures also show (in feint) the time path of the price series. During periods of rapidly rising prices, the BSADF statistic and the price tend to rise together but this co-movement stops if the price falls back even if only temporarily.[12] For comparison, Figures 4A and 4B show the same for the deflated one-month prices for gold and silver.

[Figures 4A and 4B around here]

A question arises as to why a mildly explosive period was declared in silver in 2004 using bootstrap-adjusted critical values and not in the standard case when the critical value should have been lower. Figure 5A shows the *computed* bootstrap-adjusted critical value sequences based on 5,000 replications – the same as used by PSY (2015a) in the standard case – to highlight how potentially unsmooth the generated sequence can be. In the early period, the computed critical value sequence is actually *marginally below* the sequence in the standard case and this is enough for a mildly explosive period to be declared. In the sequel we therefore discount this finding for silver as being a facet of critical value generation and simply note that choosing an optimal number of replications in what is a highly computationally demanding procedure is a topic for future research. For comparison, the platinum critical value sequences displayed in Figure 5B are much smoother, reflecting that platinum prices exhibited fewer shifts in volatility than did silver prices during the sample period.

[Figures 5A and 5B around here]

As discussed above, a consequence of using weekly data in a context of a minimum duration condition that may be more appropriate for monthly data might mean that too much froth gets reported as evidence of a structural shift in the data. We therefore also report estimates based on a minimum duration condition of 13 weeks (or one quarter) and 26 weeks (or a half-year), which is facilitated by changes in the tuning parameter. The results here show a dramatic reduction in the number of declared mildly explosive periods. Under the 13-week condition, mildly explosive

[12] Charts for the corresponding spot prices are similar but are omitted to conserve space.

periods are still identified for all the metals at the 10% significance level. At the 5% level, however, for gold nominal prices only two periods are now identified, one in the run-up to the financial crisis and another in 2011; though for platinum the original periods are still reported, including the one in the run-up to the financial crisis. The periods for silver and palladium reported in the standard case are now not detected. For the SDR-adjusted prices, at the 5% level there are only reported explosive periods in gold and for the deflated prices only one instance of an explosive period is reported at the 10% significance level, in the palladium spot price, also reported at the 5% level. Under the minimum duration condition of half-a-year, no mildly explosive periods are reported at the 5% level for *any* price series, whether nominal or adjusted. Here, the results are similar to those obtained by Etienne et al. (2014, 2015) for agricultural commodities and Figuerola-Ferretti et al. (2015) for non-ferrous metals. The results taken at face value would indicate that there are no long bubbles. However, any dip in the BSADF sequence excess, say as a result of profit taking or a brief market correction, could mean that no long mildly explosive period would be declared even if such a dip were relatively short-lived. The issues of the impact of the minimum length condition and the general issues of size distortion and temporal aggregation are currently the subject of ongoing work but, in the absence of hard results in this area, it is worth noting that if there really were contextually a long bubble with a short-lived dip within it, it could manifest itself in the PSY framework through the detection period being split into shorter bubble periods. Such behaviour might be reflected in gold and silver nominal prices in 2011.

5. Fundamentals and speculation

The third stage of the PSY procedure formally sets the test in the context of the rational asset pricing model (8) to enable an assessment of whether the detected mildly explosive regions are bubbles. This relies on the availability of suitable data upon which to construct fundamentals proxy variables. As discussed earlier, this is not entirely straightforward for commodities on account of the desirability of using relatively high frequency data at the bubbles-dating stage, with the data for many natural proxies being available only monthly or even quarterly. And, as we shall show by example, analogues of proxy variables that work well in seemingly related contexts do not necessarily work well in commodity markets. For these reasons, we need to consider a wider evidence base to discuss precious metals than just one natural fundamental as was the case in PWY's (2011) study of NASDAQ stock prices using dividend yield.

We shall initially take the results obtained under the standard application of the PSY test with a 7-week minimum duration condition at face value, and assess whether as a whole they points towards any behaviour that is non-fundamentals-based. The main detected mildly explosive periods were in the first quarter of 2006 in platinum followed by gold and silver in the second quarter; the run-up to the financial crisis in 2008 in gold and platinum; two instances in the palladium spot price only, from around the end of the year in 2009 and 2010 for two or three months; and for periods in 2011 in gold and silver. The evidence using SDR-adjusted prices is broadly similar but only the silver explosive period in 2006 and palladium, both spot and one-month futures towards the ends of 2009 and 2010 are detected using deflated prices. The evidence under the application of the wild-bootstrap-adjusted critical values and under the more stringent duration conditions points to significantly fewer mildly explosive episodes and therefore fewer departures from trend, supporting a conclusion that, while the precious markets were certainly frothy, the evidence for actual bubbles in or around the financial crisis is in fact quite weak.

5.1. Convenience yield

The formal counterpart in storable commodities markets of the dividend yield in equity markets is the convenience yield, which is the implied value of any benefits, net of insurance, deterioration and storage costs, that accrue from holding inventories of the commodity (see, e.g. Pindyck, 1993). Convenience yield may be interpreted as the premium stockholders will pay for immediate access to inventory of known specification and location. Figuerola-Ferretti et al. (2015) explain in the context of non-ferrous metals that using convenience yield as a measure of fundamental value can be problematic in the PWY/PSY methodology, where the statistical test is based on the ratio of the nominal price and fundamental proxy variable. We now show this same argument is relevant to precious metals, perhaps even more so. The convenience yield arises as the residual in a cost of carry relationship that links the spot price with deferred prices.[13] Given that this relationship is based on arbitrage considerations, there is no reason to suppose a departure of price from fundamental value would

[13] See Miltersen and Schwartz (1998). The cost of carry, or carrying charge, is the cost of storing the physical commodity over a period of time.

disrupt it. If it were disrupted, we would expect periods of explosive prices to be common to both the spot and futures prices but absent from the convenience yield. If, instead, the explosion arises from the convenience yield process itself, say because of a pending limitation to the supply of storage, this should be transmitted to either or both the spot and futures prices. For this reason, we considered both the spot and futures prices in our analysis and treat convenience yield as a candidate fundamental.[14] For practical reasons we use a standard approximation to convenience yield – the interest-adjusted basis – that does not include warehousing costs. Specifically, if S_t and F_t are respectively the spot price and one-month futures price at time t, we approximate the convenience yield by

$$cy_{approx,t} = \frac{(1 + r_t)S_t - F_t}{S_t} \tag{10}$$

where r_t is the one-month rate of interest expressed at an annual rate. We use the weekly one-month U.S. dollar Intercontinental Exchange London Interbank Offered Rate (ICE LIBOR) as the rate of interest for the 2000-13 period.[15]

The final column of Table 1A reports the GSADF statistics for the four convenience yield series. All four statistics are negative, and so the null hypothesis of no mildly explosive period is not rejected. Taken at face value, this suggests any identified explosive periods common to both the spot and futures prices of a given metal are absent from the convenience yield, implying that any explosive property arises out of the price and not the convenience yield process. We draw the conclusion that either explosive prices had the effect of leading to a departure of prices from fundamental values, or that convenience yield is not a satisfactory measure of fundamental value in precious metals markets when using the PSY test. Given the negative values found on the basis of (10) for all four precious metals, we argue for the latter, for the same reasons as given by Figuerola-Ferretti et al. (2015). Indeed the argument pertaining to precious metals may even be stronger than for non-ferrous

[14] This position implicitly considers convenience yield as a derived process. A referee pointed out that there is a significant, even prevalent, view in the commodities literature that would see spot prices and convenience yield modelled in a way that the former is explicitly made more persistent than the latter. Under this viewpoint, the potential role for convenience yield within a bubbles-testing framework would be diminished. Recent empirical evidence consistent with this view is given by Gospodinov and Ng (2013).

[15] This is the average of the interest rates that certain of the world's leading banks charge each other for short-term loans. ICE is the parent company of the New York Stock Exchange and around two dozen other exchanges and markets around the world. It took over the administration of LIBOR from the British Bankers Association in early 2014.

metals. It is normal for a non-perishable commodity that has a cost of carry to be in contango, meaning that the futures price is higher than the expected spot price owing to the willingness of agents to pay a premium to have the commodity in the future, rather than paying the costs of storage and carrying cost arising from buying the commodity today. This would mean (10) taking on negative values.[16] Precious metals, with their investment asset role, differ from non-ferrous metals, which themselves differ from, say, crude oil, in the extent to which the commodity is storable and available. The crude oil market is often in backwardation, meaning that the futures contract trades below the expected spot price, for little oil is stored in comparison with the quantity of physical oil demanded. The negative values of measured convenience yields we find for previous metals not only make the ratio between the commodity price and the convenience yield proxy unusable as a basis for testing for mild explosivity using the PSY approach; they also damage the efficacy of the approach applied directly to the approximate convenience yield process itself.

5.2. Gold lease rates

Lucey and O'Connor (2013) and Barone-Adesi et al. (2014) have argued that lease rates – the interest that can be earned by lending the physical metal at various maturities – are potentially a more effective measure of fundamental value than convenience yield or its interest-adjusted basis proxy used above. In practice, lease rates exist because central banks hold quantities of gold that they may lease out for a return. Given that today central banks predominantly hold only gold, we only report results obtained using gold lease rates, here the annualized over-the-counter (OTC) interest rates that can be earned by lending gold over 1, 2, 3, 6, or 12 months. On the basis of a Markov switching approach, Lucey and O'Connor (2013) found evidence for mildly explosive episodes only in cases where a constant variance was imposed across regimes, specifically for the 2, 3 and 12 month lease rates, but not for the 1 and 6 month rates.

[Table 1D about here]

Table 1D shows that using the PSY test, all the GSADF statistics are above the critical value at the 1% significance level indicating that the hypothesis of no mildly explosive period is rejected. The BSADF sequence for each lease rate fails, however, to date a mildly explosive period. While there is strong evidence to suggest there

[16] Figuerola-Ferretti and Gonzalo (2012) also reported measured convenience yields that were negative.

were one or more spikes in the lease rates, they were not of sufficient duration for a mildly explosive period to be detected under the PSY procedure. The one-month gold lease rate BSADF sequence is displayed in Figure 6 as an exemplar.

[Figure 6 about here]

Here, a short spike is notable in the midst of the crisis in 2008. At the 5% significance level, this would only offer statistical evidence that the early-2008 rise in gold lease rates in the run-up to the high point of the crisis was a bubble if a shorter minimum duration condition were imposed. To do so would be to take a position against the evidence that the period of exuberance in gold prices around this time in fact lasted for a few months. Computing bootstrap-adjusted critical values to take account of non-stationary volatility in gold lease rate data would only reinforce the conclusion that there are no mildly explosive periods in gold lease prices, with the implication that, if lease rates have efficacy as representing the fundamental value of gold, as Lucey and O'Connor (2013) and Barone-Adesi et al. (2014) have suggested, the mildly explosive period in gold prices in early-2008 was not reflected in the fundamental and would therefore be a bubble that could be a result of non-fundamentals-based speculation.

5.3. Supply and demand fundamentals

A full treatment of supply and demand fundamentals in and around the 2007-08 financial crisis would represent a considerable undertaking beyond the scope of the current paper, and so we continue to restrict ourselves to the topic in hand, which is to assess through the lens of the crisis whether the evidence points towards any detected mildly explosive periods are fundamentals-based or speculatively driven. We only focus on the platinum and gold episodes in 2008, and the silver and gold episodes in 2011. While in early 2008 platinum was subject to the same macroeconomic environment as gold, including a depreciating dollar, its price may have been significantly bolstered by the decision of Eskom, a South African electricity company, in January 2008 to introduce "load shedding", namely intentional rolling blackouts of electricity power distribution during periods where short supply threatens the integrity of an electricity grid. In January and February mines were first shut down and then restricted in their electricity use, and during this period platinum and palladium reached record highs. The evidence would therefore seem to point to the mildly explosive period in platinum – which was the only mildly explosive period identified in nominal prices when using bootstrap-adjusted critical values – being caused by actual and anticipated supply shortages, rather than being a speculatively-driven bubble. Given that South Africa was then supplying as much as 85% of the world's platinum production but only around 30% of its palladium might explain why the bubble manifested itself only in platinum even although the effect of the Eskom power shortages was common to both.

Our discussion in this section of plausible gold price fundamentals in 2008 considers not just the run-up in prices but also the collapse in the price and its aftermath, with a view to gaining some insight into why the gold price might have fallen from around the supposed high point of the crisis given gold's supposed safe haven status. In Section 2, we noted there were four gold price spikes, in March, July, September and December, reflecting the high volatility in the market as the crisis unfolded. Dollar weakness in the first half of the year until July may have intensified the general run-up in commodity prices seen particularly in energy and grains around this time. The rise in the price of oil is likely to have been significant influence; indeed the oil price hit a record high in July at almost the same time that the dollar dropped to a record low against the Euro. Closer inspection of the wider data, however, reveals that the dollar traded essentially sideways through much of January and February, during the time the mildly explosive episode was detected. Instead, we point to net investment in gold, particularly in the OTC market, and bar hoarding, particularly in East Asia and the Middle East, as having been potentially significant fundamental factors that can be associated with price movements. Unfortunately, we report only the available annual data, but the GFMS Gold Survey (2009), alongside reporting a rise of 52% in gold investment in 2008, notes "tremendous" levels of speculative inflows during the first quarter, then liquidation through to the third quarter, followed again by investment in the final quarter. The Survey also reports a 62% year-on-year rise in bar hoarding, with Chinese holdings notably rising more than threefold from under 20 tonnes to just over 60 tonnes.

[Table 4 about here]

Large, speculative inflows at the same time as the detected mildly explosive period in gold would point to there having been a quarter-long speculatively-driven bubble in gold in early 2008; and indeed this was the only mildly explosive period in any metal detected using SDR-adjusted prices (which adjust for changing exchange rates) using a minimum duration condition longer than for the standard PSY test. The evidence that investment demand in gold then fell sharply, just after the highpoint of the crisis, would support a hypothesis of positions being unwound to facilitate margin calls being met in more traditional financial assets,[17] with the later investment implying a resumption in gold's safe haven status once feasible. The strong investment demand recorded into 2009, in both physical gold and ETFs, adds weight to this assertion.

Finally, we consider supply and demand fundamentals evidence around the time of the detected mildly explosive periods in gold and silver in 2011. There was only a modest increase in mine production of gold and a small fall in scrap supply. On the demand side, world investment in gold dropped by 10%; there were heavy redemptions in the futures and OTC markets; the demand for ETFs only saw modest growth; and fabrication demand grew negligibly. This contrasts with physical bar investment in gold which, in 2011, accounted for around three-quarters of world investment, compared with around half in 2010, which represents a rise in value of over one-third, year-on-year. Indeed, gold bar investment was only a quarter of world investment in 2009.

[Table 5 about here]

Significantly increased official and non-official purchases of gold were seen in 2011 in Europe, where holdings rose to a record, and in China and India. Physical bar investment may therefore be seen to have represented the major *source* of world demand in 2011 but we hypothesize that the major *driver* of this demand, in a context of more or less fixed supply, stemmed from the macroeconomic and geopolitical environment. Price rises from early February correlate with the Arab Spring and heightened Middle East tension; in mid-March with an ambiguous FOMC statement and the Tōhoku earthquake and tsunami; and in April with credit rating agency downgrades of Irish and Portuguese debt and concerns over a need for Greece to restructure its debt. The safe-haven view of gold is also supported by a fall in its price in June and July, during a period in which the International Energy Agency released 600 million barrels of stockpiled oil and the Greek government passed austerity cuts, and then the subsequent rise in gold's price in the aftermath of Standard and Poor's debt downgrading. Unfortunately, monthly data on physical bar holding, that might help substantiate a safe-haven hypothesis, is not publicly available.

[17] The Silver Institute's *The Silver Market - An Update* (2011) also makes this assertion with respect to silver (which shares some of gold's investment characteristics).

The more substantial run-up seen in silver prices in the early part of the year took place at a time of increased investment demand in silver. The Silver Institute's *World Silver Survey* (2012) reports substantially increased investor activity coinciding almost precisely with this period, especially in the OTC market. This is not, however, evident from the available annual figure which indicated an 11% annual fall in investment demand even given that "investment was concentrated in the first four months of the year" (p. 8). All in all, the evidence points towards gold and silver prices in 2011 having both been influenced by macroeconomic and geopolitical events, with the greater rise in silver being attributable to a metal-specific rise in investment demand.

5.4. ETF launches in silver and palladium

In 2006, one potentially important event was the launch of the first silver exchange traded fund (ETF), issued by *iShares* on April 28th, within periods of identified mild explosivity in silver and gold in nominal and SDR-adjusted prices, but only in silver in the deflated price series. As noted in Section 2, the silver price showed a larger proportionate increase than gold during this period. Indeed, the explosive period in silver detected in 2006 would be the *only* genuine mildly explosive period in either silver or gold (rather than being simply froth) if the application of the PSY test using deflated prices were taken at face value. This finding may also be implicit in the results of Harvey et al. (2016) who found the existence of at least one explosive period in gold being identified only at the 10% significance level but in silver at the 5% level. The beginning of the identified explosive periods in silver (and possibly gold) could plausibly be based on the anticipation of a silver ETF launch. In general, the launch of an ETF would be expected to affect at least prices through increasing net inflows into positions in the physical metal and the over-the-counter market, especially as some ETFs are physically backed, and this has the potential to reduce liquidity in the market and thereby raise prices. Further, the evidence shows silver and gold price both peaked on exactly the same day, May 12th, a fortnight after the launch, from which point there was a notable correction in both. One plausible explanation is that gold and silver were tied to each other, with silver unusually leading gold around the silver ETF launch with a return to normality sometime later in May. Two short explosive periods were also detected in the nominal spot prices of palladium around beginning of 2010 and 2011, although only the former was declared under PPI-adjusted prices. This result may reflect that the first U.S.-based ETF in palladium was launched in January 2010.[18]

5.5. Non-commercial positions and speculation

We can provide a direct test for speculative behaviour for each precious metal using the Commitments of Traders (CoT) position data published by the U.S. Commodity Futures Trading Commission (CFTC) for the COMEX futures market. We look specifically at the net level of non-commercial positions on the COMEX market, since these are widely interpreted as speculative positions.[19] In addition, following Sanders, Irwin and Merrin (2010), we use Working's (1960) *T*-index as a measure of "excess speculation". Write long and short commercial ("hedge") positions as H_L and H_S and long and short non-commercial ("speculative") positions as S_L and S_S respectively. The net non-commercial position is $S_N = S_L - S_H$. Working's *T*-index is then defined by

$$T = 1 + \frac{1\left(H_S \geq H_L\right) \cdot S_s + 1\left(H_S < H_L\right) \cdot S_L}{H_L + H_S} \tag{11}$$

If $T = 1$, the level of non-commercial activity is just sufficient to be available as counterparties for the commercial imbalance. Any excess over unity implies that speculators are acting as counterparties for each other.

We look for periods of mild explosivity in these two measures of speculative activity.

[Table 1E about here]

The GSADF statistics for the net non-commercial positions data do not reject the null of no explosive period for gold, silver and platinum at the 10% significance level, but reject the hypothesis for palladium at the 1% level. The corresponding BSADF sequence dates one explosive episode in the palladium positions data, from May 2002

[18] Johnson Matthey's *Platinum Report* (2011) reports that net identifiable physical investment demand for palladium increased by 74% in 2010 on the back of the demand for several ETFs. This might explain why palladium's prices outperformed those of silver, platinum and gold in this particular year.

[19] Commercial positions are associated with producers and consumers of the commodity. Non-commercial positions reflect the activities of market participants for investment purposes. A referee has pointed out that, because the pre-2006 CoT data were aggregated, the efficacy of this test may be limited. Since traders need a counterparty with whom to trade, net commercial positions are necessarily offset by net non-commercial positions: the aggregate data is not informative about which traders initiated trades with whom. An implicit assumption that the net commercial imbalance is exogenous and that non-commercials provide the necessary liquidity is difficult to test, making it difficult to unscramble hedging and speculative effects. Also, the increased sophistication of financial transactions can make the distinction between commercial and non-commercial traders problematic. See CFTC (2006).

to November 2002. In terms of the raw series, the palladium price *fell markedly* in 2002 with Johnson Matthey's *Platinum Report* (2003) reporting that "[R]ussian shipments of palladium fell sharply in the weak market but production of the metal in all other regions expanded. As a result, the market remained oversupplied . . ." (For completeness, we note that the demand for platinum fell by 30% in 2002.) The excess of supply over demand therefore provides a strong fundamentals-based reason as to why palladium prices fell in 2002, with the evidence pointing very strongly against any increased activity of speculators having been the driver of price movements. The question remains as to why the net non-commercial positions data showed a sustained mildly explosive period under the PSY test in a context of falling prices. Certainly, trading volumes in palladium were generally thin in 2002, reflecting palladium's relative unimportance then as a precious metal, and it could be that any investor activity around this time was accentuated.[20]

The GSADF statistic for Woking's *T*-index marginally rejects the null of no explosive period in gold at the 10% significance level but it is insignificant for the other precious metals (including palladium). No explosive period is dated in gold from the BSADF sequence. Taken at face value, the direct statistical evidence that speculators drove prices away from trend is extremely limited.

6. Conclusion

This paper has examined the mildly explosive/bubbles properties of the main precious metals – gold, silver, platinum and palladium – in and around the financial crisis, in what we believe is the most comprehensive study of such properties in the precious metals complex to date. Using the PSY (2015a&b) procedure, which supersedes the PWY (2011) procedure used in some earlier studies, we have utilized the most up-to-date statistical technology. The mere observation that a time series is upward trending does not constitute *prima facie* evidence for bubble behaviour; for such behaviour may simply reflect the realization of a random walk with drift that

[20] Christian (2006, pp. 145-146) asserts that loans taken out in the final period of the Soviet Union and in the following decade by the Russian government, that had used palladium as collateral, were unwound by the Russian government in 2001 following the previous year's price high, with the palladium being used for payment. The European bank in receipt of this palladium, seeing prices continuing their fall in 2002, itself began selling its stock, both to industrial users and to hedge funds and other institutional investors. While this account might help explain the falling prices and simultaneous rise in non-commercial positions, it is not amenable to evidence-based assessment because the amount of palladium shipped as collateral from Russia to bonded warehouses in Europe remains unknown.

could have been generated in the context of an efficient market. The PSY procedure offers a rigorously-grounded statistical test for a departure from trend in the direction of mild explosivity, which when set in the context of a rational asset pricing model can offer a test for bubble behaviour. Here, we have used the test's efficacy to demarcate the salient features of the price behaviour of the precious metals in and around the financial crisis, as a basis of interpreting their price movements using available data and evidence. Some of this data facilitated further testing based on the PSY approach but other potentially relevant data was only available in a form that meant some of the evidence could at best be pieced together. We recognize that the approach of Batten et al. (2010), which uses a data-based search among a large number of candidate fundamentals variables, has its merits. Nevertheless, we feel that our assessment of the evidence that specifically used the fundamentals proposed in the precious metals literature has allowed us, within the scope of this paper, to offer a comprehensive description and analysis of the price behaviour of the main precious metals in the run-up to, during and in the aftermath of the financial crisis. In so doing, our paper fills a current gap in the literature.

Our general conclusion is that while the precious metals markets were certainly frothy, the evidence for there having been bubbles in or around the financial crisis is weak and is at best limited to the run-up in the gold price in early-2008 and two short episodes in silver and palladium around certain respective ETF launches. The results using the wild bootstrap to take account of increased volatility in the aftermath of the financial crisis serve to reinforce this conclusion.

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Table 1A GSADF test statistics Nominal Prices			
	Spot	**Fut. 1m**	**Conv. Yields**
Gold	4.110	3.904	-2.810
Silver	5.670	5.665	-1.440
Platinum	5.591	5.151	-2.975
Palladium	4.624	4.417	-1.307

The table reports the generalized sup ADF (GSADF) statistics for the spot and one-month futures nominal prices, and the convenience yield, of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013. (Two observations are lost in lag creation.) The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. Critical values under standard application of the PSY test: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1B GSADF Test Statistics SDR-adjusted Prices		
	Spot	**Fut. 1m**
Gold	4.237	4.298
Silver	5.173	5.097
Platinum	5.010	4.607
Palladium	4.446	4.225

The table reports the generalized sup ADF (GSADF) statistics for the spot and one-month futures dollar-adjusted prices of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013. (Two observations are lost in lag creation.) The adjusted prices were obtained by dividing by the SDR index. The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. Standard PSY critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1C
GSADF Test Statistics
US-PPI-Deflated Prices

	Spot	**Fut. 1m**
Gold	3.609	3.999
Silver	4.039	5.665
Platinum	5.106	4.653
Palladium	3.840	3.477

The table reports the generalized sup ADF (GSADF) statistics for the spot and one-month future deflated prices of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013. (Two observations are lost in lag creation.) Prices are deflated using the US PPI index. The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. Standard PSY critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%).

Table 1D
GSADF Test Statistic
Gold Lease Rates

Maturity (months)	**1**	**2**	**3**	**6**	**12**
GSADF	10.106	7.925	8.094	6.022	6.081

This table reports GSADF statistics for Gold lease rates for different maturities. The lease rate at maturity *t* is derived as the *t*-month U.S. dollar ICE LIBOR minus the *t*-month Gold Forward Offered (GOFO) rate. (A GOFO rate is a rate at which contributors are prepared to lend gold in a swap against U.S. dollars.) The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. Standard PSY Critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%). **Although the GSADF statistic is significant, there is no date-stamping for any of the maturities using the BSADF sequence given under application of the standard minimum duration condition.**

Table 1E GSADF Test Statistics CFTC Position Data		
	Net Positions	**Working's T-index**
Gold	0.438	2.092
Silver	-0.209	-0.0154
Platinum	1.784	1.327
Palladium	5.766	2.176

This table reports GSADF statistics for the level of speculative activity in the COMEX precious metals market which we employ in Section 6 of the paper. Working's *T*-index of excess speculation is defined by equation (11). The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. Standard PSY critical values: 2.069 (10%), 2.282 (5%) and 2.664 (1%). **The GSADF statistic for palladium net non-commercial positions data is significant and a mildly explosive period is dated from May 2002 to November 2002 by the BSADF sequence.**

Table 2A Number of Mildly Explosive Periods Identified Nominal Prices													
Minimum bubble length		1			7			13			26		
Minimum bubble calibration		1			1			1			1		
Test size		10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%
Gold	Spot	6+10	5+13	2+3	5+2	4+0	1+1	3+1	2	0+1	1	0	0
	Fut. 1m	9+7	6+12	7+4	4+1	4+1	1	3	1	0	1	0	0
Silver	Spot	5+7	3+4	3+6	2+2	2+1	2	1	0	0	0	0	0
	Fut. 1m	6+5	4+4	4+4	3	2+1	2	0	0	0	0	0	0
Platinum	Spot	4+4	6+1	5+2	2+1	2+1	1	2	2	1	0	0	0
	Fut. 1m	6+2	5+4	3+3	2+1	2	1	2	2	1	0	0	0
Palladium	Spot	2+9	3+5	1+5	2+2	2+1	1+1	0+1	0	0	0	0	0
	Fut. 1m	2+8	2+4	2+5	0+2	0+2	0+1	0+1	0+1	0	0	0	0

The table reports the number of mildly explosive periods identified for the spot and one-month futures prices of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013. (Two observations are lost in lag creation.) The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. The minimum bubble length is set at 7 weeks (columns 1 and 2), 13 weeks (column 3) and 26 weeks (column 4). Critical values are calibrated for 1, 7, 13 and 26 weeks (columns 1-4 respectively).

Table 2B **Number of Mildly Explosive Periods Identified** **SDR-adjusted Prices**													
Minimum bubble length		1			7			13			26		
Minimum bubble calibration		1			1			1			1		
Test size		10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%
Gold	Spot	5+8	3+12	3+3	4+2	3+1	2	3+1	2	0+1	0	0	0
	Fut. 1m	3+12	2+9	3+2	3+3	3+1	2	3	1	0	1	0	0
Silver	Spot	3+3	2+5	1+5	2+2	2+1	1+1	1	0	0	0	0	0
	Fut. 1m	4+3	2+4	2+4	2+2	2+1	2	0	0	0	0	0	0
Platinum	Spot	4+2	2+3	1+2	1	0	0	0	0	0	0	0	0
	Fut. 1m	3+4	2+4	2+2	1+1	1+1	0+1	0	0	0	0	0	0
Palladium	Spot	3+6	3+4	0+7	2+1	2	1	0+1	0	0	0	0	0
	Fut. 1m	1+7	2+5	1+4	0+2	0+2	0+1	0+1	0	0	0	0	0

The table reports the number of mildly explosive periods identified for the cash and one-month futures SDR-adjusted prices of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013. (Two observations are lost in lag creation.) The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. The minimum bubble length is set at 7 weeks (columns 1 and 2), 13 weeks (column 3) and 26 weeks (column 4). Critical values are calibrated for 1, 7, 13 and 26 weeks (columns 1-4 respectively).

Table 2C **Number of Mildly Explosive Periods Identified** **US-PPI-Deflated Prices**													
Minimum bubble length		1			7			13			26		
Minimum bubble calibration		1			1			1			1		
Test size		10%	5%	1%	10%	5%	1%	10%	5%	1%	10%	5%	1%
Gold	Spot	1+6	2+2	0+3	0+1	0	0	0	0	0	0	0	0
	Fut. 1m	1+8	1+2	0+2	0+1	0	0	0	0	0	0	0	0
Silver	Spot	4+3	2+4	1+3	1+1	1+1	1	0	0	0	0	0	0
	Fut. 1m	2+2	2+3	1+3	1+1	1	1	0	0	0	0	0	0
Platinum	Spot	4+1	2+2	2+2	0	0	0	0	0	0	0	0	0
	Fut. 1m	1+5	1+3	1+3	0	0	0	0	0	0	0	0	0
Palladium	Spot	3+5	3+5	1+3	3	1	1+1	1	1	0	0	0	0
	Fut. 1m	1+5	1+7	1+2	3+1	1+1	1+1	0	0	0	0	0	0

The table reports the number of mildly explosive periods identified for the spot and one-month futures US-PPI-deflated prices of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013. (Two observations are lost in lag creation.) The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. The minimum bubble length is set at 7 weeks (columns 1 and 2), 13 weeks (column 3) and 26 weeks (column 4). Critical values are calibrated for 1, 7, 13 and 26 weeks (columns 1-4 respectively).

Table 2D
Number of Mildly Explosive Periods Identified using wild-bootstrap-adjusted critical values
Nominal Front-Month Futures Prices

Minimum bubble length	1			7		
Minimum bubble calibration	1			1		
Test size	10%	5%	1%	10%	5%	1%
Gold	8+4	3	2	2+1	0	0
Silver	3	4	3+1	2	1	0
Platinum	8+9	3+7	1+1	4+1	1	0
Palladium	5+5	3+4	0+1	0+1	0	0

The table reports the number of mildly explosive periods identified for the one-month futures nominal prices of the four principal COMEX precious metals estimated over the sample of 729 weekly observations from January 2000 to December 2013 using critical values derived using the wild bootstrap. (Two observations are lost in lag creation.) The initial window for recursive estimation is 56 weeks. The ADF lag is chosen to minimize the BIC over every subsample with the maximum lag length set at 5 weeks. The minimum bubble length is set at 1 weeks (columns 1) and 7 weeks (column 2).

Table 3A
Estimated start and end dates for periods of mildly explosive price growth
Nominal Prices

Minimum bubble length		**7 weeks**		**13 weeks**		**26 weeks**	
		Start	**End**	**Start**	**End**	**Start**	**End**
Gold	Spot Fut. 1m	Mar 2006 Apr 2006	May 2006	No bubble		No bubble	
	Spot + Fut. 1m	Dec 2007	Apr 2008	Dec 2007	Apr 2008	No bubble	
	Spot + Fut. 1m	Apr 2011	Jun 2011	No bubble		No bubble	
	Spot Fut. 1m	Jul 2011	Dec 2011 Sep 2011	Jul 2011	Dec 2011	No bubble	
Silver	Spot + Fut. 1m	Mar 2006	May 2006	No bubble		No bubble	
	Spot + Fut. 1m	Feb 2011	Apr 2011	No bubble		No bubble	
Platinum	Spot Fut. 1m	Oct 2005 Sep 2005	Feb 2006	Oct 2005 Sep 2005	Feb 2006	No bubble	
	Spot + Fut. 1m	Jan 2008	Apr 2008	Jan 2008	Apr 2008	No bubble	
Palladium	Spot Only	Dec 2009	Feb 2010	No bubble		No bubble	
	Spot Only	Dec 2010	Mar 2011	No bubble		No bubble	

This table reports the mildly explosive periods in the nominal prices of the four principal COMEX precious metals that are identified using the PSY procedure with a 5% size. Following PSY (2015a), critical values are calculated without taking account of the minimum bubble length and are therefore the same in each column of the table.

Table 3B
Estimated start and end dates for periods of mildly explosive price growth
SDR-adjusted Prices

Minimum bubble length		**7 weeks**		**13 weeks**		**26 weeks**	
		Start	**End**	**Start**	**End**	**Start**	**End**
Gold	Spot Fut. 1m	Mar 2006 Dec 2005	May 2006	No bubble		No bubble	
Gold	Spot + Fut. 1m	Jan 2008	Mar 2008	Dec 2007	Apr 2008	No bubble	
Gold	Spot + Fut. 1m	Jul 2011	Sep 2011	No bubble		No bubble	
Silver	Spot + Fut. 1m	Mar 2006	May 2006	No bubble		No bubble	
Silver	Spot + Fut. 1m	Feb 2011	Apr 2011	No bubble		No bubble	
Silver	Spot+ 1m Fut	Aug 2011	Sep 2011	No bubble		No bubble	
Platinum	Fut. 1m Only	Jan 2008	May 2008	No bubble		No bubble	
Palladium	Spot	Jan 2010	Mar 2010	No bubble		No bubble	
Palladium	Spot	Nov 2010	Feb 2011	No bubble		No bubble	

This table reports the mildly explosive periods in the SDR-adjusted prices of the four principal COMEX precious metals that are identified using the PSY procedure with a 5% size. Following PSY (2015a), critical values are calculated without taking account of the minimum bubble length and are therefore the same in each column of the table.

Table 3C
Estimated start and end dates for periods of mildly explosive price growth
US-PPI-Deflated Prices

Minimum bubble length		**7 weeks**		**13 weeks**		**26 weeks**	
		Start	**End**	**Start**	**End**	**Start**	**End**
Gold	Spot + Fut. 1m	No bubble		No bubble		No bubble	
Silver	Spot + Fut. 1m	Mar 2006	May 2006	No bubble		No bubble	
Platinum	Spot + Fut. 1m	No bubble		No bubble		No bubble	
Palladium	Spot Fut.1 m	Dec 2009	May 2010 Feb 2010	Dec 2009	May 2010	No bubble	

This table reports the mildly explosive periods in the US-PPI-deflated prices of the main COMEX precious metals that are identified using the PSY procedure with a 5% size. Following PSY (2015a), critical values are calculated without taking account of the minimum bubble length and are therefore the same in each column of the table.

Table 3D
Estimated start and end dates for periods of mildly explosive price growth under wild-bootstrap-adjusted critical values

Front-Month Nominal Futures Prices

Minimum bubble length	**1 week**		**7 weeks**	
Gold	May 2002	Jun 2002		
	Jan 2006	Feb 2006		
	Apr 2006	May 2006	No bubble	
Silver	Jan 2004	Jan 2004		
	Feb 2004	Apr 2004		
	Apr 2006	May 2006		
	Apr 2011	May 2011	Feb 2004	Apr 2004
Platinum	Jan 2001	Jan 2001		
	Dec 2003	Dec 2003		
	May 2006	June 2006	Feb 2008	Mar 2008
Palladium	Jan 2011	Jan 2011		
	Jan 2011	Feb 2011	No bubble	

This table reports the mildly explosive periods in the nominal prices of the four principal COMEX precious metals that are identified using the PSY procedure with a 5% size after implementation of the wild bootstrap to adjust critical values for the post-crisis increase in volatility in the data. A platinum negative bubble was detected in 2008 under the one-week minimum duration condition: given our focus on only positive bubbles, it does not appear in the above table. The explosive periods in palladium in 2011 detected when not applying the minimum duration condition were both one week long.

Table 4
World Gold Supply and Demand (in Tonnes)

	2007	2008	2009	2010	2011
Supply					
Mine production	2,498	2,430	2,612	2,739	2,838
Net official sector sales	484	235	34	-	-
Old gold scrap	1,005	1,350	1,735	1,723	1,669
Net producer hedging					11
Total Supply	3,986	4,015	4,381	4,462	4,517
Demand					
Fabrication					
Jewellery	2,423	2,304	1,816	2,020	1,975
Other	680	723	703	767	785
Total Fabrication	3,103	3,027	2,787	2,787	2,760
Net official Sector purchases	-	-	-	77	457
Bar hoarding	240	622	498	886	1,197
Net producer de-hedging	436	357	234	106	-
Implied net investment	207	10	1,130	607	103
Total Demand	3,986	4,015	4,381	4,462	4,517
Gold Price (London PM fix, U.S. $/oz)	695	872	972	1,224.52	1,571.52

Table 4 reproduces the part relevant to our argument of Table 1 on page 8 of the GFMS Gold Survey (2013), which used source data from Thomson Reuters. Totals may not add due to independent rounding. Net producer hedging is the change in the physical market impact of mining companies' gold loans, forwards and option positions. Implied net investment is the residual from combining all other Thomson Reuters GFMS data on gold supply/demand as shown in the table above. As such, it captures the net physical impact of all transactions not covered by the other supply/demand variables.

Table 5: Physical Bar Investment for Selected Countries and World Regions (in tonnes)

	2007	2008	2009	2010	2011
Western Countries					
Europe	-2.3	192.2	211.2	215.2	312.8
North America	2	30.8	37.9	22.4	15.4
Total Western Countries	-0.3	223	249	237.6	328.2
Total Latin America	-1.2	0.1	4.3	4.8	5.4
Total Middle East	46.8	63	36.5	66	93.2
Indian Sub-Continent					
India	148.6	159.9	117.5	266.3	288
Pakistan	2.6	-4.4	-19.4	7	14.6
Other Countries	7	6.2	2.9	7.3	16.4
Tot. Indian Sub-Cont.	152.3	156.6	98.5	273.6	304.4
Total East Asia	37.1	171.7	100.9	290.5	447.8
of which:					
China	21	60.8	102.3	178.6	250.3
Thailand	4.6	42.6	-10.1	63.0	103.6
Vietnam	56.1	96.2	58.2	67.0	87.8
Japan	-56.4	-39.4	-30.8	-41.0	-47.2
Total CIS (incl. Russia)	4.2	4.4	4.9	3.1	2.8
World Total	239.9	621.6	498.5	885.7	1,197.40

Table 5 reproduces the part relevant to our argument of Table 2 on page 35 of the GFMS Gold Survey (2013), which used source data from Thomson Reuters.

Figure 1A: One-month spot nominal prices, 2000-13

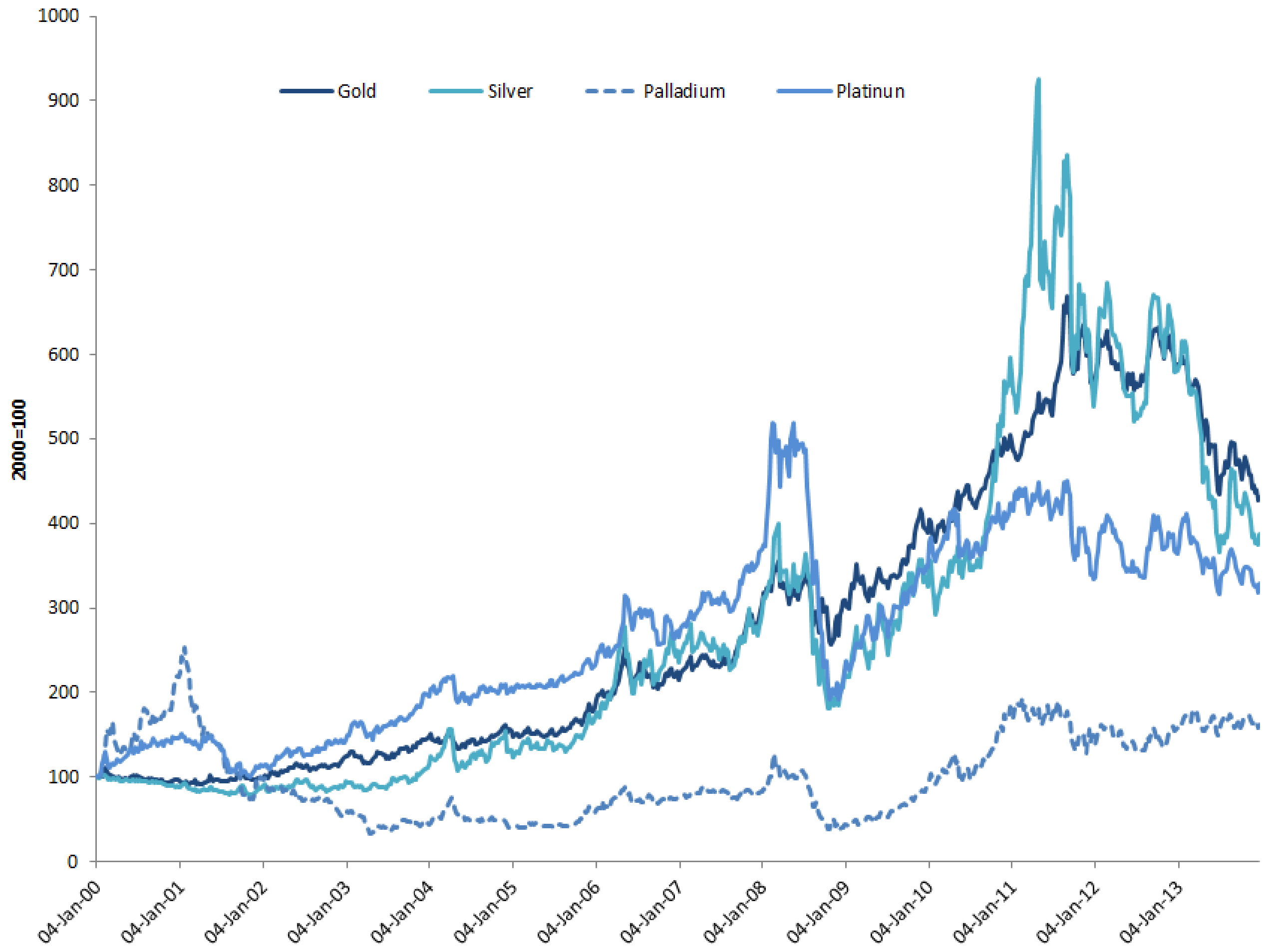

Figure 1B: One-month futures nominal prices, 2000-13

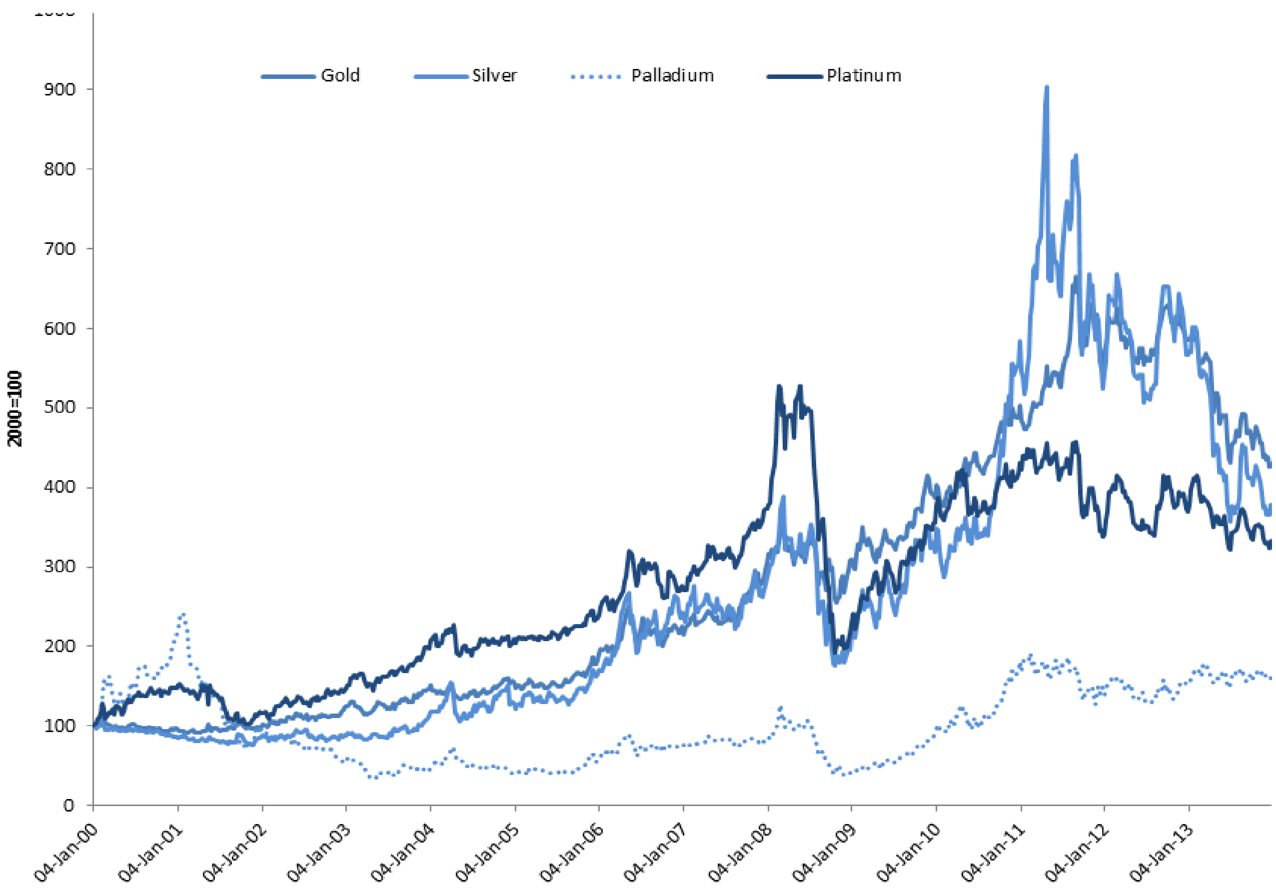

Figure 1C: One-month futures SDR-adjusted prices, 2000-13

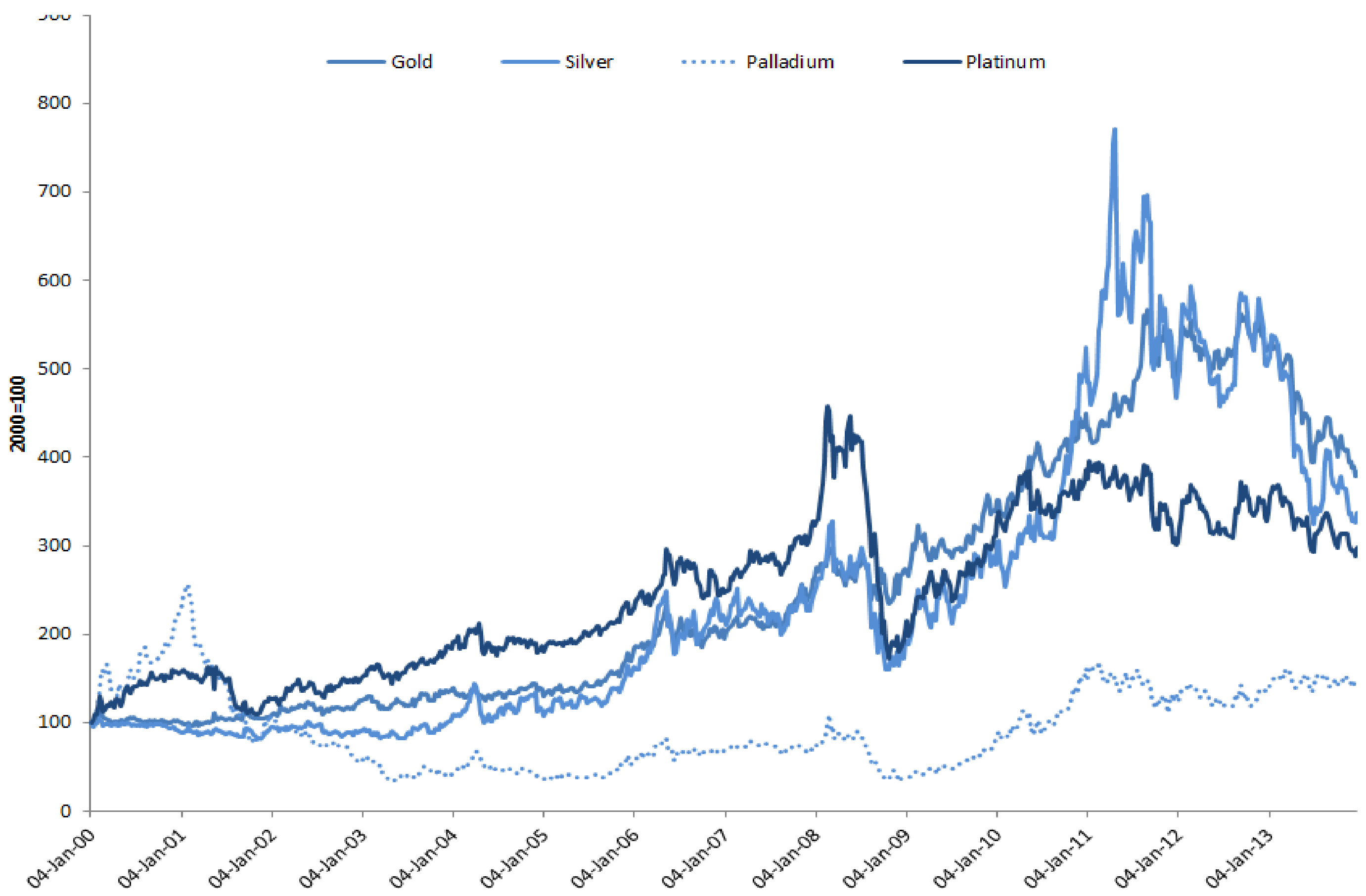

Figure 1D: One-month futures U.S. PPI-deflated prices

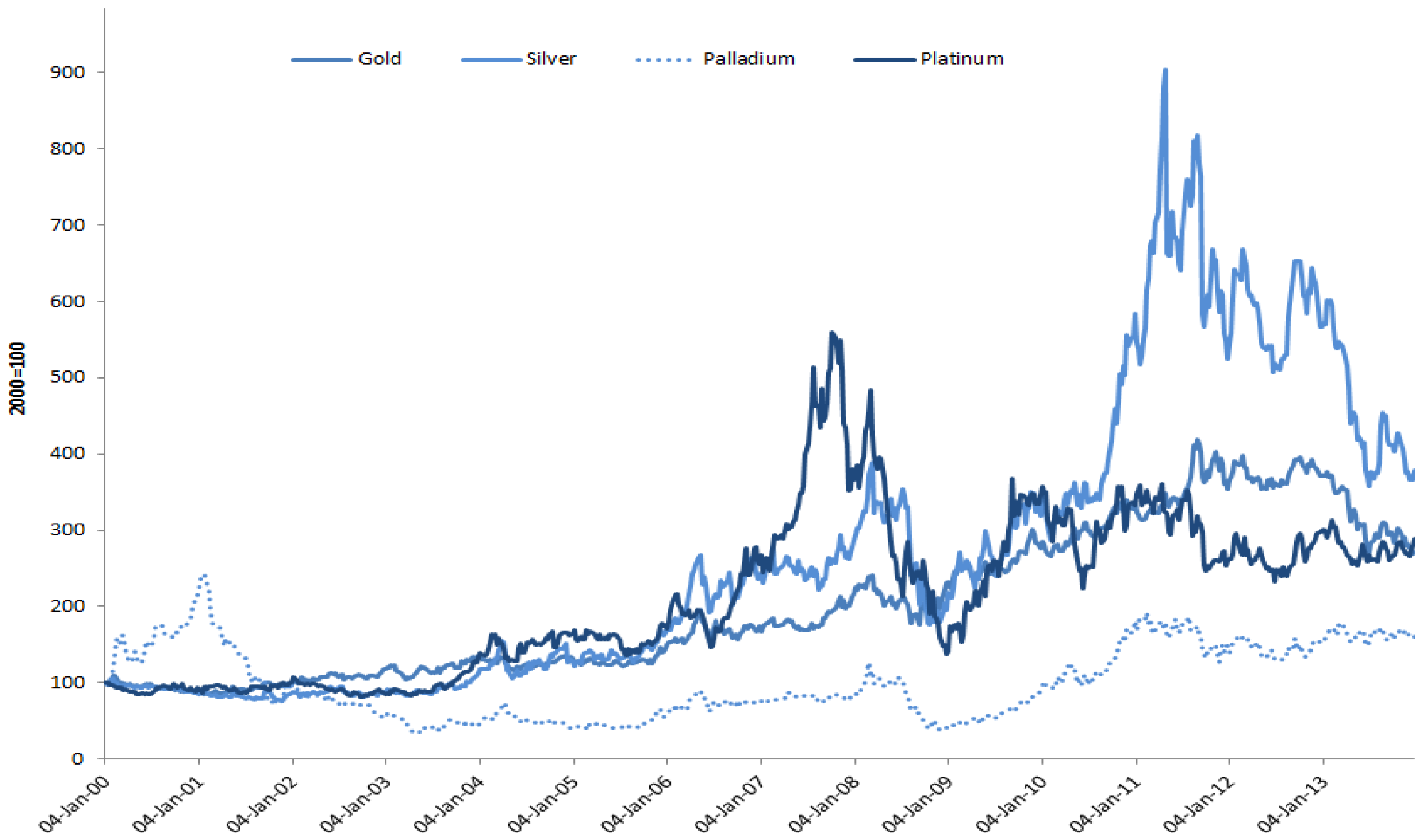

Figure 2A: Gold one-month futures first-differenced series

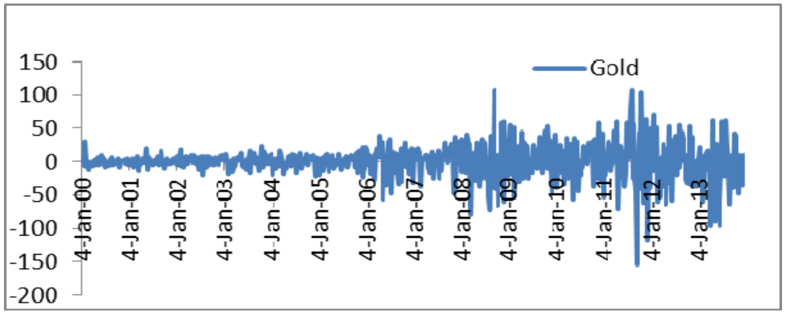

Figure 2C: Platinum one-month futures first-differenced series

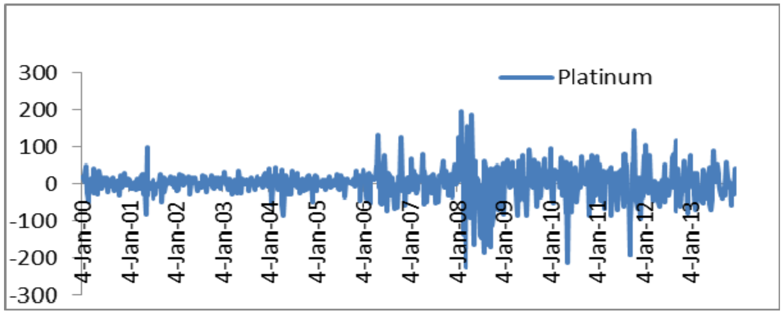

Figure 2B: Silver one-month futures first-differenced series

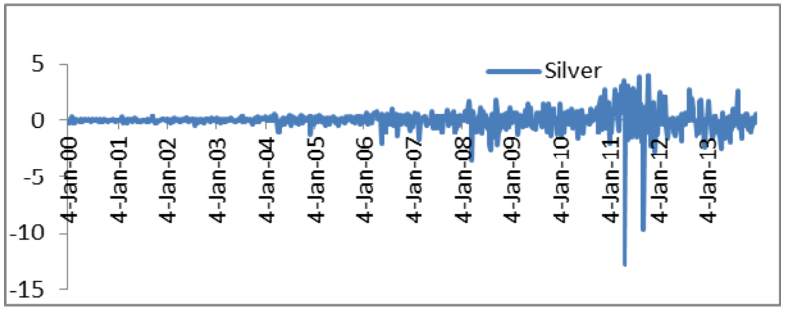

Figure 2D: Palladium one-month futures first-differenced series

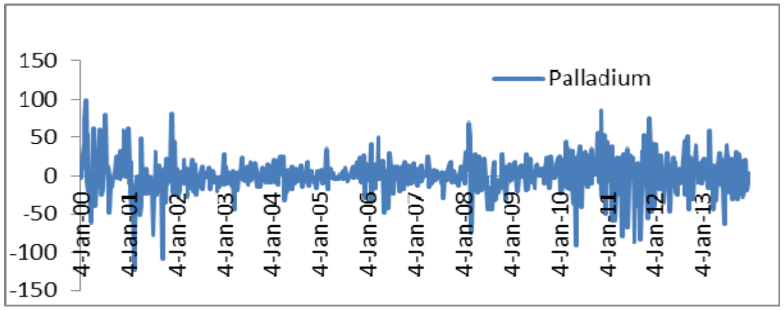

Figure 3A: Gold one-month futures nominal prices BSADF sequence

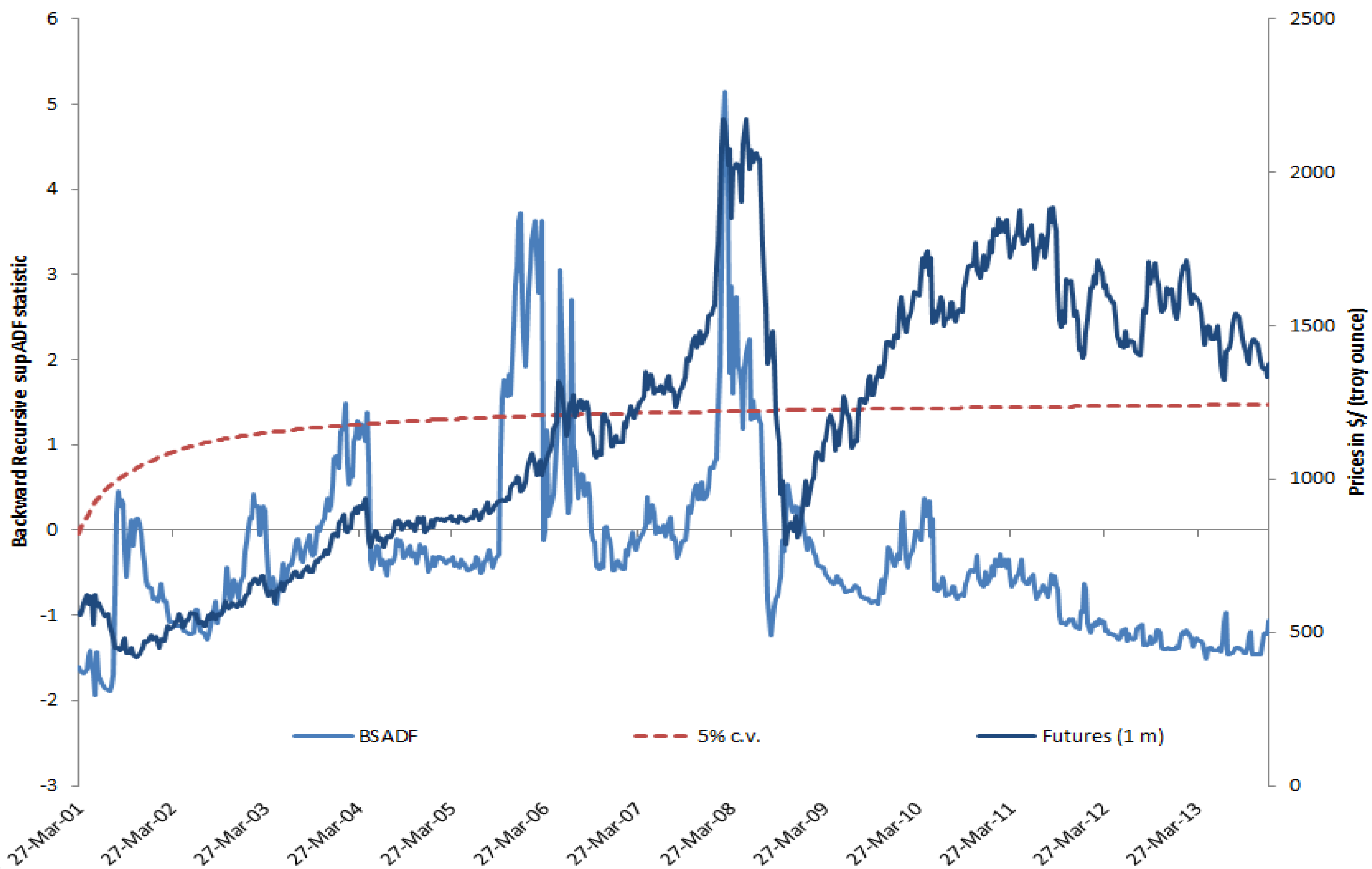

Figure 3B: Silver one-month futures nominal prices BSADF sequence

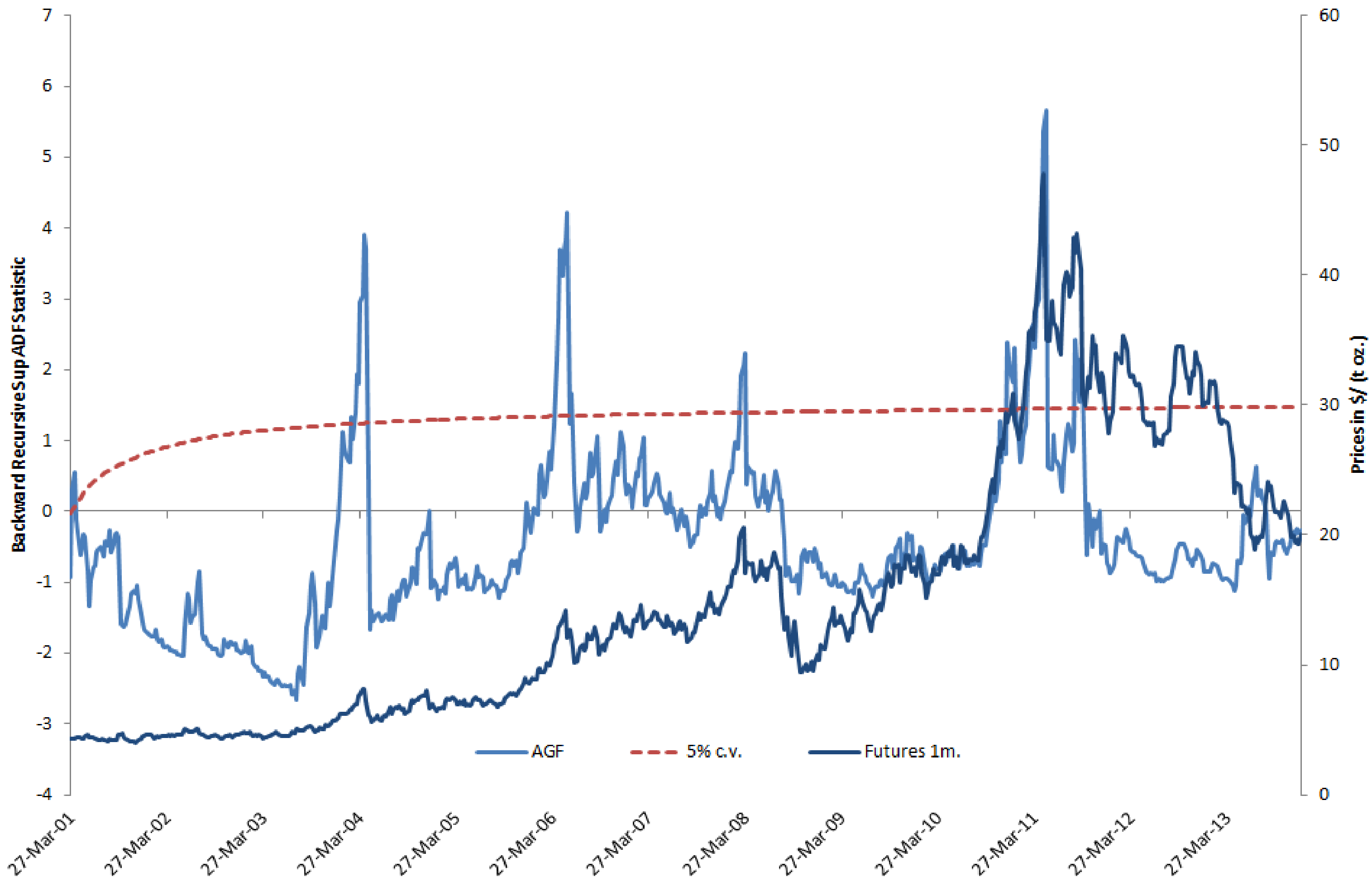

Figure 3C: Platinum one-month futures nominal prices BSADF sequence

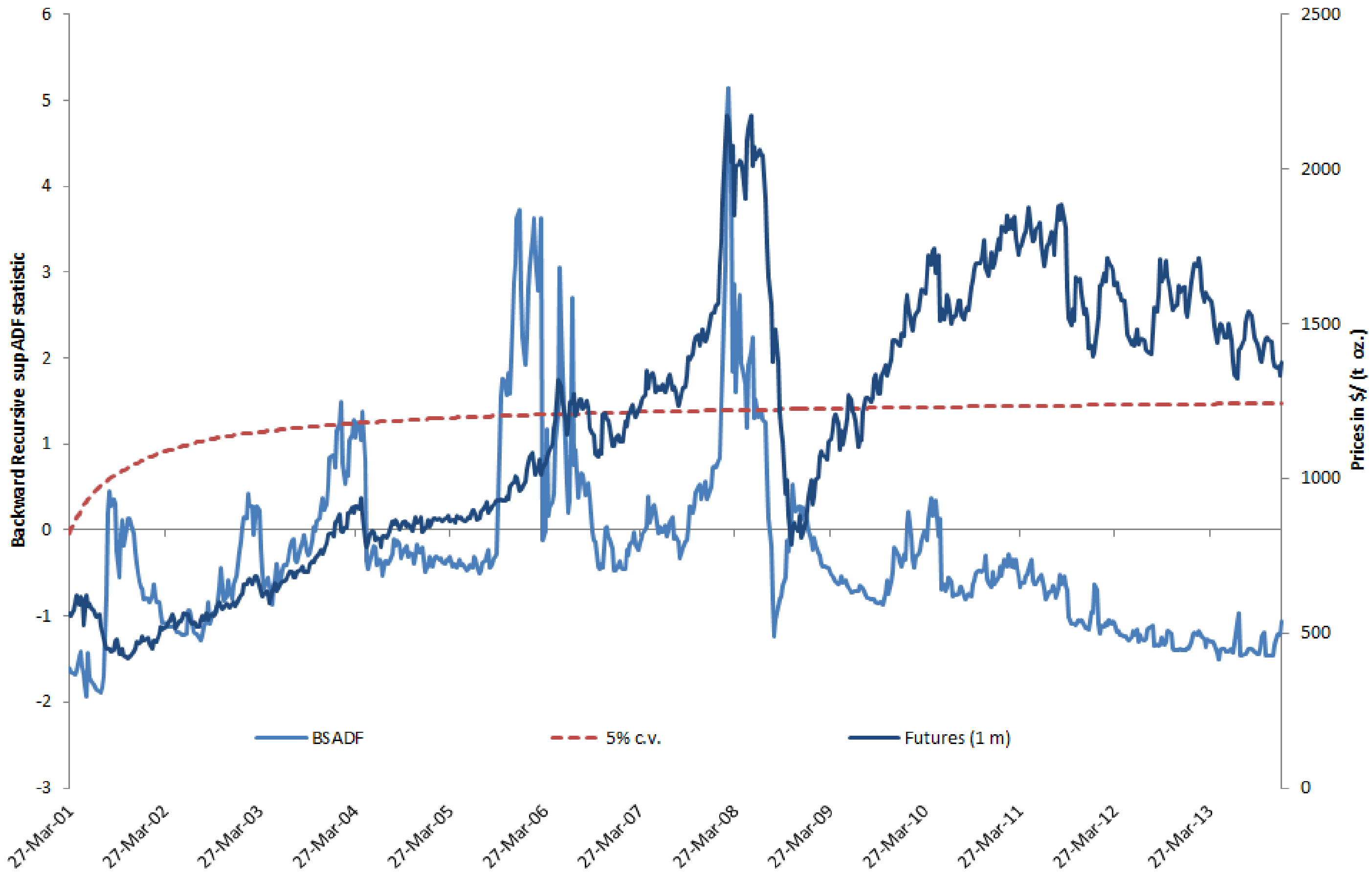

Figure 3D: Palladium one-month futures nominal prices BSADF sequence

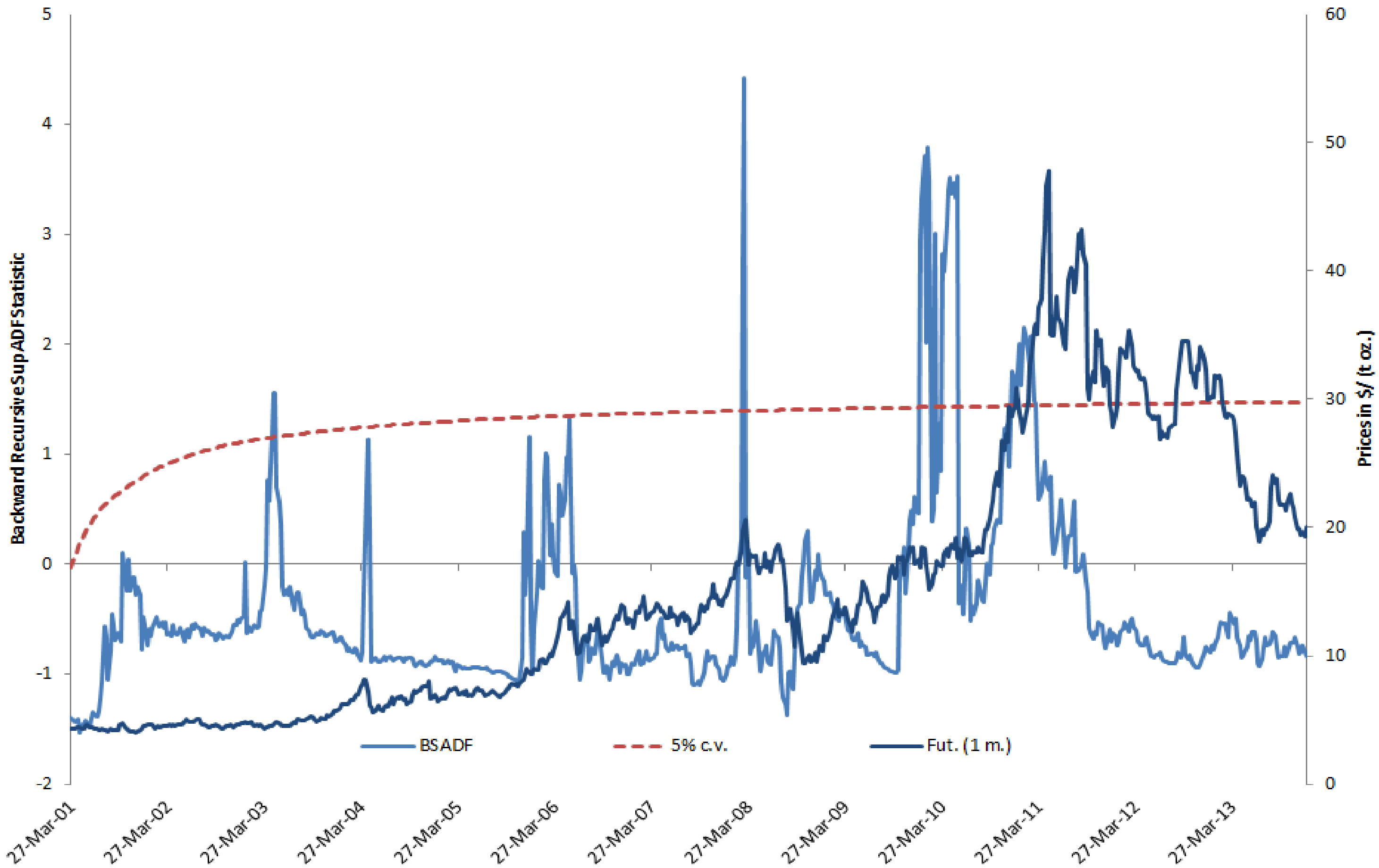

Figure 4A: Gold one-month futures U.S.-PPI deflated prices BSADF sequence

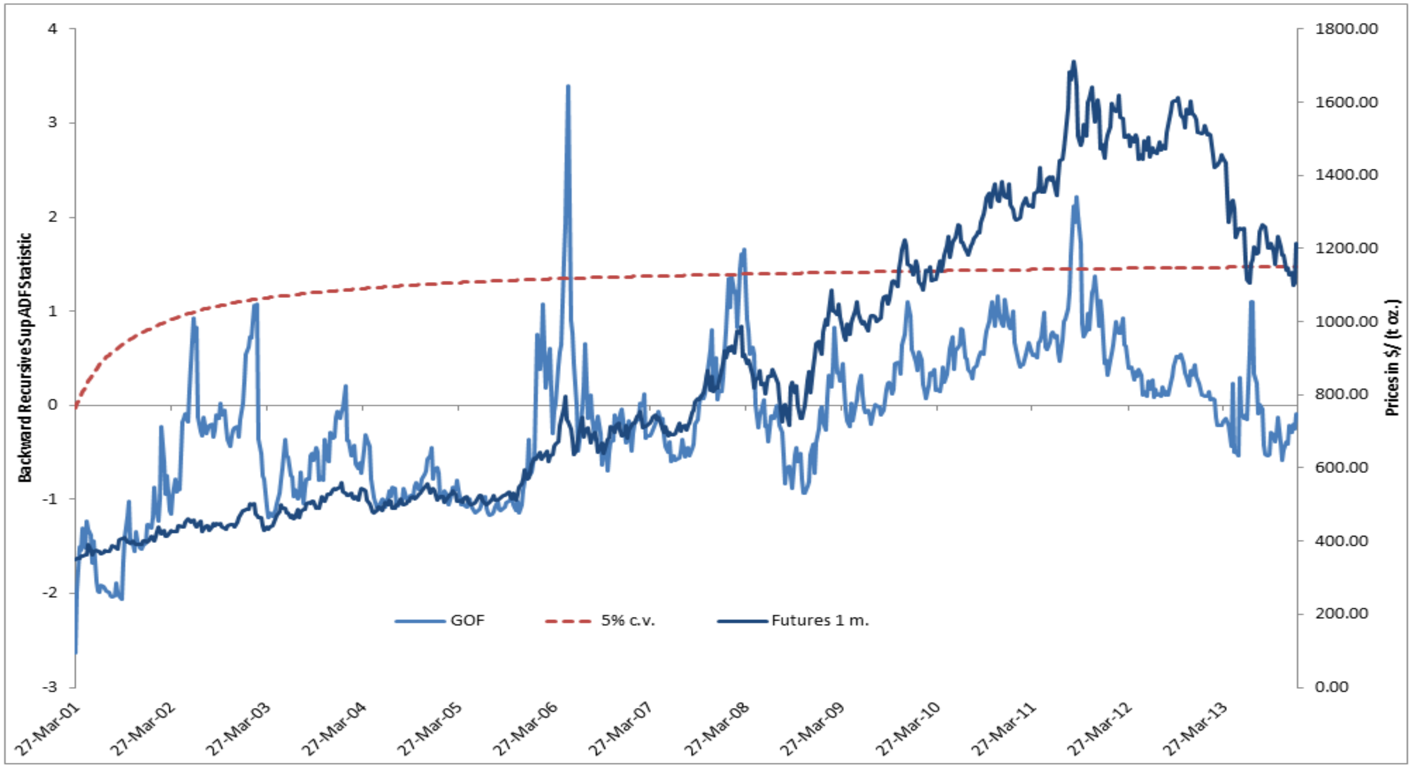

Figure 4B: Silver one-month futures U.S.-PPI deflated prices BSADF sequence

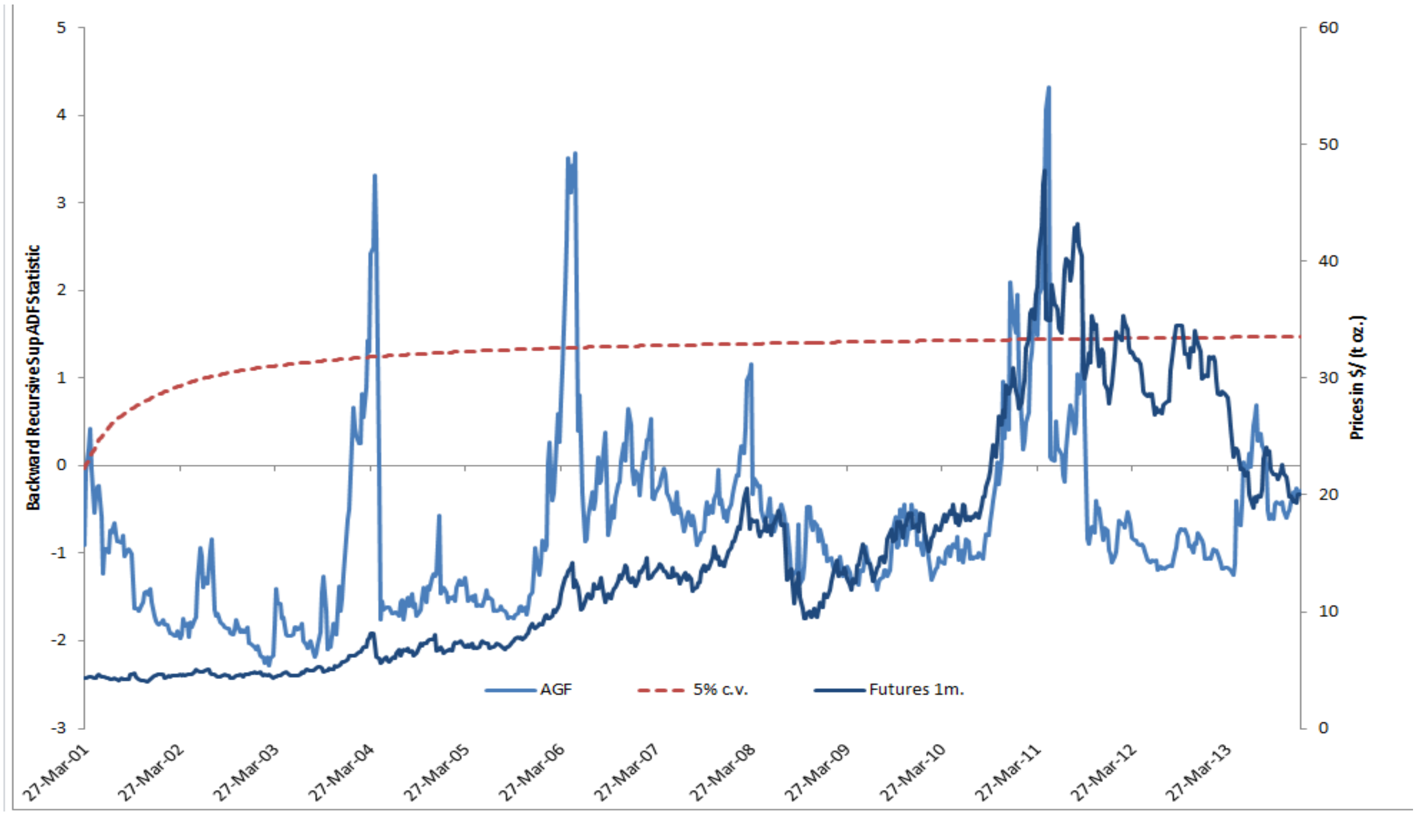

Figure 5A: Silver one-month futures nominal prices BSADF sequence with wild-bootstrap-adjusted critical values

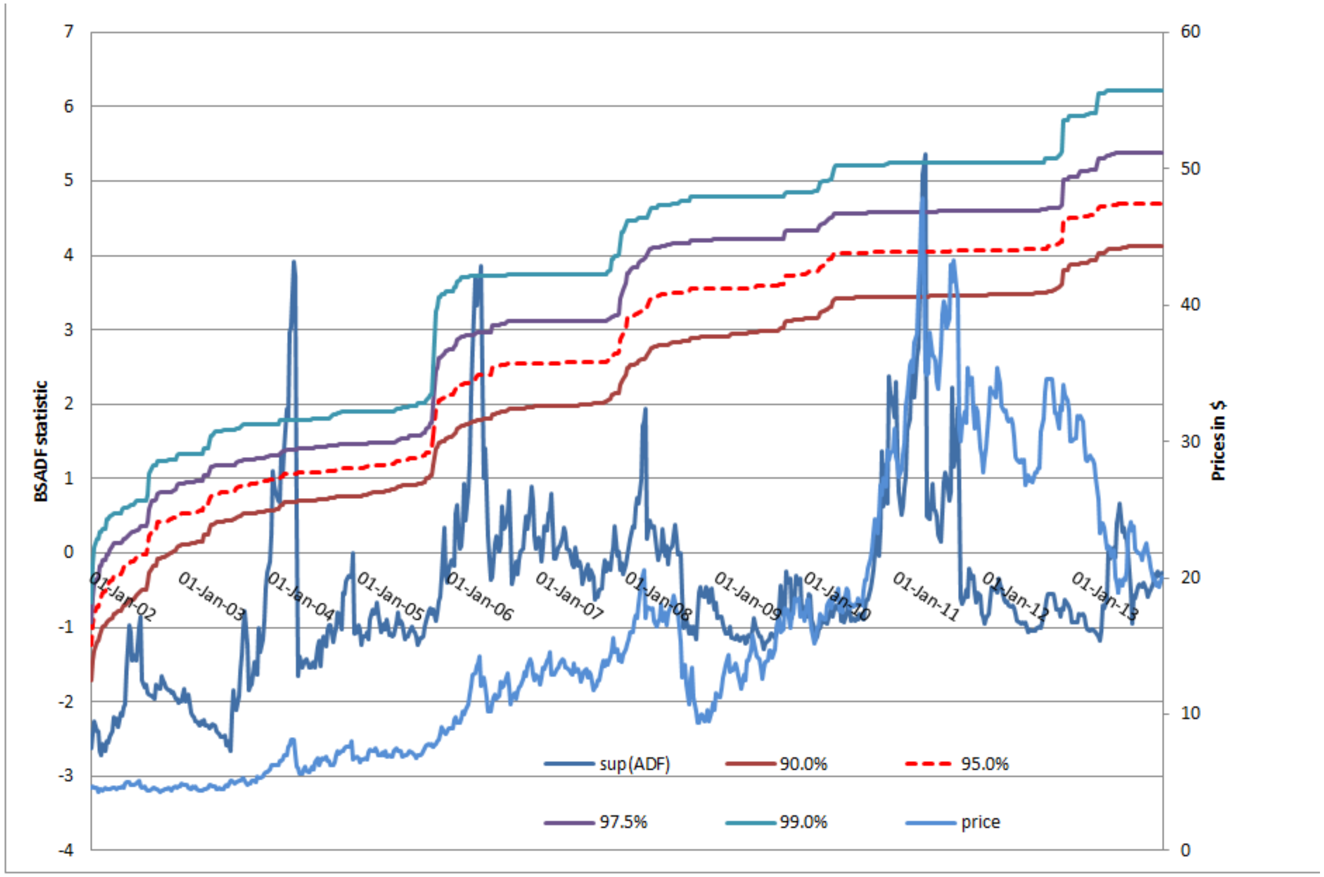

Figure 5B: Platinum one-month futures nominal prices BSADF sequence with wild-bootstrap-adjusted critical values

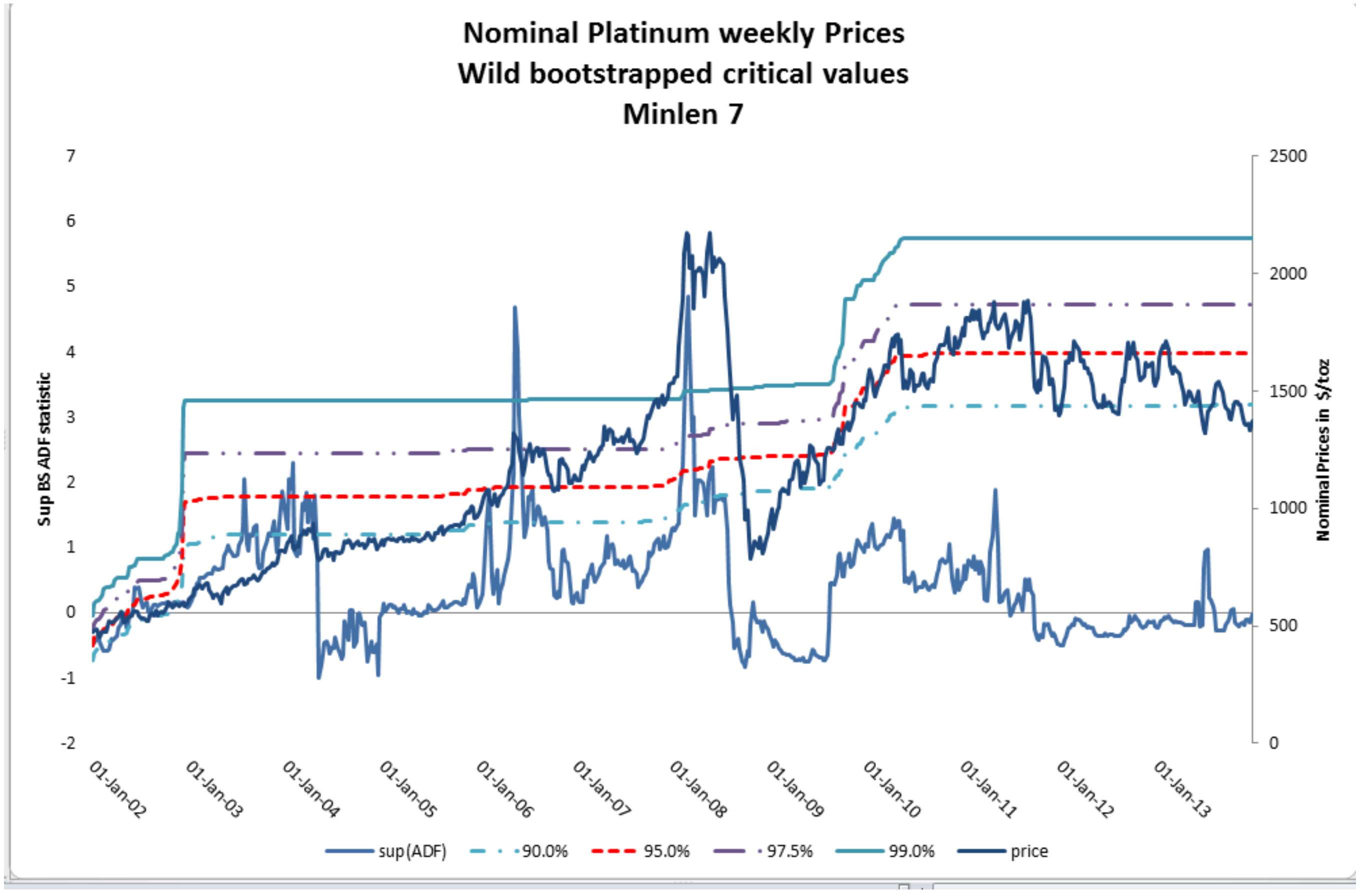

Figure 6: Gold one-month lease rates BSADF sequence