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Abstract

It is often thought that the arrival of the Black Scholes Merton (BSM) model of option pricing in the early 1970s allowed traders to understand how to price and value options with greater precision. Yet, our study suggests that interwar commodity option traders may have been able to intuit 'fair' value and to adjust their prices to changes in the market environment well before the advent of this innovative model. A scarcity of historical price data has limited empirical tests of option price efficiency well before BSM to prior studies of stock options in the 1870s and the early twentieth century which reach contrasting findings. This study deals with option pricing in a different market – commodities – during the interwar period. We conclude that option prices were closer to their BSM theoretical values than suggested by prior studies. Institutional differences between interwar commodity options market and stock option markets in the 1870s and the early twentieth century may partly account for this result. Furthermore, we find that interwar option prices were no more mispriced and were as sensitive to changes in volatility – the key valuation parameter in the BSM model – as in modern times.

JEL Classification: G1, G2, N2

Keywords: Options, Warrants, Black-Scholes, commodities, London Metals Exchange, Market Efficiency, Performativity

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Commodity Option Pricing Efficiency before Black, Scholes and Merton

David Chambers and Rasheed Saleuddin[1]

This version: August 2019

Abstract

It is often thought that the arrival of the Black Scholes Merton (BSM) model of option pricing in the early 1970s allowed traders to understand how to price and value options with greater precision. Yet, our study suggests that interwar commodity option traders may have been able to intuit 'fair' value and to adjust their prices to changes in the market environment well before the advent of this innovative model. A scarcity of historical price data has limited empirical tests of option price efficiency well before BSM to prior studies of stock options in the 1870s and the early twentieth century which reach contrasting findings. This study deals with option pricing in a different market – commodities – during the interwar period. We conclude that option prices were closer to their BSM theoretical values than suggested by prior studies. Institutional differences between interwar commodity options market and stock option markets in the 1870s and the early twentieth century may partly account for this result. Furthermore, we find that interwar option prices were no more mispriced and were as sensitive to changes in volatility – the key valuation parameter in the BSM model – as in modern times.

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Options are a prime example of how financial innovation has contributed to improved economic performance.[2] Towards the end of the last century, options became widely used as firms became able to hedge a wide range of price and financial risks and investors to adjust the risk of their portfolios. A greater understanding of the fundamental drivers behind their values and the ability to compute their prices with a few key inputs contributed in part to the wider use and acceptability of options as risk management tools. This understanding came with the arrival in the early 1970s of the Black-Scholes-Merton (BSM) option pricing model, one of the most important innovations in finance for which Scholes and Merton won the 1997 Nobel prize in economics. The acceptance of the BSM model by traders and the broader financial community coincided with a surge in options trading on the Chicago Board Options Exchange (CBOE) beginning in 1973. A key insight of the BSM innovation was that options can be replicated by a leveraged position in the underlying asset.[3] As a consequence, banks and other intermediaries could create derivatives without having to find a buyer or seller on the other side of a trade and the available range of derivative products expanded dramatically.[4] Options could now be combined with futures, securities and other underlying assets using the BSM insights to complete markets by creating new portfolios and adjusting the risk profiles of commercial and financial institutions otherwise vulnerable to the vagaries of markets.[5]

Historians are interested in the extent to which financial markets were efficiently priced in the past. The extensive literature on bubbles is generally considered *prima facie* evidence of market inefficiency.[6] On the other hand, prior studies investigating other features of stock markets - the

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[2] Merton, 'Financial innovation'. Of course, we should not ignore the fact that derivatives can also lead at times to excessive risk taking and can contribute to market bubbles and crises, such as the 1720 South Sea Bubble, the 1987 US stock market crash and the 2008 Global Financial Crisis to list but a few.
[3] This replication strategy generates payoffs identical to those of a simple European-style option at maturity. The *inverse* of this replicating portfolio therefore hedges the option position.
[4] Petzel, 'Fisher Black', p. 89.
[5] Merton, 'Financial innovation', p. 19.
[6] See for example Garber, 'Famous first bubbles' on the Tulip Mania of 1636, Dale, Johnson and Tang, 'Financial markets can go mad', on the South Sea Bubble of 1720, Campbell 'Myopic rationality' on mid-

spread between bid and ask prices quoted in stock trading, the performance and pricing of closed end funds and the underpricing of initial public offerings - suggest that markets were no less efficient in the early twentieth century than they were at the end of the century.[7] Option markets offer a further important test case of pricing efficiency. Following the arrival of the BSM model, it was claimed that option prices became reasonably closely aligned to their theoretical values almost immediately.[8] The implication is that prices were far less efficient before BSM came along. This view is open to challenge, however. We know from texts on options trading published by Charles Castelli in 1877, S.A. Nelson in 1904 and Leonard Higgins in 1906 that elementary option pricing theory was already being developed and disseminated well before the advent of BSM.[9] The question for historians therefore is when did traded option prices converge to the modern ideal as represented by the BSM model. While prices of underlying assets such as stocks, bonds and commodities are often easy to obtain, uncovering historical option price data suitable for addressing this question has proved challenging and only a handful of such studies of early option pricing exist.

This study exploits a new data set of commodity option prices from the investment records of John Maynard Keynes. The famous Cambridge economist was an innovative investor who managed his college endowment and who also speculated in currencies for himself in the interwar years.[10] Since other scholars have examined his commodity trading strategy in considerable detail,

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nineteenth century British railway bubble, and White 'The stock market boom' on 1929, and Reinhart and Rogoff, *This time is different* for an overview.

7 For bid-ask spreads, see Fohlin and Gehrig, 'Trading costs'; for closed end funds, see Chambers and Esteves, 'The first global emerging markets investor' and a new working paper by Campbell and Rogers, 'The Rise and Returns of Investment Trusts'; and for IPO underpricing, see Chambers and Dimson, 'IPO underpricing', Burhop, 'The underpricing of initial public offerings', and Lehmann, 'Taking firms to the stock market'.

8 Mackenzie, 'Is economics performative?'. This claim asserts 'performativity', in other words, that in this context traded prices conform to a pricing model once it has been accepted by traders as being 'correct'.

9 Castelli, *The theory of 'options'*; Higgins, *The put and call*; Nelson, *The ABC of options and arbitrage*.

10 For his equity investing, see Chambers and Dimson, 'Retrospectives: John Maynard Keynes' and Chambers, Dimson and Foo, 'Keynes the stock market investor' and, regarding currencies, Accominotti and Chambers, 'If you're so smart'.

we do not revisit this aspect of Keynes' investment record.[11] Rather, the focus of this study is on the prices that Keynes paid in the over-the-counter market for metal options from 1921 to 1931 and the extent to which those prices provided by LME dealers in the options market were "fair" as judged by the BSM model.

Commodity markets have been analysed extensively by economic historians on such topics as market integration (principally in the case of grain), long-run price trends and volatility, the impact of the establishment of futures markets on commodity price volatility and market regulation.[12] This study examines commodity options, specifically the market for options on London Metal Exchange futures in the interwar period. Option and other derivative contracts for commodities probably originated in Mesopotamia in the nineteenth century B.C. and for stocks in Amsterdam in the early 1600s.[13] Anne Murphy has carefully documented the depth and sophistication of the fledgling stock option market in London in the late seventeenth century following the migration of knowledge and expertise from the Low Countries.[14] Her study discusses how such instruments were a fundamental component of the English Financial Revolution of the 1690s and whether or not they were profitable for investors to exercise. However, the limitations of the available price data prevented a more thorough examination of how efficiently these options were priced.

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[11] Marcuzzo and Sanfilippo, 'Keynes and the option market'; Fantacci, Marcuzzo and Sanfilippo, 'Speculation in commodities'; 'Cavalli and Christiano 'Keynes in the tin market'

[12] O'Rourke and Williamson, 'Globalization and history' examine commodity market integration in the nineteenth century and Hynes, Jacks and O'Rourke, 'Commodity market disintegration' focus on the market disintegration in the interwar period; Jacks, 'From boom to bust' documents the evidence on commodity prices including metals over the twentieth century and Jacks, O'Rourke and Williamson, 'Commodity price volatility' consider price volatility and market integration over three centuries; Jacks, 'Populists versus theorists' considers the impact of futures markets on commodity prices; and Saleuddin, *Government of markets* studies the evolution of modern commodities markets and their regulation during the interwar years.

[13] Weber, 'A short history of derivative securities', p. 432; Gelderblom and Jonker, 'Amsterdam and options trading'.

[14] Murphy, 'Trading options before Black-Scholes'. For the importance of commodity futures markets, see Jacks, 'Populists versus theorists'.

Availability of suitable historical price data with which to test pricing efficiency is critical. Yet, such historical data is very scarce. To the best of our knowledge, only two option price datasets have been analysed to date. Joseph Kairys and Nicholas Valerio and, later, Scott Mixon analysed US stock options in the early 1870s and Lyndon Moore and Steve Juh examined South African stock option and warrants in the early twentieth century.[15] Kairys and Valerio, who were the first to exploit the 1870s US stock option data, reached the conclusion that options were far from efficiently priced.[16] On the other hand, both the Mixon and the Moore and Juh studies find that early option markets were efficient in that they displayed some similarities with modern option markets. At the same time, the former clearly states that option prices were substantially less efficient than they are today.[17] All three of these prior studies examine *stock* options and warrants. In contrast, we analyse the pricing of *commodity* options – more precisely, options on metal futures – traded by John Maynard Keynes from 1921 to 1931. We find that pricing errors, defined as the difference between traded prices and BSM-theoretical prices, averaged 15% – a similar level to modern times. In comparison, the pricing errors implied by the three prior studies were two to three times this level. There were important institutional differences between commodity option markets and stock option markets in the past. The interwar commodity market is better suited to testing for option price efficiency than is the stock market of a century or more ago due to the greater ease of short selling both options and the underlying futures. Our contribution in this article is to add to our knowledge of how efficiently options were priced in pre-BSM markets by looking at a different market and a different period.

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15 Kairys and Valerio, 'The market for equity options'; Mixon, 'Option markets'; Moore and Juh, 'Derivative pricing 60 years before'.
16 Kairys and Valerio, 'The market for equity options'.
17 Mixon, 'Option markets', p. 184.

I. Option Pricing and the Black, Scholes and Merton model

In this section, we briefly review the key features of an option and of the BSM model, highlighting the central role played by the volatility of the underlying asset in pricing options. [18] Figure 1 graphs an illustration of a 3-month call option with a strike price of 140. A European call (put) offers the buyer the right to buy (sell) a certain pre-specified amount of the underlying traded asset at a pre-specified price, the strike price, on a certain expiry date.[19] The payoff to a call option at its expiry is the difference between the underlying price and the strike price and is represented by the solid line. If the underlying price is below the strike price, described as 'out-of-the-money' for calls, the payoff is zero and the option is worthless; above the strike price, there is a one-for-one relationship of the payoff, and therefore the option value at expiry, with the underlying asset price. The call option in this case is said to be 'in-the-money'.

The dashed line in Figure 1 captures a combination of both the 'time value' and 'intrinsic value' of an option prior to expiry. Time value reflects the asymmetric payoff possibilities to the call option. While there is always some likelihood that the underlying asset price moves above the strike (or further above the strike if the option is already in-the-money), the losses are always capped at zero, should the option expire out-of-the-money. At very high prices of the underlying asset, a very deep in-the-money option has little or no time value and has largely 'intrinsic value', represented by the difference between the stock price and the strike price. In this case, the option price and that of the underlying asset move almost in lock-step. Similarly, a deep out-of-the-money option with very little probability of being exercised at maturity trades at a very low price and has zero intrinsic value and no significant time value.

[Insert Figure 1 here]

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[18] See Bodie, Kane and Marcus, *Investments*, chapters 20 and 21 for an accessible introduction to options.
[19] In contrast, American style options can be exercised at any time, and require adjustments to the BSM model to be priced correctly.

Whilst estimating intrinsic value was straightforward even before the BSM model, estimating time value was not. Based on texts on options trading published a hundred years or more ago, traders understood the value of an option to vary with the underlying asset price and the time to expiry and that the riskiness of the underlying asset was also important. [20] However, the concepts of the volatility of the returns of the underlying asset price and, to a lesser extent, the effect of the risk-free interest rate may not yet have been fully appreciated. The ground-breaking theoretical pricing model linking these variables together in order to compute the fair value of an option did not make its appearance until the early 1970s. We refer to this model, independently but concurrently derived by Fisher Black and Myron Scholes, and Robert Merton, together with its assumptions as BSM or the BSM model (see Appendix A).[21]

According to Black and Scholes, the underlying asset volatility constitutes 'the big unknown in the options pricing formula'.[22] The model assumes that volatility is constant over the time to expiry, despite volatility being neither constant nor known in advance.[23] Hence, traders try and estimate it by first taking into account *historical* volatility, defined as the standard deviation of the natural log of price changes of the underlying asset over previous periods.[24] Of course, simply using only the most recent observation of historical volatility in a BSM model leads to inaccuracies in pricing options.[25] Traders accordingly also try to take into account future changes in volatility by attempting to take account of factors that might cause realized volatility to be different from

[20] See Castelli, *The theory of 'options'*; Higgins, *The put and call*; Nelson, *The ABC of options and arbitrage*.
[21] Black and Scholes, 'The pricing of options'. Merton, 'Theory of rational option pricing'. The model computes the fair value of an option on a single stock given an ex *ante* known and constant future standard deviation (volatility) of the returns on the underlying stock. See Cox, Ross and Rubinstein, 'Option pricing' for the binomial approximation of BSM.
[22] Black and Scholes, 'The valuation of options contracts', p. 400.
[23] Black, 'Fact and fantasy', p. 36; Poon and Granger, 'Forecasting volatility', p.481.
[24] It is well-known that traders are interested, in the first instance, in the historical volatility of the underlying asset price. Fischer Black's first option pricing service provided BSM prices based on historical volatility, Black, 'Option service' p. 5 as quoted in MacKenzie 'An engine' p. 162. Note also that Mixon, 'Option markets' examines historical volatility, although he refers to historical volatility as lagging *realized* volatility.
[25] Black 'Option service', p. 36.

historical, including structural shifts and idiosyncratic events.[26] Following the approach of prior studies, we proxy expected volatility by *realized volatility*, defined as the actual *ex post* volatility of the underlying asset over the life of the option, which is unobservable at the time of the trade.[27] Along with historical and realized volatility, there is a third type of volatility which is important, namely, *implied volatility*. When all other input parameters to the BSM model, including the traded option price, are known (or can be very closely approximated) at the time of valuation, we are able to compute *implied volatility* by backwards induction. The BSM-implied volatility is employed by traders to determine how cheap or expensive an option is as compared with their expectations of future volatility.

In the rest of the paper, we define 'BSM-efficiency' in the first instance by the gap between observed option prices and theoretical prices derived from the BSM model, or equivalently, the gap between realized volatility and implied volatility.[28] We also consider BSM-efficiency in a second sense, namely, the extent to which traders might have been aware of the effect of volatility on options prices by examining the co-movement of actual (realized and historical) volatility with implied volatility.

II. Prior Studies of Option Pricing Efficiency before BSM

Empirical studies of option pricing efficiency in the years just before the arrival of the BSM model suffered from certain data limitations stemming from the use of quoted rather than traded prices and from not being able to match option prices with the underlying asset prices at the time of any trade.[29] Stronger tests of efficiency require better access to accurate pricing data than was available

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26 For example, Taleb, *Dynamic hedging*, p. 95.

27 For example, Moore and Juh, 'Derivative pricing 60 years before'.

28 We do not wish to imply that the BSM model is free of problems, far from it - simply that, as a working pricing model, it provides us with the best first approximation of fair value and is reasonably accurate for modern short-dated exchange-traded options.

29 Kruizenga, 'Profit returns' had access only to very rough indications of option prices, and not to traded prices or even bid/offers. Boness, 'Put and call options' did use actual trades but did not have enough data to run tests systematically.

to these early scholars. In their place, these studies assessed price efficiency by whether a trader made profits or not from buying and selling options. However, such tests are often substantially influenced by the general direction of the underlying markets during the sample period, irrespective of how efficiently options are priced.[30] For example, simply being able to exercise a large number of calls (puts) and make a profit in a strongly rising (falling) market can generate profits for an investor even when the options are priced expensively. Subsequent studies of option pricing going back to earlier time periods than the mid-twentieth century therefore avoided testing for price efficiency on the basis of whether or not traders made money. Scott Mixon analysed US stock option pricing in the early 1870s and Lyndon Moore and Steve Juh examined South African mining stock option and warrants pricing in the early twentieth century.[31] Both studies find that early option markets displayed some similarities with modern markets.[32] At the same time, Mixon points to the biggest change in the markets between the 1870s and the 1970s being 'the diminishing gap between implied and realized volatility', which indicates that 1870s' option prices were actually far from BSM-efficient.[33] A third study by Kairys and Valerio, exploiting the same US stock option price data from the early 1870s as Scott Mixon, also concluded that the pricing gap was much wider than today.[34]

However, some features of the data employed in these three early option market studies create difficulties when it comes to estimating price efficiency. The primary issue is that the data are not *traded* prices. Kairys and Valerio and Mixon analyse option price *quotations* advertised in newspapers targeted at retail investors of the early 1870s. There is no evidence that any options were ever

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[30] For example, Kruizenga, 'Profit returns' found that option buyers made out slightly better than options sellers; Boness, 'Put and call options' found the opposite.
[31] Mixon, 'Option markets'; Moore and Juh, 'Derivative pricing 60 years before'.
[32] Mixon, 'Option markets', states on p. 186 that 'the actual practice of option pricing has been remarkably consistent throughout the centuries' and that 'equity option markets displayed precisely the same empirical regularities in the nineteenth century as they do in the twenty-first century'; Moore and Juh, 'Derivative pricing 60 years before', p. 3069, 3071 and 3097.
[33] Mixon, 'Option markets', p. 184.
[34] Kairys and Valerio, 'The market for equity options'.

transacted at these prices. The fact that these advertisements disappeared shortly after in 1875 may be indicative of the lack of investor interest and of actual trades.[35] Furthermore, according to Mixon, these indicative *ask* quotations were for only one side of the market – no bid prices were available and likely did not exist.[36] Similarly, Lyndon Moore and Steve Juh examine price *quotations*, advertised in local newspapers, of call options on South African stocks in the late 1900s and early 1910s. Again, these are not *traded* prices but *offer* price quotations without an accompanying bid quotation with which to calculate a mid-price. Both stock option data sets suffer from a further challenge, namely, that they are most often not at-the-money. As described in section I, options which are closer to at-the-money provide a truer test of BSM efficiency than do deep in- or out-of-the-money options because time value becomes more important relative to intrinsic value. In addition, the need to make adjustments for the 'volatility smile' becomes irrelevant in the case of options close to at-the-money.[37] As well as options, Moore and Juh examine a sample of warrants, some of which are far away from at-the-money and do not, therefore, provide a very demanding test of BSM pricing efficiency given the minimal time value component. [38] The long-dated nature of these warrants, with original time-to-expiry ranging between 1 and 5 years, also invites problems.[39] The longer the time to expiry, the more sensitive are option fair value estimates to

[35] Kairys and Valerio, 'The market for equity options', p. 1708.
[36] Kairys and Valerio, 'The market for equity options', p. 1710, report that '…this was a *one-sided market* for the retail customer'. Nevertheless, the authors interpret the two advertised prices for each option to be the bid and offer. Mixon, 'Option Markets', p. 177, claims the prices to represent the range of offer prices with no bid available.
[37] The volatility smile refers to the fact that, for a given expiry, deep in- and out-of-the-money options should command different prices (and thus implied volatilities) than is suggested by the BSM model, Derman and Miller, *Volatility smile*. This anomaly arises from the limitations of the model's assumptions, namely, that volatility is not constant and the underlying returns distribution is typically not lognormal. Not adjusting BSM theoretical prices for the volatility smile tends to overprice out-of-the-money calls and warrants. This problem does not arise for at-the-money options or warrants.
[38] Moore and Juh, 'Derivative pricing 60 years before', Table II, p. 3080, include two warrants in their sample of 15 warrants which are extremely deep-in-the-money, making them straightforward to price even for pre-BSM investors. Once these warrants are excluded from their sample, the average pricing error equally weighted across the remaining warrants increases substantially (see our Table 1, note 5).
[39] The same is true for long-dated options.

assumptions about the structure of volatility, in particular, and to the choice of discount rate.[40] Consequently, in all three of these studies, there are doubts about whether the underlying data are well-suited to testing the price efficiency of the options being traded at that time.

All of the studies discussed so far examine stock options. Our study examines the market for commodity options. This setting offers some advantages when testing pricing efficiency. Futures trading was already centralized on the LME in the interwar period, and there were no major subsequent institutional changes to this market which might confound our tests of option pricing efficiency.[41] Furthermore, the interwar commodity option market was similar in structure to modern markets in that traders were able both to buy and sell options as well as to buy and sell short the underlying asset for hedging purposes. 'Selling short' involves selling a traded asset one does not own. In the case of interwar LME futures, selling short was very straightforward and was simply a promise to sell the underlying commodity (in our case, a quantity of tin or copper) at some determined point in the future.[42] The relative ease of shorting in the interwar commodity futures market may have facilitated greater option pricing efficiency and contrasts with the difficulty of shorting in early stock markets.[43] Commodity options have always been European-style and so they suffer from none of the complications of possible early exercise, especially in the case of put options. Futures options are also less sensitive to interest rate assumptions when estimating fair value.

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[40] The characteristics of warrants generally 'make some of the assumptions…even more unrealistic than they are in the case of short-term call options', Veld, 'Warrant pricing', p. 71. See also Lauterbach and Schultz, 'Pricing warrants', p. 207.
[41] This contrasts with the US stock option market where a centralized equity option exchange (the CBOE) appeared in the 1970s around the same time as the BSM model.
[42] Economist Intelligence Unit, *The LME*.
[43] Borrowing a security from someone else in order to short sell is rarely a riskless exercise, Gene D'Avolio, 'The market for borrowing stock'. Yet, short selling equities was most likely more difficult in earlier times. According to Moore and Juh, 'Derivative pricing 60 years before', p.3078, short selling was very rare in the equity option and warrant markets of the early twentieth century. The stocks traded in South Africa, an emerging market, were mostly highly speculative mines, and shorting these types of stocks was, in all likelihood, not easily done, and may not have been risk-free.

Previous studies have analysed early commodity option markets. Paul Mehl examined a sample of extremely short-dated wheat options traded on the Chicago Board of Trade from 1926 to 1931 and the frequency with which they were exercised.[44] He finds that puts were exercised frequently suggesting that traders made profits and that this is therefore indicative of price inefficiency. However, this result is not surprising since, as he himself acknowledges, the market trended downward during the sample period. In other words, the frequency of put option exercise would have been substantially affected by the overall direction of the market irrespective of how efficient prices were. As discussed above, this is a weak test of price efficiency. A study of interwar commodity option markets in London by Maria Marcuzzo and Eleonora Sanfilippo had as its primary focus being the option trading strategy of John Maynard Keynes, not option price efficiency.[45] In comparison with both these prior studies, our study offers direct evidence on the efficiency of commodity options prices before the BSM model and uses appropriate tests.

III. Metal Option Prices in the Interwar Period

The data we employ consist of *traded* prices of *short-dated* options on metal futures traded on the London Metal Exchange between 1921 and 1931.[46] We possess all of the inputs required by the BSM model to estimate the theoretical price of the options, including daily prices of the underlying commodity and, especially, the price of the underlying future of matching maturity at the time the option actually traded. Notably, our options are at-the-money and offer a more appropriate test of BSM efficiency than deep in- or out-of-the-money options.

We hand-collected traded prices of three-month options on copper and tin futures traded on the London Metal Exchange (LME) over the period 1921 to 1931. The prices and other details of the

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[44] Mehl, 'Trading in privileges'.

[45] Marcuzzo and Sanfilippo 'Keynes and options'. On p. 332, they state that they are unable to find evidence of any systematic pricing rules.

[46] While commodity futures were, as now, exchange-traded in the interwar years, to the best of our knowledge, the options were traded over-the-counter between LME brokers and their clients.

options are taken from the investment records of John Maynard Keynes. The LME began trading in copper and tin in 1877, followed by lead in 1903 and spelter (zinc) in 1915. Trading was halted during the World War 1.[47] By the early 1920s, however, active trading had resumed.[48] In fact, 'London's long control over tin prices has been ascribed as due in no small measure to the presence of an organized futures market in that center'.[49] In the interwar years, the LME was the dominant metals exchange worldwide and, according to the Economist Intelligence Unit, 'the London price was effectively the world price'.[50] Trading on the LME in each metal took place in rotation for 10 minutes at a time twice a day at 12 noon and 3:45 P.M. Trading would begin with the secretary calling 'Copper, Gentlemen, copper', followed ten minutes later by 'Tin, Gentlemen, tin'.[51] Round lots were 25 tons for copper and 5 tons for tin. The standard traded option was a European-style option with a three-month expiry in the case of copper and tin. The three-month expiry was originally chosen to match the transport times for tin from South East Asia and copper from Chile.[52] LME dealers such as Vivian Younger and Bond, the largest tin dealer, traded contracts for spot, futures and options. Plain vanilla options (put, calls and straddles, called "double options" at the time) were struck at-the-money – that is, the strike price was set equal to the futures price, regardless of whether buying or selling. Unlike contemporary commodity futures privileges in Chicago, nineteenth century French government bond options in Paris and equity options quotations in New York of the 1870s, the quotation system was based on a price for at-the-money options, mirroring modern market practice, rather than a fixed price for a quoted spread away from at-the-money.[53]

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47 LME 103th Anniversary Supplement.

48 According to the Economist Intelligence Unit, *The LME*, Table XVI, annual futures turnover ranged between 163,000 and 711,000 tons for copper and 68,000 and 208,000 tons for tin between 1924 and 1938.

49 Baer and Saxon, *Commodity exchanges,* p. 121.

50 Economist Intelligence Unit, *The LME*.

51 Forrester, 'Commodity Exchanges in England', p. 205-206.

52 LME 103th Anniversary Supplement.

53 For Paris markets, see Bachelier, 'Theory of speculation'.

Our commodity option prices along with the transaction date and contract details are taken from the trades by John Maynard Keynes on his own account.[54] Keynes was an experienced and innovative investor in stocks and currencies.[55] In the case of commodities, he believed himself to possess an 'extremely wide practical acquaintance with commodity markets and their habits'.[56] He spent a great deal of time examining the fundamentals of such markets, best illustrated by the seven *Special Memoranda on Stocks of Staple Commodities* published between 1923 and 1930 by the London and Cambridge Economic Service, where Keynes was a director.[57] As a hands-on speculator, he became acquainted with the technical aspects of these markets as revealed in his correspondence with his stockbroker, Buckmaster & Moore, and his friends.[58] In addition, around this time he formulated his theory of normal backwardation, first outlined in the *Manchester Guardian* in 1923.[59] Keynes frequently executed sophisticated trades, including buying options to hedge his often large exposures to the underlying future markets.[60]

Other scholars have documented Keynes' commodity trading in some detail, using the same archival sources to analyse his trading strategies and the link with his economic thinking.[61] These studies also describe some of the institutional features of the interwar metal commodity markets. Since Keynes' trading strategy in commodity options has already been well covered, our intention is not to repeat this analysis here. Instead, we focus our attention on the prices at which the trades

54 Keynes Papers at King's College Cambridge: SE/11/2/3-60. He also traded commodity options for his college.
55 Chambers and Dimson, 'Retrospectives: John Maynard Keynes'; Accominotti and Chambers, 'If you're so smart'.
56 Keynes to Hawtrey, 6 January 1936, in Keynes, *Collected writings 12,* p. 627-8.
57 Keynes, *Collected writings 12*, p. 267-647.
58 A good example is Rupert Trouton's letter to Keynes, Keynes Papers, King's College Cambridge: JMK/SE/2/1/126-7.
59 'Some aspects of commodity markets' in Keynes, *Collected writings 12*, p. 255-66.
60 Occasionally, however, he made what appear to be elementary mistakes, such as exercising several out-of-the-money options. In a single copper option trade (but no tin trades), Keynes exercised an in-the-money option which resulted in a loss after commissions. It is probable that either Keynes misunderstood the commissions he would pay, or this option hedged an underlying cash position in the metal. This purchase remains in the sample.
61 Marcuzzo and Sanfilippo, 'Keynes and the option market'; Fantacci, Marcuzzo and Sanfilippo, 'Speculation in commodities'; 'Cavalli and Christiano 'Keynes in the tin market'.

took place between Keynes' primary broker, Buckmaster & Moore, and the LME dealers. In particular, we examine how close these prices were to the theoretical prices implied by the BSM model and whether or not they co-moved with the BSM inputs as predicted by the model. In keeping with the studies by Mixon and Moore and Juh and with modern studies, we analyse prices before commissions.[62]

In total, Keynes executed 241 trades in metal options, averaging £8,670 of underlying futures exposure per trade.[63] His trade size was large but not overwhelmingly so relative to the underlying LME futures market. A typical trade was the purchase of a European call option on copper on 23rd February, 1922. Buckmaster & Moore wrote as follows:

> We beg to report that we have to-day bought on your behalf a Call Option on :-
> 50 Tons Standard Copper……….for May 23rd, prompt, on the basis of £58. 10. 0 per ton at the price of 27/6 per ton.[64]

Keynes then subsequently exercised the option just before expiry and sold the physical metal. Accordingly, Buckmaster & Moore again wrote on May 22nd, 1922 as follows:

> We beg to report that we have to-day sold for you :-
> 50 Tons of Copper (23rd May delivery) at £62. 2. 6. per ton
> Against Call Option on the same amount purchased on 23rd February.[65]

Buckmaster & Moore traded on Keynes' behalf with three metals dealers on the LME, Budd, Candover, and Vivian, Younger and Bond.[66] The latter were especially active in tin markets during the interwar years, acting for the British Metals Corporation (BMC).[67] The BMC, Vivian Younger

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[62] Commissions paid by Keynes on buying or selling an option were 3/16th's of one percent of the notional amount traded, paid to the metals dealers, plus 0.1% of the notional amount, paid to the broker. Upon exercise of the option, Keynes paid exactly the same charges again. The latter effectively moves the strike price by a very small amount, 0.2875%. Keynes Papers, King's College Cambridge, JMK/SE/11/9 and SE/11/90.
[63] This is four times the size of his average stock trade for his college in the same period. Chambers, Dimson and Foo 'Keynes the stock market investor', p. 847, Table 1.
[64] Keynes Papers, King's College Cambridge, JMK/SE/2/2/4.
[65] Keynes Papers, King's College Cambridge, JMK/SE/2/2/4.
[66] The three metal brokers are referenced in the correspondence and statements in the Keynes Papers in the King's Archives. For example, JMK/SE/2/2/170, SE/2/5/95, SE/11/2/90.
[67] Harrison, *A century of metals broking*, p. 46. BMC was established on Armistice Day, 1918, as the government's sole marketing agent to 'foster trade in non-ferrous metals in the United Kingdom and in the Commonwealth generally [and] maintain the position of the London Metal Exchange'.

and Bond, and the LME were closely connected, not least through Sir Cecil Budd, the managing director of all three.[68]

We examine all calls, puts and straddles transacted by Buckmaster & Moore on Keynes' behalf for which there exists (i) a price for the futures contract matching the option expiry at the time of the option's execution[69] and (ii) three-month histories of daily futures prices both before and after each trade date. Daily three-month futures prices are hand-collected from the *Home Commercial Markets* section in *The Times* newspaper from 1 January 1921 to 31 December 1931 and are displayed in **Figures** 2a and 2b. For some of his trades, the lack of sufficient detail about the transaction or the price of the futures contract matching the expiry of the option at the time of the option trade invites errors in the estimation of BSM theoretical prices. Hence, although Keynes also traded options on spelter, lead, rubber and linseed oil, the forward maturities of the futures contracts listed in *The Times* did not match the expiry date of the options he traded and we exclude these trades from our analysis. Our final sample consists of 135 option trades for copper (40) and tin (95) for which we have actual LME futures prices and all BSM model inputs.[70] The sample includes 13 straddles, a combination of a put and a call. Most of the trades involved buying an option – 114 calls and 14 puts; and there were relatively few short sales – 2 calls and 18 puts. All of these options were held until the day of expiry, at which point Keynes either allowed an out-of-the-money option to expire or exercised an in-the-money option and then liquidated the corresponding futures position.

[Insert **Figure** 2a and b here]

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[68] Harrison, *A century of metals broking,* p. 47. By 1922, the BMC had absorbed Vivian, Younger and Bond. Through the BMC and then, later, also through the powerful Consolidated Tin Smelters, Vivian, Younger and Bond was able to expand their already substantial business in the tin markets.

[69] Other studies often must approximate the strike price, the underlying price at the time for the trade, or both. See Mixon, 'Option markets', p. 177 and Moore and Juh, 'Derivative pricing 60 years before', pp. 3074 and 3076 for their estimation problems and their required workarounds.

[70] We use nominal UK treasury bill returns as our risk-free interest rate variable from Dimson, Marsh and Staunton, *Global investment returns.*

IV. Option pricing efficiency on the interwar LME

According to our definition of BSM-efficiency, we test for both (i) low pricing errors between theoretical prices, computed with the BSM model, and traded option prices, as well as (ii) how well option prices reflect changes in the market environment. The first test computes theoretical prices for each commodity option with a known strike price and time to expiry, using the BSM model with realized volatility over the life of the option as the key input, along with the futures price and the risk-free rate. The lower are the pricing errors, the more BSM-efficient prices are. The second test examines the degree of co-movement of the implied volatility of each option trade with both historical and realized volatility. As Black himself stated about historical volatility: 'it is not an infallible guide' to pricing an option.[71] The empirical literature has subsequently shown that historical and realized volatilities are significantly related to implied volatility in the modern era.[72]

We estimate the average pricing error of our interwar metal options to be 15% (**Table** 1). This level of mispricing compares favourably with the average errors implied by the findings of the prior studies by Moore and Juh, and Mixon ranging between 32% and 50%. These estimates and our own estimate do not take account of commissions.[73] Kairys and Valerio include commissions and their results imply average mispricing of between 50% and 75%. A scatter plot of theoretical versus traded options prices points to some individual pricing errors in our sample being substantial (**Figure 3**). This is not surprising. Traders struggle to forecast volatility accurately for every options trade and such large errors also populate modern studies.[74] We pay most attention to average mispricing. In comparison with historical results, Mixon estimated average mispricing of 12% in modern markets.[75]

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[71] Black, 'Fact and fantasy', p. 36.
[72] See, for example, Lamoureux and Lastrapes, 'Forecasting stock-return variance'.
[73] If commissions are taken into account, average mispricing across our sample increases by about 9%.
[74] Adams and Wyatt, "Biases in option prices", p. 549-562.
[75] Mixon, 'Option markets'. In reality, we would not expect to find zero mispricing in the modern era since traders generally price slightly above the BSM theoretical price to take account of the weaknesses in the BSM model.

There are one or two caveats needed when comparing average percentage pricing errors across different option and warrant samples such as in Table 1. Firstly, the linear relationship between price accuracy and volatility accuracy is not linear. Secondly, the existence of in-the-money and out-of-the-money options in the sample affects the magnitude of average pricing errors due to variation in the relative contribution of time value (based on the BSM formula) and intrinsic value. The Mixon/Kairys and Valerio and Moore and Juh options samples are short-dated and slightly out-of-the-money. As a result, the sensitivity of the option price to volatility forecasting errors is similar in each of these cases with ours. Therefore, we derive a certain confidence that our comparison of percentage price errors across studies is meaningful when assessing BSM efficiency. In the case of warrants, price data – combining long dates and a mixture of options with varying moneyness (and therefore different sensitivities to volatility and model errors) – do not constitute as good a test of BSM efficiency as discussed above. Yet, primarily due to these options being out-of-the-money or deep in-the-money, the price effect of a given forecasting error will be smaller than in our sample, *ceteris paribus*.

[Insert Table 1 here]

[Insert Figure 3 here]

Turning to our second test, we use the BSM model to compute the implied volatility for each option where the traded option price as well as the futures price, the strike price, time to maturity and the risk-free rate are all known at the option trade date. We first look for co-movement of implied volatility and historical volatility. Since all options have three months to expiry, our window for estimating for both historical volatility and realized volatility is also three months. A plot of the BSM-implied volatility against the trailing 90-day historical volatility for tin (**Figure** 4a) and for copper (**Figure** 4b). In both cases, implied volatility tracks historical volatility quite closely. The only exception is the second half of 1922 when the implied volatility was around twice historical volatility. It is possible that 1922 prices were influenced by the greater uncertainty in the aftermath of the crisis in 1921, when many commodities experienced unprecedented deflation.[76] More importantly, a scatterplot (**Figure** 5) confirms that implied and historical volatilities have a strong positive relationship in our sample.

[Insert Figure 4a and b and Figure 5 here]

[Insert Table 2 here]

In Table 3, we report results from OLS regressions which test for a relationship between implied volatility (IV) for tin and copper against the trailing 90-day historical volatility (HV) (regression 1), and then against 90-day realized volatility (RV) (regression 2). Results suggest a strong positive linear relationship of IV with HV and RV.In regression (3), we test for the co-movement of IV with both HV and RV together. Traders set option prices based on their expectations about future volatility over the time to expiry of an option at the time of a trade.[77] Their expectations are only partly based on HV since they also make adjustments for the future being different to the past which we proxy by RV. Our results show that both HV and RV are positively related with IV and are statistically significant. The sum of the coefficients on the two right-hand side volatilities in regression (3) is close to unity, indicating that a linear combination of historical and perfect foresight volatilities explains almost all of the observed level of implied volatility. Furthermore, the inclusion of both volatility variables leads to an improvement of the adjusted R-squared. These results suggest that traders may in some sense have employed a combination of historical and expected volatility in setting option prices.

The tin market was of course notorious for being the subject of considerable manipulation in the 1920s.[78] To control for any idiosyncrasies of this market, we include a dummy variable for all

[76] Krugman, 'The conscience of a liberal'.
[77] MacKenzie and Millo, 'Constructing a market', p. 107-45.
[78] Thoburn, *Tin in the world economy*. See the 'Tin' sections in the *Special memoranda on Stocks of Staple Commodities* in Keynes, *Collected writings 12*, p. 267-647.

traded tin option contracts in regression (4). RV, HV and the tin dummy are all highly statistically significant. The coefficient on the tin dummy is positive, implying that IV's were on average 4.5% higher for tin than copper over our sample period. One possible explanation for this premium is that traders understood that the tin market was subject to attempts at intense manipulation and was therefore prone to larger-than-expected outcomes (compared to a lognormal distribution) and to possibly severe mis-estimation of volatility on a per trade basis. In other words, the very large potential forecasting error of tin price volatility and its distribution pushed option prices further above their BSM theoretical price than for copper, where little or no market manipulation occurred.[79]

[Insert Table 3 here]

Since our data include option sales, we are able to test the hypothesis that short trades might have taken place at lower implied volatilities, if the short side of the market was relatively illiquid and inefficient.[80] In fact, we find that the coefficient on a dummy variable taking the value 1 in the case of an option sale is close to zero and not statistically significant. Sales appear to be as efficiently priced as purchases, indicating the presence of a two-way market in options. We also tested dummy variables for puts versus calls and for single options versus straddles and found no differences in pricing. These results are not included in Table 3 but are available on request.

One possible issue with our data set is that the option trades are solely those of a single investor, and, moreover, those of Keynes, an educated and sophisticated trader in options as discussed above. However, we would emphasise that these trades were entered into by his broker, Buckmaster & Moore, with three LME dealers. Since his broker could source business with several dealers, one might reasonably expect any dealer entering into a transaction to set their prices

[79] This is a risk that modern-day traders call the 'vol of vol' (volatility of volatility).
[80] An alternative hypothesis consistent with options sales exhibiting lower implied volatilities is that Keynes was a very good trader who bought underpriced options and sold overpriced options.

competitively and not overprice them. On the other hand, any consistent underpricing by the dealers would prove expensive for them given Keynes' transaction size. One might worry that less sophisticated investors than Keynes did not obtain the fair prices he did.[81] However, this does not undermine our test of efficiency which simply relies on the existence of some well-informed investors able to obtain fair prices from the market.

Modern pricing is close to the BSM standard, on average (see Table 1). We should not expect zero pricing errors on average. Implied volatility is likely to be biased upwards as an estimator of realized volatility reflecting the fact that traders set the option price higher than BSM option price to account for the limitations of the BSM model in practice.[82] As with pricing errors, our results show correlation between volatilities compares very favourably to that in modern markets. For complex reasons highlighted by David Bates, there are very few studies that focus on implied volatility as the dependent variable.[83] More common are studies that seek to determine the accuracy of implied volatility as a predictor of realized volatility. Bates tests this same relationship for S&P futures in the late twentieth century and reports very similar results to those obtained when we regress RV on IV.[84] A major empirical study of thirty-five types of option contracts including equity, interest rate, currency and metal futures over the 1980s and 1990s corroborates these findings.[85]

V. What interwar traders understood about pricing options

It would appear from the analysis in the previous section that interwar commodity options were modestly mispriced – actually, they are slightly overpriced as in modern markets. In addition, option prices responded systematically to changes in the market environment as proxied by

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[81] In this same sense, it is less likely that stock option price quotes advertised to retail investors were 'fair' and therefore they are less suited to testing option price efficiency.
[82] Poon and Granger, 'Forecasting volatility', p. 489.
[83] Bates, D. S., 'Testing option pricing models.' NBER Working Paper 5129 (1995), p. 16.
[84] Bates, 'Empirical options pricing', p. 398, reports a coefficient of 0.76 on IV with an R-squared of 0.45. We find a coefficient of 0.72 on IV and an R-squared of 0.43 on our combined sample of copper and tin options (not reported). Both coefficients are statistically significant at the 1% level.
[85] Szakmary et al, 'Predictive power of implied volatility'.

volatility, despite traders having no knowledge of the BSM model. These results naturally invite the question as to how traders set option prices in a pre-BSM world. Certainly, they understood that the riskiness of the underlying asset was a key driver of options pricing as far back as the late seventeenth century.[86] Early texts on options revealed a reasonably sophisticated understanding of the basic determinants of option prices. In 1877, Charles Castelli published one of the first analyses of stock options in which he states:

> the Premium… fluctuates according to the variations of the Stock to be contracted: if the fluctuations are violent and numerous, and its future course liable to a great rise or great fall, then the premium asked is very heavy; if, however, the Stock has evenly kept its quotation, Options can be negotiated for a very trifling premium.[87]

Leonard Higgins in 1906 identified a more precise measure of past stock price fluctuations as a key input to any option trading decision by focusing on the historic average stock price range over non-overlapping periods when setting a minimum price for a straddle.[88] Equally, he understood that historical experience must be tempered by 'any special influence at work calculated to modify that average result in the immediate future'. In other words, he posited that the expected volatility over the life of the option influences its price.[89] Thomas Conway's observations of options pricing in 1913 are also easily explained by and consistent with BSM.[90] A knowledge of Conway, Higgins and indeed Castelli clearly suggests that traders in the first half of the twentieth century would have understood that increased volatility, both in the past and in expectation, would increase the potential risk to the option seller, without any knowledge of the theory underlying the BSM model.

Given that Higgins suggests a more precise measure of historic price range, how well might this explain our option price data? We proxy Higgins' historical ranges by computing the average of

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86 Murphy, 'Trading options before Black Scholes'.
87 Castelli, *The theory of 'options',* pp. 7-8.
88 Higgins, *The put and call*, pp. 55-57. Castelli and Higgins are acknowledged in the Preface and cited throughout Nelson, *The ABC of options*.
89 Leonard Higgins, *The put and call*, p. 70.
90 Conway, *Investment and speculation*. See Kairys and Valerio, 'The market for equity options', p. 1711.

the trailing four quarterly absolute changes in the underlying metal futures price over the year preceding the options trade date for each option in our sample. Higgins proposed that the price of a written straddle should vary directly with the latter historical price ranges of the underlying asset. Hence, we compare the historical range as defined with the prices of the 20 straddles in our sample, and, where we only have a single call or a put, we double the price to create a 'synthetic' straddle.[91] **Figure 6** displays scatter plots of our traded tin option prices against each of these ranges. There is a clear positive relationship between traded prices and the historical ranges. However, individual pricing errors can be quite large, as can be seen in **Figure** 6. Compared to the 45-degree line, traded option prices are generally below the ranges except at very low historical volatilities, where they exceed them. In other words, Higgins heuristic does not fit our option price data as well as the BSM model and would have been of limited help in setting accurate options prices.

[Insert Figure 6 here]

It is possible that interwar option traders were aware of the very sophisticated mathematical approximations of options value authored by Louis Bachelier in 1900 and Vinzenz Bronzin in 1908.[92] Yet, there is no evidence that interwar traders accessed this literature. Espen Haug and Nassim Taleb claim that both works had an influence; yet, they focus their analysis and discussion entirely on the mid-twentieth century and refer to the Thorp-Bachelier model.[93] The Thorp herein referred to incorporated the essence of the BSM model in the pricing algorithms he used to trade options in the years leading up to BSM.[94] However, Bachelier's work was not disseminated until

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91 As all of our options are at-the-money. The synthetic straddle price would be simply twice the call or the put price. This is due to the put call-parity. See equation [2] in Black, 'The pricing of commodity contracts', p. 169.

92 Bachelier, 'Theory of speculation'. Bronzin, *Theorie der Prämiengeschäft*.

93 Haug and Taleb, 'Option traders'. There is no evidence that Bronzin's work was widely distributed. See Zimmermann and Hafner, 'Vinzenz Bronzin's models'.

94 Thorp and Kassouf, *Beat the market*.

1967. Furthermore, he was very rarely cited in the years immediately after publication, and, even then, only by academic mathematicians. Interwar traders in all probability never became acquainted with his work.[95]

VI. Conclusion

In this study of a new data set of interwar copper and tin options, we exploit traded prices rather than indicative price quotations sourced from newspaper advertisements previously used in the case of stock options. Our options are short-dated and at-the-money compared to the long-dated and sometimes far from-the-money features of the warrants that have been studied previously. These features make our option sample more amenable to testing for price efficiency. One of our main findings is that traders of tin and copper options in the 1920s transacted with Keynes via his broker at prices fairly close to their BSM theoretical values. Our estimated pricing errors are lower than those reported by prior studies in stock option markets in earlier time periods and similar to the magnitude of errors observed post-BSM. The second main finding is that, for our sample of option trades, any changes in their theoretical values, characterized by implied volatility, were associated with changes in observable parameters (historical volatility) and expectations (proxied by realized volatility). These results hold for puts, calls and straddles at-the-money, where the time value (as measured by BSM) would be the highest, in two different metals, and for options both bought and sold.

Notwithstanding the advantages of our commodity option price data for assessing price efficiency, we acknowledge that our option data have limitations. Firstly, our sample is trades for only two metals. Other metal commodities may have displayed greater mispricing. In mitigation, tin and copper were particularly important metals in LME trading. Secondly, our trades are from a single investor, Keynes. One might argue that because Keynes was a particularly smart investor, this

[95] According to Jovanovic, 'Bachelier', there were only 21 citations in the 18 years from 1912 to the end of our sample period.

downwardly biases any mispricing estimates and that other less sophisticated investors would not be the recipient of the same efficient pricing. We do not deny this possibility but at the same time we believe that this does not invalidate our test or weaken our results. What matters, whether in the 1920s or today, is whether trades between informed participants exhibit very little mispricing.[96] Furthermore, we would emphasize that our focus is on the execution price of these transactions agreed between Keynes' broker and the LME dealers. These trades therefore provide us with a glimpse of the wholesale market for trading commodity options in the interwar period.

Our results provide evidence that runs counter to claims about performativity in option markets. One possible explanation for our findings compared to those of prior studies may be attributable to the institutional differences between the equity options and the commodity option markets. Firstly, shorting in interwar commodity markets was easier than in the US stock market of the 1870s and the South African stock market of the 1900s and 1910s. Secondly, there is an important difference in market structure. The fact that the interwar LME was a centralised market with competing member dealers who participated in both cash and derivatives markets may have been instrumental in promoting 'fair' prices. In contrast, a decentralized stock option market with at most a very limited number of distinct "put and call brokers" may well have contributed to a limited supply of option sellers and correspondingly higher prices for buyers. It is noteworthy that whilst the underlying metal futures traded on the LME, interwar options were most likely traded over-the-counter. This casts some doubt on claims that trading on an exchange, rather than the BSM innovation itself, had a larger beneficial impact on price efficiency in the case of stock options.[97]

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[96] For example, the fact that in modern times structured products sold to less sophisticated investors at much higher prices are often repackages of simple options sourced from the wholesale market does not invalidate modern pricing tests.

[97] Malkiel and Quandt, 'Strategies and rational decisions', p. 168-9; Kairys and Valerio, 'The market for equity options', p. 1720; Deusker, Gupta and Subrahmanyam, 'Liquidity effect in options'. But for counterarguments, see Mixon, 'Option pricing', p.184; and Brennor, Eldor and Hauser, 'Price of options illiquidity'.

There are a number of empirical studies of BSM option price efficiency on the stock market of the 1950s and 1960s but they suffered from availability of suitable data and their understanding of what constituted efficiency. These studies may explain why convergence to efficiency was dated at around the same time as the publication of the BSM model and, coincidentally, the opening of the CBOE. However, there has been little empirical research on options before the 1950s. Taken together with the Kairys and Valerio, Mixon and Moore and Juh studies, the present study provides an understanding of price efficiency across two different markets with different institutional settings and across two time periods – the 1870s and the 1900s to the 1920s. We still lack knowledge of what happened in between.

Although we show that BSM efficiency arrived before the model in the case of commodity options, we cannot easily explain how exactly traders were able to intuit such prices. Certainly, traders had some notion of 'volatility' and were aware of the importance of variation in prices for option prices, as reflected in the rudimentary analysis in the texts of Higgins and Castelli. Yet, it does appear that interwar traders may have been more sophisticated when given the chance to trade in a two-way market in the underlying and, at least occasionally, in the options themselves. When institutional conditions were more favourable – compared to those of an emerging market in mining stock warrants in the early twentieth century and the US stock option market of the 1870s – option traders appear to have had an intuitive grasp of BSM-price efficiency. Given the complexity of the BSM formula itself, it is perhaps difficult to explain how the interwar commodity option markets could have been so sophisticated. One answer is hinted at by the work of Brenner and Subrahmanyam, who showed in 1988 that the relationship between an at-the-money straddle and the volatility of returns is reasonably straightforward.[98] It is not beyond the realm of possibility that traders fixing the time input in their option model and assuming reasonably steady prices in the underlying could have observed that option prices seemed to vary with historical (and possibly

[98] Brenner and Subrahmanyam, A simple formula'. We thank an anonymous referee for this suggestion.

realized) "volatility" in a predictable way. How this could happen remains difficult to imagine, however, especially given the leading academics of the time were exploring a very different assumed underyling distribution.[99] We leave to subsequent research the task of filling in these gaps in our knowledge and documenting more precisely the path along which both stock and commodity option markets moved toward price efficiency.

[99] Arithmetic Brownian motion rather than the geometric version assumed in BSM. See Bachelier 'Theory of speculation'.

Appendix A: Black (1976) Model

Since we are pricing commodity options in this study, we make use of Fisher Black's 1976 model, which is very similar to the Black Scholes Merton model, normally used for pricing stock options.[100] This Black (1976) model remains popular for basic futures option valuation, as evidenced by its inclusion on today's LME website.[101] The main difference between the two models is that in the Black (1976) model the underlying futures price enters the model in place of the forward stock price to take account of the fact that any option exercise happens in the future (at expiry).[102] Both models assume that underlying asset returns are lognormal, and therefore that the return distribution can be sufficiently characterized by its volatility. According to this model, the value of a call option is represented as follows:

$$Value\ of\ a\ call\ option, C = F\,e^{-rt}N(d_1) - K\,e^{-rt}\,N(d_2)\ [1]$$

where:

$$N(d_1) = \frac{\ln\left(\frac{F}{K}\right) + (0.5\sigma^2)t}{\sigma\sqrt{t}}$$

$$N(d_2) = d_1 - \sigma\sqrt{t}$$

$$F = futures\ price$$

$$\sigma^2 = variance\ of\ the\ return\ of\ the\ futures\ contract$$

$$K = strike\ price$$

$$t = time\ to\ expiry$$

$$r = risk\ free\ short\ term\ interest\ rate$$

Note that we model the futures price and not the forward price as in the Black model. Both theory and empirical evidence suggests that the errors between futures and forwards are small for the commodities in question.[103] Therefore, for our purposes we take the futures price matching the expiry of the option as the relevant input.

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100 Black, 'The pricing of commodity contracts'.

101 https://www.lme.com/Trading/Contract-types/Options/Black-Scholes-76-Formula.

102 The futures price replaces the discounted value of the stock price in the following: $Value\ of\ a\ call\ option\ on\ common\ shares, C = S\,N(d_1) - K\,e^{-rt}\,N(d_2)$.

103 French, 'A comparison of futures and forward prices'.

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Table 1: Pricing errors from prior historical studies

Study		Derivative type	Market	Period	Average error (multiple)	Average error (%)
1.	Kairys and Valerio (1997)	calls and puts	US stocks	1873-75	2x to 4x	50-75%
2.	Mixon (2009)	calls and puts	US stocks	1873-75	2x	50%
3.	Moore and Juh (2006)	warrants	S. African stocks	1908-22	1.6x	37%
4.	Moore and Juh (2006)	call options	S. African stocks	1908-11	1.5x	32%
5.	Mixon (2009)	calls and puts	US stocks	2001-4	1.1x	12%
6.	This study	calls and puts	Metals futures	1921-31	1.1x	15%

Notes and Sources:

1. Average error (multiple) is the average ratio of Traded Price to Theoretical Price from the BSM model.
2. Average error (percentage) is the average (Traded Price – Theoretical Price)/Theoretical Price.
3. Kairys and Valerio (1997) show that stock options between 1873 and 1875 were between 2x and 4x overpriced, equivalent to a pricing error between 50% and 75%. Their main test of price efficiency is the frequency with which option prices departed from fair value using 12-, 24- and 60-day historical volatilities as inputs into the BSM model.
4. Mixon (2009), p. 178 estimates BSM implied volatility and compares it to historical volatility. Note that Mixon labels four-week historical volatility as 'realized volatility'. Although Mixon did not explicitly report pricing errors, we estimate these errors by converting his average volatilities into average prices. Our calculation is based on the average realised volatility of 24.7% and implied volatility of 49.7% as reported by Mixon.
5. Moore and Juh (2006) report warrant mispricing as the mean absolute deviation of the traded price from the theoretical price. We exclude two deep in-the-money warrants (out of a total of 15) from their Table II (p. 3080) and compute the simple average of the difference between theoretical and traded prices reported by the authors. See Appendix 1 for more discussion re warrants.
6. Moore and Juh (2006) also show pricing errors for short-dated but non-exchange traded call option prices from January 1908 to September 1909 and August 1910 to May 1911. While these are absolute values of the percentage differences, as they report that almost 4/5ths of the options were overpriced, absolute levels will not be vastly different from strict average as reported by us and estimated by us for Mixon. Moore and Juh (2006: 3086) point out, however, that methodological limitations 'probably underestimate the degree of overpricing' in options.
7. Mixon (2009) also analyses a modern sample of stocks option. Our estimate of pricing errors is based on a realised volatility of 37.8% and implied volatility of 43.1% as reported by Mixon.
8. Our calculation is based on splitting the 13 straddles into individual puts and calls, for a total sample size of 148.
9. The difference in our study is calculated before commissions. Adding commissions would add 6 to 7 percentage points of overpricing. Kairys and Valerio (1997) include commissions, while Moore and Juh (2006) and Mixon (2009) do not.

Table 2: Summary statistics of implied volatility of 3-month options on tin and copper futures and historical and realized volatilities of underlying tin and copper futures

Tin					
	Implied (IV)	Historical (HV)	Realized (RV)	IV - HV	IV - RV
Mean	18.12	14.21	13.86	3.91	4.27
Median	16.70	11.45	10.83	4.19	4.71
10th percentile	12.20	8.97	8.25	0.69	-0.88
90th percentile	26.28	21.26	26.14	7.53	10.67
High	31.50	33.34	36.61	9.03	14.16
Low	11.55	7.54	7.28	-6.64	-12.30
Std dev	5.33	6.09	6.80	3.10	4.65
Copper					
	Implied (IV)	Historical (HV)	Realized (RV)	IV - HV	IV - RV
Mean	11.58	10.91	12.39	0.66	-0.81
Median	11.90	9.55	12.93	0.95	-1.70
10th percentile	9.71	7.48	7.63	-3.84	-3.63
90th percentile	12.56	15.35	15.30	4.50	3.23
High	16.30	16.71	16.81	5.60	3.53
Low	9.30	7.23	7.30	-4.61	-4.89
Std dev	1.40	3.18	3.21	3.20	2.76

Notes: see section I for definitions of implied, historical and realized volatilities. Implied volatilities are computed using the BSM model and the traded option prices, the time to expiry, the strike price and the risk-free interest rate as inputs. Historical and realized volatilities are estimated using daily three-month futures prices for tin and copper.
Source: see section II for source of option price. Futures prices required to compute theoretical prices are sourced from *Home Commercial Markets* section, *The Times* digital archive.

Table 3: OLS Regressions of implied volatility of tin and copper traded options on the historical and realized volatilities of tin and copper futures prices, 1921-31

	(1)	(2)	(3)	(4)
Historical volatility coefficient	0.781***		0.627***	0.508***
	(0.062)		(0.095)	(0.075)
Realized volatility		0.594***	0.235***	0.265***
		(0.076)	(0.089)	(0.060)
Tin Dummy				0.045***
				(0.005)
Intercept	0.058***	0.082***	0.047**	0.028***
	(0.008)	(0.011)	(0.009)	(0.007)
N Obs	135	135	135	135
Adj R Squared	0.64	0.42	0.68	0.82

Notes: See notes to Table 2 for definitions of implied, historical and realized volatilities. The implied volatility of tin and copper traded options is the dependent variable. The Tin dummy takes a value of 1 if tin is the underlying metal in the traded option contract. Robust (Newey-West) standard errors are in parentheses; * $p<1$, ** $p<0.05$, *** $p<0.01$.

Figure 1: Illustration of a three-month metal futures call option with a strike price of 140.

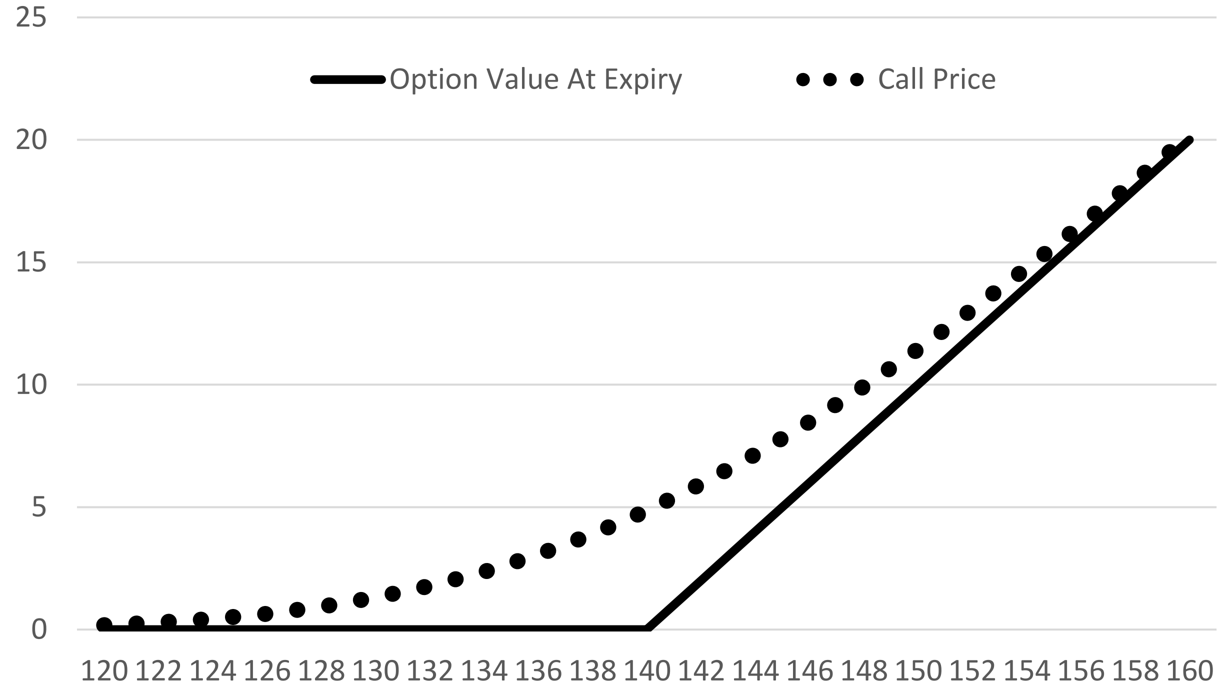


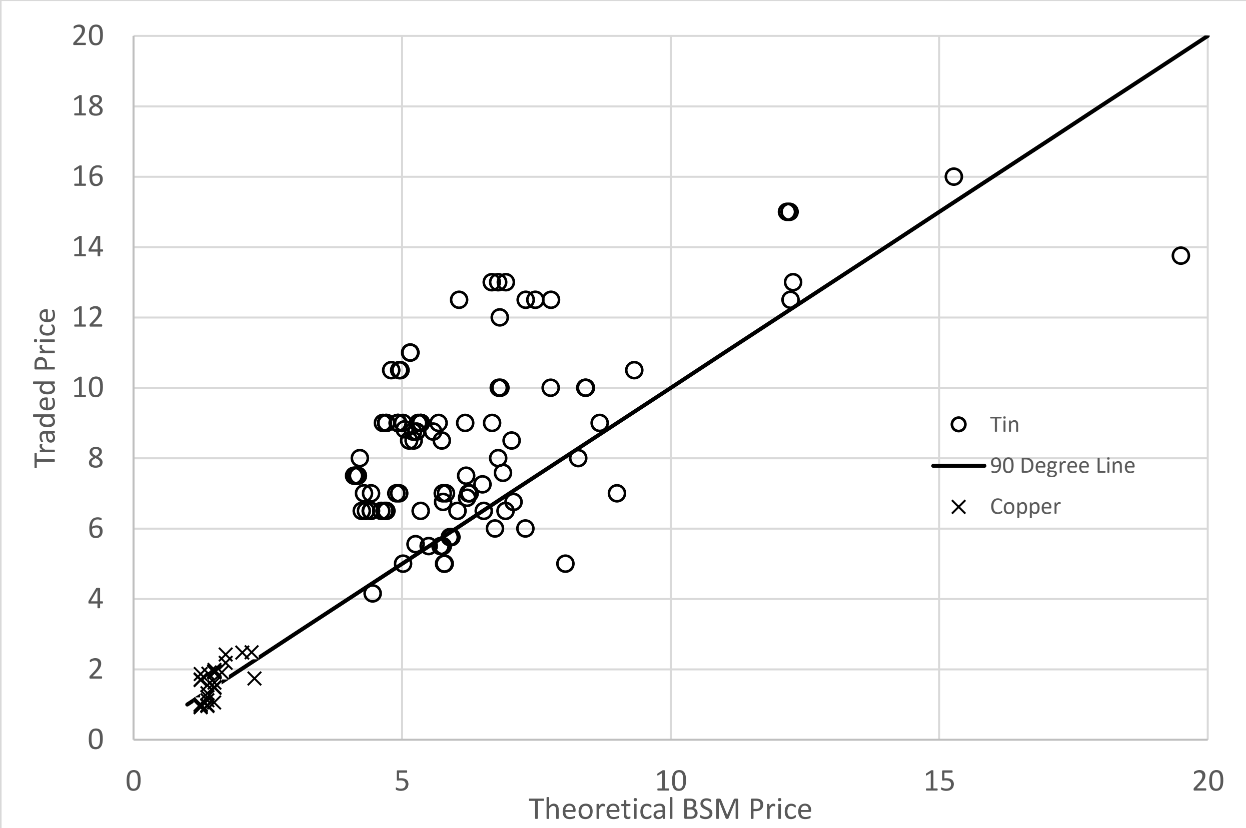
Figure 2: Historical three-month futures prices of Copper and Tin traded on LME

(a) Tin Futures Price (£ per ton)

(b) Copper Futures Price (£ per ton)

Source: daily three-month futures prices are sourced from *Home Commercial Markets* section, *The Times* digital archive.

Figure 3: Traded Prices vs. Theoretical Prices of 3-month Tin and Copper options 1921-31

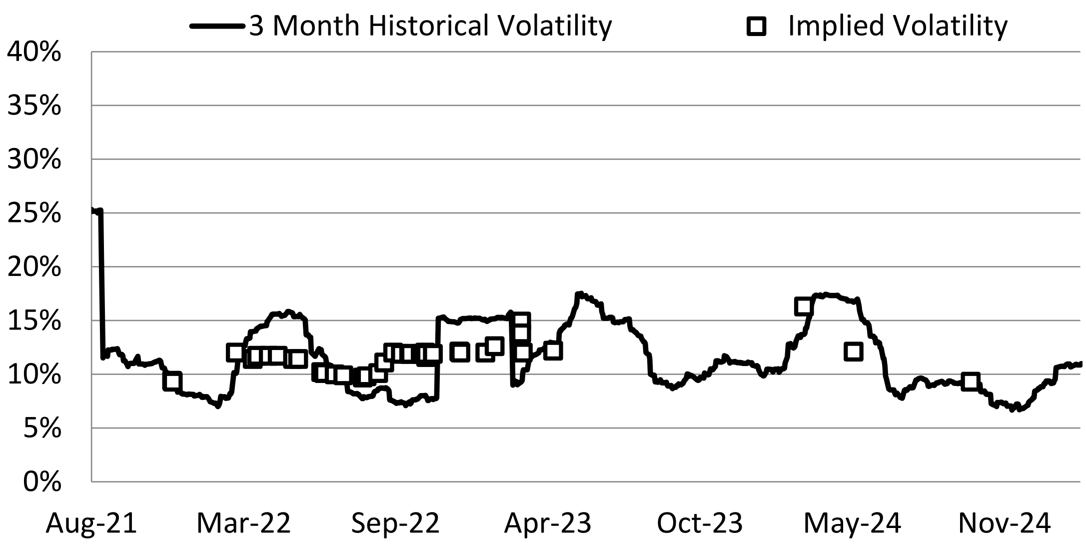


Notes: Traded prices are the prices at which Keynes bought and sold call and put options on Tin and Copper futures between 1921 and 1931. Theoretical prices are the prices computed using the BSM model with the time to expiry, the tin or copper futures price at the option trade date, realized volatility of tin or copper futures over the tenor of the option, and the risk-free rate as model inputs.

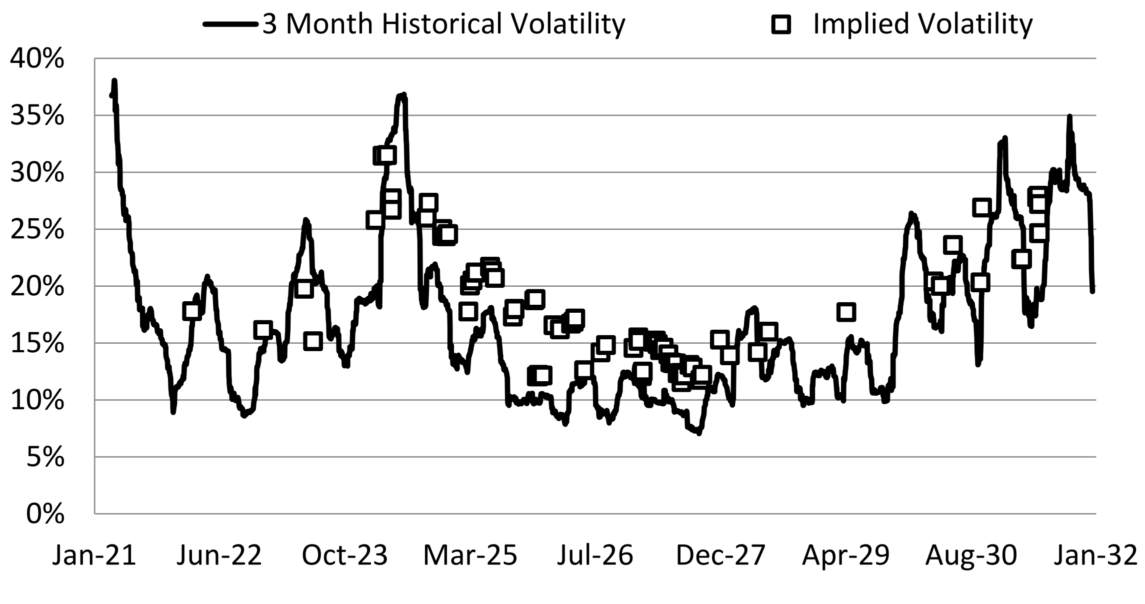
Source: see section II for source of option price. Daily three-month futures prices required to compute theoretical prices are sourced from *Home Commercial Markets* section, *The Times* digital archive.

Figure 4: Implied Volatility versus Historical Volatility of 3-month options on Tin and Copper futures, 1921-31

(a) Tin

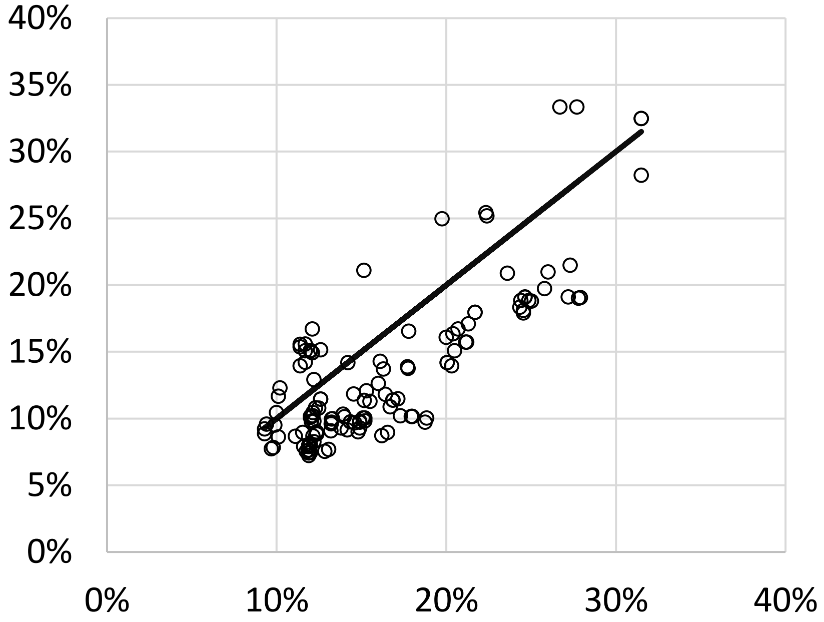


(b) Copper



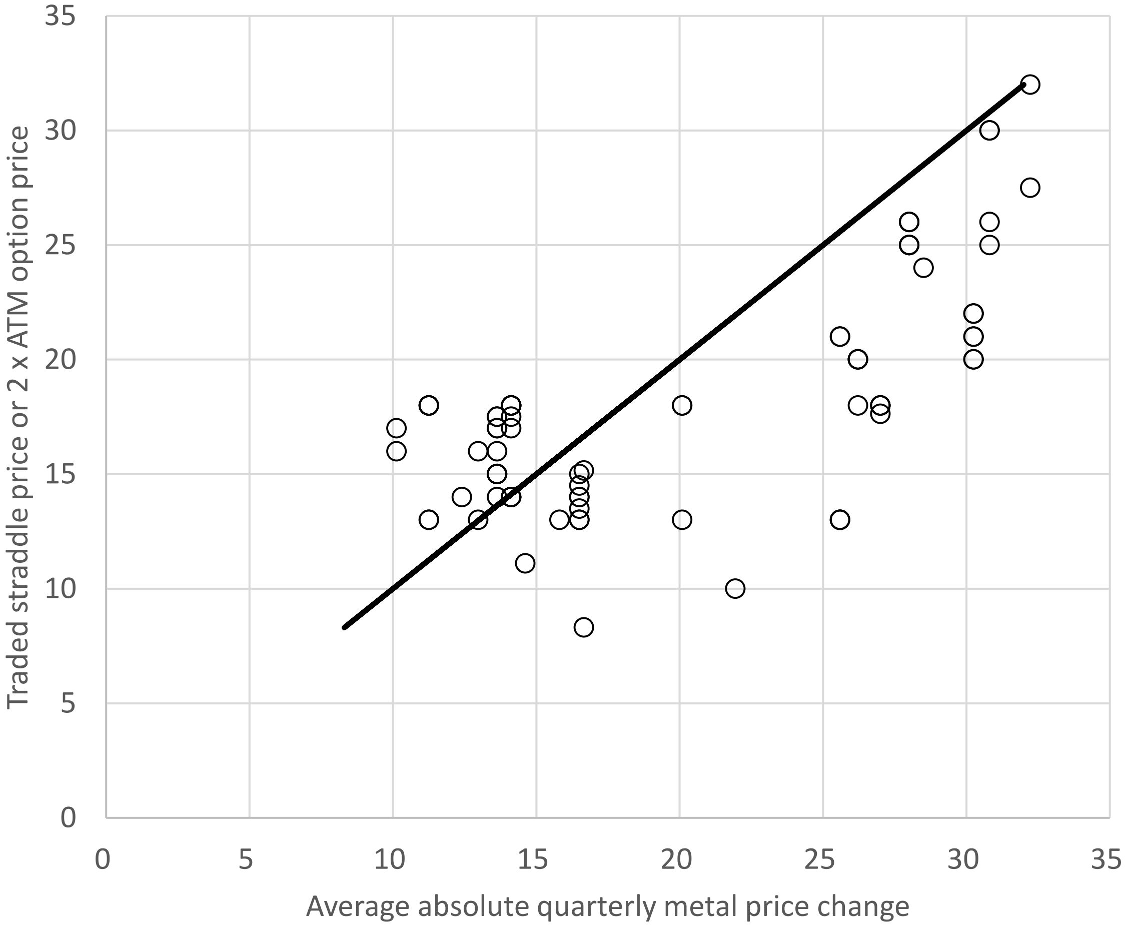
Notes: see section I for definitions of implied and historical volatilities. Historical volatility is the volatility of the tin and copper futures price computed over the 3-months prior to the trade date of the option. Implied volatilities are computed using the BSM model and the traded option prices, the time to expiry, the strike price and the risk-free interest rate as inputs. Implied Volatility is computed from the BSM model for each traded option price.
Source: see section II for source of option price. Daily three-month futures prices required to compute theoretical prices are sourced from *Home Commercial Markets* section, *The Times* digital archive.

Figure 5: Scatter Diagram of Implied Volatility vs. Historic Volatility of 3-month options on Tin and Copper futures, 1921-31



Notes and Sources: see Figure 4.

Figure 6: Traded Option Prices vs. Average absolute quarterly metal price change



Notes: Traded prices on the Y axis are the observed straddle prices or the simple call or put options doubled to create a 'synthetic' straddle. The X axis is the average of the trailing 4 quarterly absolute quarterly changes in the underlying metal futures price over the year preceding the options trade date. This analysis is based on Higgins' assertion that straddles should be priced by taking into account the latter 1-year Moving Average.
Source: see section II for source of option prices. Futures prices required to compute 1-year Moving Average are sourced from *Home Commercial Markets* section, *The Times* digital archive.