

Order Book Slope and Price Volatility

Huu Nhan Duong and Petko S. Kalev*

Department of Accounting and Finance

Monash University

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Abstract

This paper investigates the information content of the limit order book on the Australian Stock Exchange (ASX). We document a negative relation between future volatility and variations in the liquidity provision in the order book, as captured by the order book slope. We also find the order book slope of the buy side to be more informative than the order book slope of the sell side and institutional investors' limit orders to be more informative over future permanent component of volatility than individual limit orders. Finally, we document that the removal of broker IDs in the ASX has a significant impact on the predictive power of the limit order book with the limit order book slope becomes more informative after the move to anonymity, especially in large cap stocks.

JEL classification: G10, G20, G24.

Keywords: Anonymity, Order book slope, Limit order book information, Price volatility, Permanent volatility.

*Corresponding author: Petko Kalev, Department of Accounting and Finance, Faculty of Business and Economics, PO Box 197, Caulfield East, VIC 3145 Australia. Tel: +613 9903 2431 Fax: +613 9903 2422. Email: Petko.Kalev@BusEco.Monash.edu.au.

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1. Introduction

In this paper we examine how the information inherent in the contents of the limit order book influences price volatility in an order driven market, the Australian Stock Exchange (ASX). More specifically, we investigate the informativeness of variations in the liquidity provision in the limit order book, as captured by the limit order book slope, in explaining price volatility. In addition, we analyze the effect of a change in market transparency on the information content of the limit order book. In so doing, we address four research questions. First, is the slope of the limit order book informative over future price volatility? Second, which side of the limit order book is more informative over future price volatility, the buy (demand) side or sell (supply) side? Third, are institutional investors' limit orders more informative than individual limit orders over future price volatility? Forth, does anonymity have any impact on the informativeness of the limit order book and if it does, are institutional or individual limit orders more affected by this change?

Investigating the informativeness of the limit order book slope for price volatility is important because volatility is essential for pricing options, determining order choices¹ and making optimal investment decisions.² Furthermore, an understanding of the relation between the limit order book slope and future price volatility can provide insights about the process through which information is incorporated into prices. In other words, the analysis undertaken in this paper provides evidence regarding the order-choice decision of informed traders when they exploit their private information.

¹ See, for example, Foucault (1999), Hasbrouck and Saar (2002), Bae et al. (2003), Ranaldo (2004), Beber and Caglio (2005), Wald and Horrigan (2005) and Duong et al. (2008) for discussion of the effect of volatility on investors' order submission strategies.

² Fleming et al. (2001) and Fleming et al. (2003) demonstrate the substantial value of volatility timing in the context of investment decisions. Fleming et al. (2003) suggest that an investor implementing the volatility-timing strategies would be willing to pay on the order of 50 to 200 basis points per year to capture the incremental gains generated by the realized volatility-based estimator.

We investigate the informativeness of the slope of the order book for the constituent stocks of the S&P/ASX 100 index. Our study contributes to the literature in the following ways. First, we contribute to the current debate regarding whether informed traders use limit orders by examining the informativeness of the limit order book slope for future price volatility. If informed traders base their trades solely on market orders, as suggested by Glosten (1994) and Seppi (1997), we should find that limit orders (the order book slope) do (does) not convey any information regarding future price movements. In contrast, if limit orders are an important component of the order submission strategies of informed traders, as highlighted by Chakravarty and Holden (1995), Bloomfield et al. (2005), Anand et al. (2005), Wald and Horrigan (2005) and Kaniel and Liu (2006), we should find the limit order book slope to be informative for future short-term price volatility.

In addition, since different volatility components might exist at the intraday level,³ we examine the predictive power of the order book slope on the permanent (long-run) component of volatility.⁴ The results of this investigation provide insights about whether informed traders use limit orders so that the limit order book contains private volatility information relating to the underlying efficient price of a security. Furthermore, as the order book slope describes how the quantity supplied in the order book changes as a function of prices, our investigation also extends prior work which examines the informativeness of the limit order book based on the quantity (measured by the number of shares or orders) or the order imbalance in the demand and supply side of the order book (Ahn et al., 2001; Pascual and Veredas, 2006).

³ See, for example, Andersen and Bollerslev (1997a) and Muller et al. (1997).

⁴ Bae et al. (2003) emphasize the importance of distinguishing between transitory and informational (permanent) volatility for the analysis of the relation between volatility and investors' order submissions. They find that traders place more limit orders relative to market orders when they expect high transitory volatility. In contrast, a rise in informational (permanent) volatility has no effect on the placement of limit orders.

Second, we contribute to the literature by analyzing how a reduction in market transparency affects the information content of the limit order book. Our examination is based on a natural experiment, with the ASX switched to an anonymous trading system on 28 November 2005. Starting from this date, the ASX stopped disclosing the broker's identification behind every order. Prior to this change, brokers were able to identify in real-time the broker number (broker ID) associated with every order in the central limit order book for each security traded on the ASX.

According to Foucault et al. (2007), in a transparent market uninformed traders extract information regarding future volatility from the limit order book, which contains the order submissions of informed traders. In an anonymous trading system, however, the authors argue that uninformed traders cannot identify the order submissions of informed traders. In this case, if the participation rate of informed traders is small (large), uninformed traders will be more (less) aggressive and improve on the already-posted orders more (less) often. Therefore, if the participation rate of the informed traders is small, a move to anonymity will decrease the bid-ask spread and its correlation with future volatility. In supporting the prediction of their model, Foucault et al. (2007) observe a reduction in the bid-ask spread of the constituent stocks of the CAC 40 index after the move to anonymity in the Euronext Paris. They also document that the strength of the relation between the price volatility and lagged bid-ask spread is lower after the move to anonymity.

We extend the analysis of Foucault et al. (2007) by examining the effect of anonymity on the informativeness of the limit order book slope. If, as suggested by Foucault et al. (2007), investors are less aggressive in their order submission when they expect price volatility to increase, the results will be a widening of the bid-ask

spread and a gentler order book slope.⁵ This suggests that the order book slope also contains information on future price volatility. In this way we contribute to the literature by providing evidence regarding the predictive power of the order book slope on future volatility and by analyzing whether the move to anonymity has any effect on this predictive power. In addition, Foucault et al. (2007) present evidence of declining the informativeness of the bid-ask spread, which reflects the information contained in the first step of the limit order book, after the move to anonymity. By investigating the changes in the information content of the limit order book slope after the move to anonymity, we also complement Foucault et al. (2007) analysis by investigating the information content of the limit order book beyond the best quote. The importance of the limit order book beyond the best quote as demonstrated in Cao et al. (2008) provides further support for our examination.

Thirdly, we contribute to the literature regarding who are more informed, institutional or individual investors? Prior literature often tackles this question by investigating market orders or the transactions initiated by institutional and individual investors. For example, Chakravarty (2001) documents that medium-size trades initiated by institutions account for the majority of cumulative price movements. We differ from prior literature by analyzing the limit orders submitted by institutional and individual traders. Investigating the period between November 1990 and January 1991, Anand et al. (2005) and Kaniel and Liu (2006) document that institutional limit orders have higher price impact than individual limit orders for the 144 NYSE stocks included in the TORQ database. We differ from Anand et al. (2005) and Kaniel and Liu (2006) by examining this issue in a pure order driven market, the ASX and for a

⁵ According to Naes and Skjeltorp (2006), when the majority of the share volume in the order book is concentrated near the best quotes, the limit order book slope will be steep. In contrast, a gentle order book slope arises when more share volume in the order book is distributed away from the best quotes. Therefore, if investors are less aggressive in their order submissions, more share volume will be located away from the best quotes. This results in a gentler limit order book slope.

longer and more recent time period between 1 July 2005 and 30 June 2006. We also extend prior studies by analyzing whether the informativeness of the limit order book changes as a result of a change in market transparency and whether the changes in the information content of the limit order book arises as a result of changes in the informativeness of institutional limit orders or individual limit orders.

We document supportive evidence for the informativeness of the order book slope over future price volatility in the majority of the constituent stocks of the S&P/ASX 100 index over the period between 1 July 2005 and 30 June 2006. The informativeness of the order book slope is observed for both the overall volatility and the permanent component of volatility, with stronger results observed for the permanent component of volatility. Consistent with the theoretical models of Chakravarty and Holden (1995), Wald and Horrigan (2005) and Kaniel and Liu (2006), our findings support the use of limit orders by informed traders on the ASX. We also find that the slope of the limit order book on the buy side are more informative than the slope of the limit order book on the sell side and institutional limit orders are more informative than individual limit orders over future permanent component of volatility.

Consistent with Foucault et al. (2007), we find that the removal of broker IDs in the ASX has a significant impact on the predictive power of the order book slope on future volatility. The move to anonymity has a significant impact on the informativeness of institutional limit orders but a minimal impact on the individual limit orders. Finally, among the stocks that experience significant changes in the informativeness of the limit order book slope, the limit order book slope tends to become more informative after the removal of broker IDs in the ASX, especially in large cap stocks.

The remainder of the paper is organized as follows. Section 2 provides the literature review of development of hypotheses. Section 3 details about the data examined and the measurement of variables used in the current study. Section 4 describes the research methodology. Section 5 discusses the results and their implications while Section 6 concludes the paper.

2. Literature Review and Hypotheses Development

2.1 The information content of the limit order book

In the literature, limit orders are viewed as non-aggressive type of order, which supply liquidity to the market while market orders are aggressive orders and demand liquidity. Therefore, the information content of the limit order book is linked to the questions of whether informed traders use the non-aggressive (limit) orders to exploit their information advantage. The current literature, however, is inconclusive with regards to latter issue. Glosten (1994) and Seppi (1997) present theoretical models of limit order markets in which informed traders carry out their trades using market orders. This preference for market orders over limit orders reflects the presumed impatience of informed traders to capitalize on their information. Harris (1998) incorporates limit orders in the informed traders' order submission strategies, but argues that informed traders are less likely to use limit orders than are liquidity traders.

In contrast to the traditional theoretical models, some studies published recently provide both theoretical background and empirical evidence supporting the use of limit orders by informed traders. Chakravarty and Holden (1995) show that, for a risk neutral informed trader, combining market and limit orders can be more profitable than a strategy of placing market orders only. Similarly, Wald and Horrigan

(2005) develop a theoretical model to derive the optimal limit and market order decision from the perspective of risk-averse traders. The authors suggest that rather than market orders, it is optimal for informed traders to place slightly discounted limit orders, often inside the bid-ask spread, because the execution risk for these limit orders is minimal.

Consistent with both Chakravarty and Holden (1995) and Wald and Horrigan (2005), Kaniel and Liu (2006) provide a Glosten-Milgrom (Glosten and Milgrom, 1985) type of theoretical model supporting the use of limit orders by informed traders. The authors emphasize the role of the informed traders' private information horizon as the key determinant of their use of limit orders versus market orders. When the expected time horizon for their private information is high, informed traders are more likely to submit limit orders instead of market orders. Moreover, when the probability that information is long-lived is high enough, limit orders might be more informative than market orders.

Bloomfield et al. (2005) also emphasize limit orders as important components of informed traders' order submission strategies. According to Bloomfield et al. (2005), when trading begins, informed traders are much more likely to take liquidity (use market orders) to profit from their information advantage. As the trading day progresses and prices converge to their true values, informed traders switch to limit orders to earn profit based on the spread. Bloomfield et al. (2005) further argue that towards the end of the trading day, informed traders, on average trade more with limit orders than uninformed traders.

Foucault et al. (2007) develop a theoretical model for a limit order market where traders differ in terms of their private information on future volatility. According to Foucault et al. (2007), the limit order book is a conduit for volatility

information because of the option-like features of limit orders.⁶ As prices of option depend on volatility, limit order traders should incorporate volatility information in their limit order submissions. Therefore, the limit order book should contain private volatility information. In particular, Foucault et al. (2007) document that it is optimal for informed traders with private information on volatility to bid less aggressively if volatility is expected to increase.

With the availability of order book data, the ability of information contained in the limit order book to predict future returns, volume, and volatility has been documented. Irvine et al. (2000) propose a measure of liquidity, the Cost of Round Trip, which aggregates the limit order book information at any moment in time as a measure of liquidity. The authors support the significance of this liquidity measure by showing its ability to predict the number of trades in forthcoming periods. Harris and Panchapagesan (2005) document that both asymmetry between buys and sells in terms of quantities as well as the option values provided by limit orders help explain future returns in the New York Stock Exchange. Similarly, Cao et al. (2004) find empirical support for the role of imbalance between demand and supply in the order book of the S&P/ASX 20 index stocks in explaining future short-term returns.

Empirical findings regarding the informativeness of the limit order book for future volatility are presented in Ahn et al. (2001) and Pascual and Veredas (2006). Ahn et al. (2001) find a negative relation between the market depth and future short-term price volatility for the 33 component stocks in the Hang Seng index of the Stock Exchange of Hong Kong. Decomposing volatility into transitory and informational components based on a dynamic state-space co-integration model for ask and bid quotes, Pascual and Veredas (2006) also provide supportive evidence for the

⁶ Copeland and Galai (1983) were first to stress that a sell (buy) limit order is similar to a call (put) option with an exercise price equal to the limit order price.

informativeness of the limit order book for the future informational component of price volatility.

Based on the above discussion of the use of limit orders by informed traders, we formulate the following hypothesis regarding the informativeness of the limit order book slope over future volatility:

Hypothesis 1: The limit order book slope is negatively related to future price volatility.

Andersen et al. (1997a) and Muller et al. (1997) suggest that different component of volatility may exist at intraday level. Bae et al. (2003) emphasize the importance of differentiating between volatility that arises from noise or liquidity trading and volatility that arises from information in the analysis of order placements. In the current study, we argue that if informed traders do use limit orders to exploit their information advantage, the limit order book slope should not only be informative over future volatility, but also be informative over future permanent component of volatility. The second hypothesis regarding the informativeness of the limit order book slope over future permanent component of volatility is formulated as follows:

Hypothesis 2: The limit order book slope is negatively related to future permanent component of price volatility.

The limit order book consists of orders submitted by buyers on the buy (demand) side and orders placed by sellers on the sell (supply) side. Burdett and O'Hara (1987) observe that large buyers are more likely to be motivated by information than are large sellers. Similarly, Griffiths et al. (2000) also provide evidence that aggressive buy orders on the Toronto Stock Exchange are more informative than aggressive sell

orders. Based on the findings of Burdett and O'Hara (1987) and Griffiths et al. (2000), we argue that the information advantage of buyers over sellers are not only limited to aggressive orders, but also extends to non-aggressive (limit) orders. Therefore, we should find the limit order book slope on the buy (demand) side to be more informative than the limit order book slope on the sell (supply) side. The hypothesis is formulated as follows:

Hypothesis 3: The limit order book slope of the demand (buy) side is more informative over future permanent component of price volatility than the limit order book slope of the supply (sell) side.

The limit order book contains orders submitted by institutional and individual investors. It is therefore important to investigate whether the informativeness of the limit order book slope arises as a result of the liquidity provisions by institutional investors or individual investors. Analyzing a sample of NYSE stocks included in the TORQ database, Anand et al. (2005) document that for institutional traders' limit orders outperform those of retail (individual) traders, even after controlling for stock and order characteristics. Utilizing the same dataset, Kaniel and Liu (2006) provide evidence that limit orders actually contain more information and thus outperform market orders. Furthermore, the relative informativeness of limit orders over market orders is greater for institutional orders than orders placed by individuals. Based on the evidence presented in Anand et al. (2005) and Kaniel and Liu (2006) and on the findings in prior literature that institutional investors are better informed investors⁷, we formulate the following hypothesis regarding the informativeness of institutional slope and individual slope over future permanent component of volatility:

⁷ See for example, Szewczyk et al. (1992), Alangar et al. (1999), Dennis and Weston (2001) and Chakravarty (2001).

Hypothesis 4: The slope of the limit order book of institutional investors is more informative over future permanent component of price volatility than the slope of the limit order book based on orders submitted by individual investors.

2.2 Anonymity and the information content of the limit order book

Foucault et al. (2007) develop a theoretical model for limit order markets to explain the changing behaviour of informed and traders after the removal of brokers IDs. Foucault et al. (2007) argue that a transparent market, where broker IDs are displayed, fosters the front-running activities of uninformed investors. More specifically, uninformed investors infer information about future price movements from the orders submitted by informed traders. They try to front-run the informed traders to benefit from the information by setting more competitive quotes than those posted by the informed traders. In response, informed traders sometimes adopt “bluffing” strategies by posting non-aggressive orders and setting wider spreads than appropriate. An anonymous trading system eliminates the traders’ ability to distinguish informed traders’ orders from those of uninformed traders. Therefore, in an anonymous trading system, uninformed traders submit orders based on their belief about the identity of the traders with the orders in the limit order book. In this case, if the participation rate of informed traders is small (large), uninformed traders will be more (less) aggressive, and improve on the already posted orders more (less) often.⁸

In the ASX, prior to 28 November 2005, the ASX disseminates, in real-time, the broker IDs associated with every order in the central limit order book for each security traded on the ASX. However, this type of information is only disseminated to

⁸ Alternatively, Simaan et al. (2003) argue that a transparent trading system can facilitate collusion among liquidity suppliers. This collusion results in lower traders’ aggressiveness under the non-anonymous trading system compared to the anonymous system. In support of this hypothesis, Simaan et al. (2003) document evidence that dealers post more aggressive quotes in an anonymous market (the ECNs) than in a transparent market where dealers’ IDs are displayed (the NASDAQ).

the broker community. From 28 November 2005, brokers can no longer observe the identification of other brokers submitting orders in the ASX. The ASX provides market share information only at the end of the trading day and releases the full trading history with broker IDs after a delay of three days.

The main reason for the ASX to stop disclosing broker IDs is that exposing broker IDs fosters front-running activities. These activities suppress liquidity and impose extra costs on investors. This results in investors seeking execution outside the central market (the limit order book), which in turn, impairs the overall market liquidity (Australian Stock Exchange, 2005). In addition, constant breaches in the confidentiality agreement required by the SEATS access are also a major driver behind the move to anonymity. Although the release of broker IDs information to third parties is strictly prohibited, institutional clients and very high net worth individuals often request and receive this information from their brokers (Australian Stock Exchange, 2005). This creates an information advantage for those investors using full advisory broking services over those investors making their own trading decisions (Australian Stock Exchange, 2003).

Empirical findings on the impact of removing broker IDs are provided by Comerton-Forde et al. (2005), Foucault et al. (2007), Comerton-Forde and Tang (2008) and Duong et al. (2008). Comerton-Forde et al. (2005), Foucault et al. (2007) and Comerton-Forde and Tang (2008) observe a reduction in the bid-ask spread following the move to anonymity in the Euronext Paris, the Tokyo Stock Exchange and the ASX. An increase in bid-ask spread is documented by Comerton-Forde et al. (2005) for the Korea Stock Exchange after it started disclosing broker IDs information. Besides the bid-ask spread, Comerton-Forde and Tang (2008) find a reduction in adverse selection risk, trade execution costs, order exposure risk and

order aggressiveness after the removal of broker IDs on the ASX. Duong et al. (2008) also find order aggressiveness to decline after the move to anonymity and this result applies for both institutional and individual investors. To the best of our knowledge, Foucault et al. (2007) is the only study that analyzes the impact of anonymity on the information content of the limit order book. They find the limit order book at the best quote, as reflected by the bid-ask spread to be less informative over future volatility after the removal of broker IDs on Euronext Paris.

Drawing on the insights of Foucault et al. (2007), we argue that if institutional investors are better informed than individual investors, in an anonymous trading system where the risk of front-running activities is reduced, institutional investors are more willing to submit informative limit orders. This will result in an increase in the informativeness of the slope of the overall limit order book and the institutional limit orders. For individual investors, the move to anonymity does not significantly change their information environment, except for some very high net worth individuals. Therefore, we should not observe significant changes in the informativeness of the individual slope over future volatility after the move to anonymity in the majority of stocks under investigation. Based on the above discussions, we formulate the following hypotheses:

Hypothesis 5: The move to anonymity results in an increase in the informativeness of the limit order book slope over future permanent component of price volatility.

Hypothesis 6: The move to anonymity has a larger impact on the informativeness of the institutional slope than the individual slope over future permanent component of price volatility.

3. Data

3.1 Data Description

Our samples include one year of proprietary Order Book Dataset from 1 July 2005 and 30 June 2006 for companies making up the S&P/ASX 100 index. This dataset is released by the Australian Stock Exchange (ASX) and provided to us via the Securities Industry Research Centre of Asia-Pacific (SIRCA). The proprietary Order Book Dataset records information on each order, including the order type (order submission, order revision, order cancellation and order execution), the date and time to the nearest hundredth of a second, stock code, order price, order volume and order direction (buy or sell order). Each new order is assigned a unique identification number so that we can track the order from its submission through to any revision, cancellation or execution. A unique feature of this dataset is the provision of the confidential dummy variable indicating whether the order is submitted by an institutional or an individual investor.

We investigate the informativeness of the limit order book based on a thirty-minute interval. Since the ASX's staggered opening procedure takes up to 10 minutes to complete, the data for the first 10 minutes of each day are excluded from our sample, to avoid any potential bias. Therefore, the time period examined in each trading day is from 10:10 a.m. to 4 p.m. Based on the proprietary limit order book dataset, we reconstruct the limit order book at the end of every 30-minute interval. In other words, we reconstruct the state of the limit order book at 10:30 am; 11:00 am; 12:00 pm; 12:30 pm; 1:00 pm; 1:30 pm; 2:00 pm; 2:30 pm; 3:00 pm; 3:30 pm and 4:00 pm every trading day. We partition our sample into large capitalisation (large cap) stocks and medium capitalization (mid cap) stocks. The large cap stocks are the constituent stocks of the S&P/ASX 50 index on 1 July 2005. The mid cap stocks are

the stocks included in the S&P/ASX 100 index but not in the S&P/ASX 50 index on 1 July 2005⁹. Finally, we examine only the stocks that have not been merged or acquired by other companies and the stocks in which data are available for the entire sample period. The final sample includes 90 stocks, consisting of 47 large cap and 43 mid cap stocks. The details of the stocks examined in the current study are given in Table 1.

[INSERT TABLE 1 HERE]

3.2 Return Series

Return series are constructed based on the mid-quote prices at the end of every 30-minute interval. We chose mid-quote prices instead of using transacted prices because they reduce the measurement errors due to bid-ask bounce, which can result in substantial spurious volatility, as suggested by Roll (1984). The return for each interval is calculated as the difference of the natural logarithm of the mid-quote prices at the end of the current interval and those at the end of the previous interval. Similar to Foucault et al. (2007), we exclude overnight returns in our sample. Therefore, the returns for the first interval in each trading day are calculated as the difference of the natural logarithm of the mid-quote prices at the end of the interval and those at the beginning of the interval.

Andersen and Bollerslev (1997b), Martens (2001), and Martens et al. (2002) argue that intraday patterns can severely corrupt the traditional volatility models based on raw (unadjusted) high-frequency series. Therefore, we follow the method of Andersen et al. (2003) in constructing our seasonally adjusted intraday returns. First,

⁹ Our classification criteria for large cap and mid cap stocks are consistent with those of the ASX.

we calculate seasonal factors by averaging the individual squared returns in the various intraday intervals

$$s_i^2 = \frac{1}{T} \sum_{t=1}^T r_{it}^2, \quad (1)$$

where r_{it} denotes the return for interval i on day t . The seasonally adjusted intraday returns (\tilde{r}_{it}) are then calculated as

$$\tilde{r}_{it} = \frac{r_{it}}{s_i}. \quad (2)$$

3.3 The Slope of the Order Book

Following Naes and Skjeltorp (2006), we measure the order book slope for firm i in interval t is as follows:

$$\text{SLOPE}_{i,t} = \frac{DE_{i,t} + SE_{i,t}}{2}, \quad (3)$$

where $DE_{i,t}$ and $SE_{i,t}$ represent the slope of the bid (demand) side and ask (supply) side respectively. The order book slope for the bid side for firm i in interval t is given as:

$$DE_{i,t} = \frac{1}{N_B} \left\{ \frac{v_1^B}{|p_1^B / p_0 - 1|} + \sum_{\tau=1}^{N_B-1} \frac{v_{\tau+1}^B / v_{\tau}^B - 1}{|p_{\tau+1}^B / p_{\tau}^B - 1|} \right\} \quad (4)$$

Similarly, the order book slope for the ask side can be given as:

$$SE_{i,t} = \frac{1}{N_A} \left\{ \frac{v_1^A}{|p_1^A / p_0 - 1|} + \sum_{\tau=1}^{N_A-1} \frac{v_{\tau+1}^A / v_{\tau}^A - 1}{|p_{\tau+1}^A / p_{\tau}^A - 1|} \right\}, \quad (5)$$

where N_B and N_A is the total number of bid and ask prices (tick levels) containing orders, respectively. τ denotes the tick levels, with $\tau = 0$ representing the best bid-ask mid-point and $\tau = 1$ representing the best ask (bid) quote with positive share volume.

p_0 is the best bid-ask mid-point and v_{τ}^A and v_{τ}^B is the natural logarithm of

accumulated total share volume at the price level τ (p_τ). In other words, v_τ^A (v_τ^B) is the natural logarithm of total share volume supplied (demanded) at p_τ or lower (higher). At the end of each 30-minute interval, we use the ten best bid and ask quotes together with the share volume at these quotes for the calculation of the order book slope for that particular interval. In addition, we also remove all undisclosed (hidden) orders in our calculation of the limit order book slope.

4. Research Methodology

4.1 The predictive power of the order book slope

In the current study, we investigate the predictive power of the order book slope on the future volatility and the effect of the move to anonymity on this predictive power. Since (G)ARCH-type models are widely used in those studies that deal with volatility modeling (Bollerslev et al., 1992), our analyses are based on estimating the following GARCH model:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = \omega + \alpha \varepsilon_{t-1}^2 + \beta \sigma_{t-1}^2 + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \quad (6)$$

where r_t is the seasonally adjusted stock return at interval t , μ is a constant, ε_t are the serially uncorrelated errors (innovations) of stock returns with mean zero, σ_t^2 is the conditional variance of ε_t . $Slope_{t-1}$ is the limit order book slope at the end of interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards, and zero otherwise. Consistent with Jones et al. (1994), we include the average trade size, ATS_{t-1} , and the total number of trades, NT_{t-1} , for the $(t-1)th$ interval as control variables for price volatility.

In addition to GARCH model, we also examine the predictive power of the limit order book slope using the EGARCH model, which allows us to control for the “leverage effect”, where a negative shock to financial time series is more likely to have larger impact on volatility than a positive shock of the same magnitude. The EGARCH model is specified as follows:

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, & \varepsilon_t | \Omega_{t-1} &\sim \text{i.i.d. } (0, \sigma_t^2) \\
h_t &= \omega + \beta h_{t-1} + \alpha \left| \frac{\varepsilon_{t-1}}{\sigma_{t-1}} \right| + \gamma \frac{\varepsilon_{t-1}}{\sigma_{t-1}} + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + \varphi_1 NT_{t-1} \\
&+ \varphi_2 ATS_{t-1}, & & (7)
\end{aligned}$$

where $h_t = \log(\sigma_t^2)$. We expect the order book slope to be informative about future volatility. Therefore, we expect δ_1 to be negative and significant. In both the GARCH and EGARCH model, we include an interaction term between the lagged value of the order book slope and the dummy variable D_{post} for the purpose of analyzing the effect of removing broker IDs on the information content of the limit order book slope. Consistent with Foucault et al. (2007), we expect the removal of broker IDs on the ASX to have a significant impact on the informativeness of the limit order book slope. Thus, we should observe the majority of the coefficient estimate for δ_2 to be statistically significant. If δ_2 is positive (negative) and significant, the move anonymity has resulted in a (an) decrease (increase) in the informativeness of the limit order book slope.

4.2 The order book slope and the permanent component of volatility

Recent literature on volatility modeling argues for the existence of different volatility components at intraday level. This phenomenon can be due to either heterogeneous information arrival processes, as suggested by Andersen and Bollerslev (1997a), or

due to heterogeneous traders, as proposed by Muller et al. (1997). Since intraday volatility can contain different components, we also utilize the Component GARCH model of Engle and Lee (1993) to investigate the relation between the order book slope and the long-run component of volatility. Specifically, the conditional variance equation of the GARCH(1,1) model of Bollerslev (1986):

$$\sigma_t^2 = \omega + \alpha \varepsilon_{t-1}^2 + \beta \sigma_{t-1}^2, \quad (8)$$

can be expressed as:

$$\sigma_t^2 = \bar{\omega} + \alpha(\varepsilon_{t-1}^2 - \bar{\omega}) + \beta(\sigma_{t-1}^2 - \bar{\omega}), \quad (9)$$

which shows a mean reversion to the constant $\bar{\omega} = \omega / (1 - \alpha - \beta)$ for all time. Engle and Lee's (1993) Component GARCH model allows a mean reversion to a varying level q_t as follows:

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}) \quad (10)$$

$$q_t = \omega + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2). \quad (11)$$

The conditional variance σ_t^2 is mean-reverting around a permanent component q_t with the speed of mean-reversion determined by the parameter α and β . q_t is the time-varying long-run, permanent component of volatility and the speed of mean reversion for this permanent component of volatility is determined by ρ and ϕ . $\sigma_t^2 - q_t$ is the transitory component of the conditional variance. In the current study, we investigate the predictive power of the order book slope on the permanent (long-run) component of future volatility by estimating the following Component GARCH model:

$$\begin{aligned} \sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\ q_t &= \omega + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})SLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}. \end{aligned} \quad (12)$$

Similar to the model specified in equation (6) and (7), we expect δ_1 to be negative and significant. A positive (negative) and significant estimate for δ_2 supports a decrease (increase) in the informativeness of the limit order book slope after the move anonymity. In the current study, all of the GARCH, EGARCH and CGARCH models are estimated using a student t-distribution to incorporate the potential leptokurtic distribution of the error term.

4.3 The information content of the limit order book slope on the demand (buy) side and supply (sell) side

In the current study, the limit order book slope is the average of the limit order book slope on the demand side and supply side. We therefore further examine whether the slope on the demand side is more or less informative than the slope on the supply side over future volatility. We estimate the following CGARCH models for this analysis:

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) BUYSLOPE_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}, \quad (13)
\end{aligned}$$

and

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SELLSLOPE_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}, \quad (14)
\end{aligned}$$

where $BUYSLOPE_{t-1}$ and $SELLSLOPE_{t-1}$ are the slope of the limit order book on the buy side and sell side at the end of period $t-1$, respectively. Consistent with Burdett and O'Hara (1987) and Griffiths et al. (2000), we expect that buy orders are more informative than sell orders. Therefore, we expect the slope of the limit order book on the buy (demand) side is more informative than the slope of the limit order book on

the supply (sell) side. In other words, we expect the number of negative and significant δ_I in equation (13) to be larger than the number of negative and significant δ_I in equation (14).

4.4 The information content of institutional and individual slope

The limit order book contains orders submitted by institutional and individual investors. Prior literature suggests that institutional investors are better informed than individual investors (see for example, Chakravarty, 2001; Anand et al., 2005; Kaniel and Liu, 2006). Based on these findings, we examine whether the informativeness of the limit order book slope comes from institutional or individual investors' limit orders. From the overall limit order book, we create two "smaller" limit order books: the Institutional limit order book, which contains institutional limit orders and the Individual limit order book, which consists of only individual limit orders. We calculate the slope of the Institutional limit order book and Individual limit order book in a similar manner to that presented in equation (3), (4) and (5). The slope of the Institutional limit order book is called Institutional slope and the slope of the Individual limit order book is referred to as Individual slope. We perform the following CGARCH models for analyzing the informativeness of Institutional slope and Individual slope:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})INSTSLOPE_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}, \quad (15)$$

and

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})INDISLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \quad (16)$$

where $INSTSLOPE_{t-1}$ and $INDISLOPE_{t-1}$ are the institutional and individual limit order book slope at the end of period $t-1$, respectively. We expect institutional slope to be more informative than individual slope. Therefore, the number of negative and significant δ_1 in equation (15) should be larger than the number of negative and significant δ_1 in equation (16). We also expect that the move to anonymity has a larger impact on the informativeness of institutional limit orders than individual limit orders. For this reason, the number of significant coefficient estimate for δ_2 in equation (15) should be larger than that of equation (16).

4.5 The information content of the limit order book at different levels

In the current study, we analyze the informativeness of the limit order book slope based on the ten best quotes on the demand and supply side of the limit order book. Foucault et al. (2007) use the information contained in the best bid and ask quote (the bid-ask spread) in examining the informativeness of the limit order book over future volatility. Ahn et al. (2001) and Pascual and Veredas (2006) analyze the same problem utilizing the information contained in the limit order book, up to the five best quotes.

We analyze our choice of limit order book levels against the use of best bid and ask quotes and the use of best five best bid and ask quotes. Specifically, the bid-ask spread and the market depth at the end of each 30-minute interval are used as the proxy for the information contained in the best quotes of the order book. We estimate the following CGARCH models for this analysis:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SPREAD_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \quad (17)$$

and

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) DEPTH_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \quad (18)$$

where $SPREAD_{t-1}$ is the bid-ask spread at the end of interval $t-1$, which is calculated as the percentage of the difference between the best ask and best bid quote over the bid-ask midpoint. $DEPTH_{t-1}$ is the market depth at the end of interval $t-1$, which is calculated as the sum of the number of shares at the best bid and ask quotes of the order book. We expect the limit order book up to ten levels to be more informative than the limit order book at the best quotes. Therefore, we expect the number of significant δ_l in equation (17) and (18) to be significantly lower than the number of significant δ_l in equation (12).

In addition to estimating CGARCH models for the bid-ask spread and market depth separately, we estimate the CGARCH models with both the lagged limit order book slope and lagged bid-ask spread or lagged market depth as explanatory variables for the permanent component of volatility. The following two CGARCH models are estimated for this analysis:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + (\delta_3 + \delta_4 D_{post}) SPREAD_{t-1}$$

$$+ \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \quad (19)$$

and

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + (\delta_3 + \delta_4 D_{post}) DEPTH_{t-1} \\
&\quad + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}. \tag{20}
\end{aligned}$$

The order book slope is expected to be more informative than the bid-ask spread and market depth over future permanent component of volatility. Therefore, we expect the number of significant δ_1 to be larger than the number of significant δ_3 in both equation (19) and (20).

We also compare results obtained when using ten best levels of the order book to calculate the order book slope to those obtained when only five best levels of the limit order book are used or when the entire limit order book¹⁰ is used in the calculation of the order book slope. The following CGARCH models are estimated for this examination:

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPE5BEST_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \tag{21}
\end{aligned}$$

and

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPEALL_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}, \tag{22}
\end{aligned}$$

where $SLOPE5BEST_{t-1}$ is the order book slope, calculated from the best five levels of the order book, at the end of interval $t-1$. $SLOPEALL_{t-1}$ is the order book slope, calculated from all orders up to 100 levels of the order book, at the end of interval $t-1$.

¹⁰ Consistent with Naes and Skjeltorp (2006), we define the entire order book as the order book that contains all orders up to 100 ticks away from the best quotes.

We expect that limit orders from the sixth to tenth levels also contain information regarding future volatility so that the order book slope using the ten best levels of the limit order book are more informative than the order book slope using the five best levels. In addition, using the entire order book to calculate order book slope will involve the use of some stale limit orders, which might never be executed. Therefore, the order book slope calculated using the entire order book is expected to be less informative over future volatility than the order book slope calculated using the ten best levels of the order book. Overall, we expect the number of negative and significant δ_l in equation (21) and (22) to be lower than the number of negative and significant δ_l in equation (12).

5. Results and Discussion

5.1 Descriptive statistics

Table 2 provides the summary statistics for the 90 stocks investigated in the current study. The results are obtained by averaging across thirty-minute interval for each stock and then averaging across stocks. We present the results for the whole sample and also for large cap and mid cap stocks separately. From Table 2, we observe that large cap stocks are on average more than six times larger than mid cap stocks in term of market capitalisation. The average order book slope for large cap stocks of 19.9933 is more than two times the average order book slope for the mid cap stocks of 9.8139. This result implies that the order book slope is on average steeper in large cap stocks than mid cap stocks. Therefore, the shares in the limit order book are distributed closer to the bid-ask mid point for large cap stocks than for mid cap stocks. The order book on the sell side is also slightly larger than the order book on the buy side and the institutional slope is also higher than the individual slope. This finding implies that

institutional limit orders are placed closer to the best quotes than individual limit orders. This is also consistent with the findings of Aitken et al. (2007) that institutional limit orders are more aggressive than individual limit orders. Large cap stocks are also traded more frequently than mid cap stocks, with the average number of trade in a thirty-minute interval of 76. This is more than two times the average number of trade in a thirty-minute interval of 32 for mid cap stocks. In contrast, mid cap stocks have a higher average trade size of 3984 shares, compared to 2818 shares of large cap stocks. The bid-ask spread is also lower for large cap stocks but the depth at the best quote is lower for large cap stocks than for mid cap stocks

[INSERT TABLE 2 HERE]

5.2 The predictive power of the order book slope

We examine the predictive power of the order book slope on future volatility based on the GARCH and EGARCH model as specified in equation (6) and (7). The results of this investigation are given in Panel A and B of Table 3.

[INSERT TABLE 3 HERE]

From Panel A of Table 3, we document strong support for the predictability of the limit order book slope over the price volatility in the next thirty-minute interval. Specifically, coefficient estimate for the order book slope in the previous interval is negative and significant at 5% (10%) level in 76.60% (87.23%) of large cap stocks and 81.40% (88.37%) of mid cap stocks. Similarly, utilizing EGARCH model, the coefficient estimates δ_t are negative and significant at 10% level or better in 82.98% of large cap stocks and 88.37% of mid cap stocks. The move to anonymity has resulted in significant changes in the informativeness of the limit order book slope in the majority of large cap and mid cap stocks, when using GARCH model and in the

majority of mid cap stocks when using EGARCH model. The removal of broker IDs in the ASX has significant impact on the informativeness of the order book slope in 59.57% of large cap stocks and 65.11% of mid cap stocks when we use GARCH model and in 58.14% of mid cap stocks when EGARCH model is utilized. In addition, we also find the limit order book slope to be more informative after the move to anonymity. Specifically, we observe positive and significant at 10% level or better estimates of δ_2 in 14.89% (17.02%) of large cap stocks and 30.23% (20.93%) of mid cap stocks when using GARCH (EGARCH) model. For these stocks, the move to anonymity has resulted in a reduction of the informativeness of the order book slope. In contrast, δ_2 is negative and significant at 10% level or better in 44.68% (23.40%) of large cap stocks and 34.88% (37.21%) of mid cap stocks when GARCH (EGARCH) model is used. This evidence suggests that, for these stocks, the order book slope is more informative in the anonymous market than in the transparent market.

In addition to the GARCH and EGARCH model, we investigate the predictive power of the order book slope on the permanent component of volatility by utilizing the Component GARCH model, as specified in equation (12). The results of this examination are given in Panel C of Table 3.

Similar to the results obtained when using GARCH and EGARCH model, we find the coefficient estimates for the lagged order book slope to be negative and significant at 5% (10%) level in 80.85% (89.36%) of the large cap stocks and 88.37% (93.02%) of the mid cap stocks. This finding provides strong support for the predictive power of the order book slope on the future permanent component of volatility. Furthermore, consistent with the results obtained when using GARCH and EGARCH model, the limit order book slope tends to be more informative after the move to anonymity. The limit order book slope is more informative in anonymous

market in 38.30% of large cap stocks and 39.54% of mid cap stocks and becomes less informative in 17.02% of large cap stocks and 34.88% of mid cap stocks.

Overall, the results presented in Table 5 support our first and second hypothesis. The findings are also consistent with Foucault et al.'s (2007) arguments that the limit order book is a channel for price volatility information. The predictive power of the limit order book over future price volatility is also consistent with the findings of the use of limit orders by informed traders, as highlighted in Bloomfield et al. (2005), Anand et al. (2005), and Kaniel and Liu (2006). The results in Table 5 also indicate that the move to anonymity has a significant impact on the information content of the limit order book slope for future price volatility. Among the stocks that experience significant impact of anonymity on the limit order book slope informativeness, the limit order book slope tend to become more informative for future volatility, after the removal of broker IDs in the ASX.

5.3 The predictive power of demand and supply side of the order book

Table 4 presents results of investigating the predictive power of the slope of the limit order book on the buy side (buy slope) and the slope of the limit order book on the sell side (sell slope). From Table 4, we observe that buy limit orders are more informative than sell limit orders over future permanent component of volatility. The buy slope is informative over future permanent component of volatility in 91.49% of large cap stocks and 93.02% of mid cap stocks. In contrast, the predictive power of the sell slope on future permanent component of volatility is evident in only 68.08% of large cap stocks and 79.07% of mid cap stocks. Our findings are consistent with the arguments presented in Hypothesis 3. The results also support Griffiths et al. (2000), who document that aggressive buy orders are more likely to be motivated by

information than aggressive sell orders. We also extend Griffiths et al. (2000) by demonstrating that the information advantage of buyers over sellers is not only evident in market orders, but also extend to the submission of the less aggressive type of orders, limit orders.

The move to anonymity has larger impacts on the informativeness of the buy slope than on that of the sell slope. Anonymity has significant impact on the informativeness of the buy slope in 51.06% of large cap stocks and 58.14% of mid cap stocks. The impact of anonymity on the informativeness of the sell slope is observed in only 38.30% of large cap stocks and 53.49% of mid cap stocks. In addition, the number of negative and significant δ_2 is also larger than the number of positive and significant δ_2 for both buy slope and sell slope and in both large cap and mid cap stocks. This finding suggests that among the stocks that experience significant changes in the informativeness of the buy slope and sell slope, the buy slope and sell slope tend to be more informative after the move to anonymity.

5.4 The predictive power of institutional and individual slope

The results of examining the predictive power of the institutional and individual slope over future permanent component of volatility are presented in Table 5. From Table 5, we observe that the lagged institutional slope is informative over future permanent component of volatility in 70.21% of the large cap stocks and 79.07% of the mid cap stocks. We find evidence supporting the predictive power of the individual slope over future permanent component of volatility in only 29.78% of large cap stocks and 53.49% of mid cap stocks. Consistent with prior studies and our forth hypothesis, we find institutional investors to be more informed than individual investors and their limit orders do convey their information advantage over future volatility. This result

also implies that the information content of the limit order book comes mainly from institutional limit orders.

The move to anonymity has a large impact on the informativeness of institutional slope than individual slope. We document that 63.83% of large cap stocks and 65.11% of mid cap stocks experience significant changes in the informativeness of institutional slope. In contrast, the majority of the coefficient estimates for δ_2 are not statistically significant at 10% level or better. In addition, for the investigation of institutional slope, δ_2 is negative and significant in 51.06% of large cap stocks and 34.88% of mid cap stocks. We find positive and significant estimates for δ_2 in only 12.77% of large cap stocks and 30.23% of mid cap stocks. This finding suggests that after the move to anonymity, institutional investors are not only willing to submit more limit orders, as demonstrated by Duong et al. (2008); they are also more willing to incorporate their information advantage in their limit orders submissions. The increase in the informativeness of institutional investors after the move to anonymity also supports the theoretical model of Foucault et al. (2007). If anonymity reduces the incentive for better-informed investors to submit “bluffing” limit orders, their limit orders (their order book slope) should be more informative after the removal of broker IDs. For individual investors, since their information environment is largely unchanged after the move to anonymity, the removal of broker IDs has a minimal impact on the information content of their limit orders.

Overall, the results presented in Panel C of Table 3 and Table 5 support our fifth and sixth hypothesis. We find the move to anonymity often results in an increase in the informativeness of the limit order book slope. Institutional limit orders are also more affected by this change than individual limit orders.

5.5 The predictive power of the limit order book at different levels

Table (6) presents results of examining the predictive power of the bid-ask spread and market depth over future permanent component of volatility. The bid-ask spread is informative over future permanent component of volatility in 34.04% of large cap stocks and 41.86% of mid cap stocks. The predictive power of market depth is also observed in 27.66% of large cap stocks and 44.19% of mid cap stocks. Comparing these findings with those presented in Panel C of Table 3, we conclude that the limit order book slope is more informative over future volatility than the bid-ask spread and market depth. The move to anonymity also has a little impact on the informativeness of the bid-ask spread and market depth; with the majority of the coefficient estimates for δ_2 are not statistically significant.

[INSERT TABLE 6 HERE]

We perform additional analysis on the informativeness of the order book slope and the bid-ask spread (market depth) by including both the lagged order book slope and lagged bid-ask spread (lagged market depth) as explanatory variable in the CGARCH model. The result of this analysis is presented in Table 7.

[INSERT TABLE 7 HERE]

Consistent with the results obtained in Table 6, the results of Table 7 indicate that the limit order book slope is more informative than the bid-ask spread and market depth over future permanent component of volatility. The order book slope is informative over future permanent component of volatility in 85.10% of large cap stocks and 86.05% of mid cap stocks. In contrast, the predictive power of the bid-ask spread (market depth) is evident in only 17.02% (42.55%) of the large cap stocks and 27.91% (65.12%) of the mid cap stocks. The move to anonymity also has a larger impact on the informativeness of the order book slope than on the informativeness of

the bid-ask spread and market depth. 53.20% of large cap stocks and 58.14% of mid cap stocks experience significant changes in the predictive power of the order book slope. In contrast, we observe significant changes in the informativeness of the bid-ask spread in only 21.28% of large cap stocks and 30.24% of mid cap stocks. Similarly, when controlling for the effect of market depth, the information content of the limit order book slope on future volatility is affected in 46.81% of large cap stocks and 37.21% of mid cap stocks. Anonymity has a weaker impact on the informativeness of the lagged market depth, with 34.04% of large cap stocks and 34.89% of mid cap stocks experience significant changes.

Overall, the results presented in Table 6 and 7 suggest that the limit order book beyond the best quote as captured by the order book slope is more informative over future permanent component of volatility than the limit order book at the best quote, as captured by the bid-ask spread and the market depth. Consistent with Cao et al. (2008), we support significant information contained in the limit order book beyond the best quote on the ASX. Our results also support of the recent trend towards opening up of the limit order book in equity markets and futures markets.¹¹

Table 8 reports results of investigating the information content of the limit order book slope using the five best levels of the book and using all orders in the book, up to 100 ticks away from the best quotes.

[INSERT TABLE 8 HERE]

We observe significant predictive power of the limit order book slope on future volatility in the majority of large cap and mid cap stocks when using either the five

¹¹ The NYSE introduced the OpenBook service on January 24, 2002 for all securities, which provides the aggregate limit order volume available in the NYSE Display Book system at each price point. The Korea Exchange increased the disclosure of the limit order book from three to five best quotes on March 6, 2000 and from five to ten best quotes on January 2, 2002. The Sydney Futures Exchange also increased its limit order book disclosure from depth at the best bid and ask prices to depth at the three best bid and ask prices in January 2001. See Boehmer et al. (2005), Eom et al. (2007) and Bortoli et al. (2006) for more detailed discussion on these changes.

best levels of the book or the entire order book. When using the five best levels of the order book (the entire order book) to calculate the order book slope, the order book slope is informative over future permanent component of volatility in 74.47% (53.19%) of the large cap and 83.72% (72.09%) of the mid cap stocks. Comparing the results obtained from Panel C of Table 3 and those reported in Table 8, we conclude that the limit order book slope calculated using the ten best levels in the limit order book are more informative than the limit order book slope calculated using the five best levels or up to 100 levels of the limit order book. This finding implies that the sixth to tenth best quotes of the limit order book contain additional information on volatility than that contained in the first five best quotes of the book. However, including all orders in the order book results in the inclusion of stale limit orders, which reduces the overall informativeness of the limit order book slope.

5.6 Robustness tests

We perform additional robustness tests for the results presented in the above section. First, we utilize the Kalay et al. (2004) measure of the limit order book slope to investigate the information content of the limit order book slope. The Kalay et al. (2004) measure of the order book on the supply side is measured as follows

$$SEKSW_{i,t} = \frac{1}{N_A} \left\{ \sum_{\tau=0}^{N_A} \frac{(V_{\tau+1}^A - V_{\tau}^A) / NOSH_{i,t}}{p_{\tau+1}^A / p_{\tau}^A - 1} \right\}, \quad (23)$$

where $SEKSW_{i,t}$ is the Kalay et al. (2004) measure of the slope on the supply side of the order book for firm i in interval t . $NOSH_{i,t}$ is the number of shares outstanding for firm i in interval t . V_{τ}^A is the total share volume at tick τ . The order book on the buy side is calculated in similar manner. The overall limit order book slope is then

calculated as the average of the slope on the buy (demand) and sell (supply) side. We estimate the following CGARCH model for our first robustness test:

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPEKSW_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}, \quad (24)
\end{aligned}$$

where $SLOPEKSW_{t-1}$ is the Kalay et al. (2004) measure of the order book slope at the end of interval $t-1$.

The second robustness test involves including hidden orders when calculating the order book slope. We estimate the following CGARCH model for this analysis:

$$\begin{aligned}
r_t &= \mu + r_{t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPEHIDDEN_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}, \quad (25)
\end{aligned}$$

where $SLOPEHIDDEN_{t-1}$ is the order book slope calculated when hidden orders are included at the end of interval $t-1$.

Finally, we investigate the informativeness of the order book slope based on one-hour interval instead of 30-minute interval. The following CGARCH model is estimated for this analysis:

$$\begin{aligned}
r_{1hour, t} &= \mu + r_{1hour, t-1} + \varepsilon_t, \\
\sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\
q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPE1HOUR_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}, \quad (26)
\end{aligned}$$

The results of the three robustness tests are given in Table 9.

[INSERT TABLE 9 HERE]

Consistent with the results obtained in Panel C of Table 3, the results for the first and second robustness tests indicate a strong support for the informativeness of

the limit order book slope over future permanent component of volatility. The coefficient estimates for the lagged order book slope in Panel A and B of Table 9 are negative and significant for the majority of stocks under investigation. In addition, the move to anonymity also has a significant impact on the informativeness of the order book slope with the order book slope tends to become more rather than less informative after the removal of broker IDs on the ASX.

Panel C of Table 9 reports the results obtained when we use one-hour frequency instead of 30-minute frequency. We still find support for the informativeness of the limit order book slope over future permanent component of volatility in the majority of large cap and mid cap stocks examined. However, we also observe a decline in the informativeness of the limit order book slope when using one-hour frequency instead of 30-minute frequency. For large cap stocks, the number of negative and significant coefficient estimates for lagged order book slope has declined from 89.36% when using 30-minute frequency to 59.57% when one-hour frequency is utilized. Similarly, the limit order book slope is informative over future permanent component of volatility in 93.02% of the mid cap stocks when using 30-minute frequency, but the figure drops to 69.77% when one-hour frequency is used instead.

Overall, the results of different robustness tests indicate that our findings for the informativeness of the limit order book slope over future permanent component of volatility is robust to different measures of the order book slope. The informativeness of the limit order book slope is also stronger when using 30-minute interval compared to one-hour interval.

6. Conclusion

We examine the information content of the order book slope in explaining future price volatility in the ASX. We also investigate whether the relation between the order book slope and future price volatility is affected by the removal of broker IDs in the ASX. Analysing the stocks included in the S&P/ASX 100 index for the period between 1 July 2005 and 30 June 2006, we find the order book slope to be informative in explaining the future price volatility of the majority of stocks under investigation. The predictive power of the order book slope is present in both the overall volatility and the permanent component of volatility. These findings support the importance of limit orders in the order submission strategies of informed investors and the notion that the limit order book is a channel for volatility information. We also document that the slope of the order book on the buy side is more informative than the slope of the limit order book on the sell side over future permanent component of volatility. In addition, institutional limit orders are more informative than individual limit orders over future permanent component of volatility. This finding implies that the informativeness of the limit order book comes mainly from limit orders submitted by institutional investors. The information contained in the best quote is also less informative over future volatility than the information contained in the five best quotes of the limit order book, which in turn, is less informative than the information contained in the ten best quotes of the order book. However, using all orders in the order book up to 100 ticks away from the best quotes does not yield better prediction on future volatility than utilizing information contained in the ten best quotes of the order book.

The removal of broker IDs on the ASX has a significant impact on the predictive power of the limit order book slope in both large cap and mid cap stocks. Moreover, the significant change in the informativeness of the order book slope is

observed for institutional limit orders while anonymity has a minimal impact on individual limit orders. For the stocks that experience significant changes in the informativeness of the order book slope, the order book slope tends to become more informative after the move to anonymity. This finding implies that the move to anonymity has reduced the risk of front-running activities and better-informed investors are more willing to submit and expose their limit orders in the limit order book. Overall, our results support the decision of the ASX to stop disclosing broker identities information in the central limit order book.

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Table 1: List of stocks under investigation

This table provides information regarding the stocks included in the S&P/ASX 100 index that are examined in the current study. The large cap stocks are the constituent stocks of the S&P/ASX 50 index at the beginning of the sample period (1-July-2005). The mid cap stocks are the stocks included in the S&P/ASX 100 index but not in the S&P/ASX 50 index on 1-July-2005.

| Large Cap | | Mid Cap | |
|------------------|-----------------------------------|----------------|--------------------------------------|
| AGL | Australian Gas Light Company | ALL | Aristocrat Leisure Limited |
| AMC | Ancor Limited | ALN | Alinta Limited |
| AMP | AMP Limited | ANN | Ansell Limited |
| ANZ | AUS&NZ Banking Group Limited | APN | APN News & Media Limited |
| AWC | Alumina Limited | ASX | Australian Stock Exchange Limited |
| AXA | AXA Asia Pacific Holdings Limited | AWB | AWB Limited |
| BHP | BHP Billiton Limited | BBG | Billabong International Limited |
| BIL | Brambles Industries Limited | CGF | Challenger Financial Services Group |
| BLD | Boral Limited | CNP | Centro Properties Group |
| BSL | Bluescope Steel Limited | COH | Cochlear Limited |
| CBA | Commonwealth Bank Australia | CPA | Commonwealth Property Office Fund |
| CCL | Coca-Cola Amatil Limited | CPU | Computershare Limited |
| CML | Coles Myer Limited | CTX | Caltex Australia Limited |
| CSL | CSL Limited | DRT | DB RREEF Trust |
| CSR | CSR Limited | DVC | DCA Group Limited |
| FGL | Foster's Group Limited | FCL | Futuris Corporation Limited |
| FXJ | Fairfax (John) Holdings Limited | GNS | Gunns Limited |
| GPT | GPT Group | HVN | Harvey Norman Holdings Limited |
| IAG | Insurance Australia Group Limited | IIF | ING Industrial Fund |
| JHX | James Hardie Industries N.V. | ILU | Iluka Resources Limited |
| LLC | Lend Lease Corporation Limited | IOF | ING Office Fund |
| MBL | Macquarie Bank Limited | IPG | Investa Property Group |
| MGR | Mirvac Group | LEI | Leighton Holdings Limited |
| MIG | Macquarie Infrastructure Group | LHG | Lihir Gold Limited |
| NAB | National Australia Bank Limited | LNN | Lion Nathan Limited |
| NCM | Newcrest Mining Limited | MAP | Macquarie Airports |
| ORG | Origin Energy Limited | MCG | Macquarie Communications |
| ORI | Orica Limited | MCW | Macquarie Countrywide Trust |
| PBL | Publishing & Broadcasting Limited | MOF | Macquarie Office Trust |
| PMN | Promina Group Limited | MXG | Multiplex Group |
| QAN | Qantas Airways Limited | OSH | Oil Search Limited |
| QBE | QBE Insurance Group Limited | OST | Onesteel Limited |
| RIN | Rinker Group Limited | OXR | Oxiana Limited |
| RIO | Rio Tinto Limited | PBG | Pacific Brands Limited |
| SGB | St George Bank Limited | PPT | Perpetual Trustees Australia Limited |
| SGP | Stockland | PPX | Paperlinx Limited |
| STO | Santos Limited | RMD | ResMed Inc. |
| SUN | Suncorp-Metway Limited. | SHL | Sonic Healthcare Limited |
| TAH | Tabcorp Holdings Limited | TEN | Ten Network Holdings Limited |
| TCL | Transurban Group | TOL | Toll Holdings Limited |
| TEL | Telecom Corporation New Zealand | UTB | UniTAB Limited |
| TLS | Telstra Corporation Limited | WAN | West Australian Newspapers Holdings |
| WBC | Westpac Banking Corporation | ZFX | Zinifex Limited |
| WDC | Westfield Group | | |
| WES | Wesfarmers Limited | | |
| WOW | Woolworths Limited | | |
| WPL | Woodside Petroleum Limited | | |

Table 2: Descriptive statistics

This table presents summary statistics of the 90 stocks investigated in this study. The sample period is between 1 July 2005 and 30 June 2006. The large cap stocks are the constituent stocks of the S&P/ASX 50 index at the beginning of the sample period (1-July-2005). The mid cap stocks are the stocks included in the S&P/ASX 100 index but not in the S&P/ASX 50 index on 1-July-2005. "Market capitalisation" is the market capitalisation of firms in million. R_t and $|R_t|$ are the seasonally adjusted return of the stock at the t th interval and the absolute value of the seasonally adjusted return of the stock at the t th interval, respectively. "Slope", "Slope5best" and "SlopeAll" are the limit order book slope based on tenth best quotes, 5 best quotes and up to 100 best quotes, respectively. "Buyslope" and "Sellslope" are the slope of the limit order book on the buy (demand) and sell (supply) side, respectively. "Instslope" and "Indislope" are the slope of the limit order book based on orders submitted by institutional and individual investors, respectively. "NT" and "ATS" are the number of trade and the average trade size for each 30-minute interval, respectively. "Spread" is the bid-ask spread, measured as the percentage of the difference between the best ask and best bid quote over the bid-ask midpoint. "Depth" is the market depth at the best quote, which is calculated as the sum of the number of shares at the best bid and ask quote. The results are obtained by averaging over all thirty-minute intervals for each stocks and then averaging across stocks. The table presents the average for the whole sample and for large cap and mid cap stocks separately.

| | All firms | Large cap | Mid cap |
|-----------------------|-----------|-----------|---------|
| Number of firms | 90 | 47 | 43 |
| Market capitalisation | 7794.12 | 13142.59 | 2072.52 |
| R_t | 0.0013 | -0.0025 | 0.0055 |
| $ R_t $ | 0.6716 | 0.6962 | 0.6447 |
| Slope | 15.1298 | 19.9933 | 9.8139 |
| Slope5best | 29.95 | 39.70 | 19.29 |
| SlopeAll | 5.3277 | 6.1336 | 4.4468 |
| Buyslope | 15.0808 | 19.9532 | 9.7551 |
| Sellslope | 15.1788 | 20.0333 | 9.8727 |
| Instslope | 52.7599 | 65.4734 | 38.8637 |
| Indislope | 17.1012 | 22.7963 | 10.8763 |
| NT | 55 | 76 | 32 |
| ATS | 3375 | 2818 | 3984 |
| Spread | 0.2146 | 0.1499 | 0.2853 |
| Depth | 110,999 | 98,099 | 125,101 |

Table 3: The predictive power of the order book slope

This table presents results of investigating the predictive power of the order book slope on future volatility. The results are obtained from the estimation of the following GARCH, EGARCH and CGARCH model:

GARCH:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = \omega + \alpha \varepsilon_{t-1}^2 + \beta \sigma_{t-1}^2 + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

EGARCH:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$h_t = \omega + \beta h_{t-1} + \alpha \left| \frac{\varepsilon_{t-1}}{\sigma_{t-1}} \right| + \gamma \frac{\varepsilon_{t-1}}{\sigma_{t-1}} + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

CGARCH:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha (\varepsilon_{t-1}^2 - q_{t-1}) + \beta (\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi (\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

where r_t is the seasonally adjusted return of the stock at the t th interval. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $SLOPE_{t-1}$, NT_{t-1} and ATS_{t-1} are the order book slope, total number of trades and average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for GARCH, EGARCH and CGARCH model. The GARCH, EGARCH and CGARCH model are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A, B and C. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10%, respectively.

Panel A: GARCH model

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0252 | 0.0003 | 9.06 |
| (5% level) | (0%, 76.60%) | (14.89%, 34.04%) | |
| (10% level) | (0%, 87.23%) | (14.89%, 44.68%) | |
| Mid Cap | -0.0431 | -0.0007 | 9.25 |
| (5% level) | (0%, 81.40%) | (23.26%, 30.23%) | |
| (10% level) | (0%, 88.37%) | (30.23%, 34.88%) | |

Panel B: EGARCH model

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0383 | 0.0007 | 5.46 |
| (5% level) | (0%, 65.96%) | (14.89%, 19.15%) | |
| (10% level) | (0%, 82.98%) | (17.02%, 23.40%) | |
| Mid Cap | -0.1205 | -0.0029 | 3.69 |
| (5% level) | (0%, 81.40%) | (16.28%, 32.56%) | |
| (10% level) | (0%, 88.37%) | (20.93%, 37.21%) | |

Panel C: CGARCH model

| | δ_1 | δ_2 | DoF |
|-------------|--------------|-----------------------|------|
| Large Cap | -0.0262 | 8.98×10^{-5} | 7.43 |
| (5% level) | (0%, 80.85%) | (17.02%, 27.66%) | |
| (10% level) | (0%, 89.36%) | (17.02%, 38.30%) | |
| Mid Cap | -0.0421 | 0.0010 | 8.90 |
| (5% level) | (0%, 88.37%) | (34.88%, 34.88%) | |
| (10% level) | (0%, 93.02%) | (34.88%, 39.54%) | |

Table 4: The predictive power of the buy (demand) and sell (supply) side slope

This table presents results of investigating the predictive power of the slope of the order book on the demand (buy) and supply (sell) side on future volatility. The results are obtained from the estimation of the following CGARCH models:

CGARCH model for Buy side:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) BUYSLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

CGARCH model for Sell side:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SELLSLOPE_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

where r_t is the seasonally adjusted return of the stock at the t th interval. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $BUYSLOPE_{t-1}$, $SELLSLOPE_{t-1}$, NT_{t-1} and ATS_{t-1} are the order book slope on the buy side, the order book slope on the sell side, the total number of trades and the average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for the CGARCH model. The CGARCH models are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A and B. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10%, respectively.

Panel A: Buy side

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0221 | 0.0018 | 7.04 |
| (5% level) | (0%, 78.72%) | (12.77%, 25.53%) | |
| (10% level) | (0%, 91.49%) | (14.89%, 36.17%) | |
| Mid Cap | -0.0333 | 0.0011 | 6.78 |
| (5% level) | (0%, 86.05%) | (25.58%, 27.91%) | |
| (10% level) | (0%, 93.02%) | (27.91%, 30.23%) | |

Panel B: Sell side

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0194 | 0.0010 | 5.72 |
| (5% level) | (0%, 63.82%) | (8.51%, 23.40%) | |
| (10% level) | (0%, 68.08%) | (10.64%, 27.66%) | |
| Mid Cap | -0.0260 | 0.0015 | 6.65 |
| (5% level) | (0%, 76.74%) | (23.26%, 27.91%) | |
| (10% level) | (0%, 79.07%) | (25.58%, 27.91%) | |

Table 5: The predictive power of the Institutional and Individual slope

This table presents results of investigating the predictive power of the slope of the order book based on the orders submitted by institutional and individual investors on future volatility. The results are obtained from the estimation of the following CGARCH models:

CGARCH model for Institutional slope:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})INSTSLOPE_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}$$

CGARCH model for Sell side:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})INDISLOPE_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}$$

where r_t is the seasonally adjusted return of the stock at the t th interval. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $INSTSLOPE_{t-1}$, $INDISLOPE_{t-1}$, NT_{t-1} and ATS_{t-1} are the order book slope based on institutional orders, the order book slope based on individual orders, the total number of trades and the average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for the CGARCH model. The CGARCH models are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A and B. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10%, respectively.

Panel A: Institutional slope

| | δ_1 | δ_2 | DoF |
|-------------|--------------|-----------------------|------|
| Large Cap | -0.0010 | 8.30×10^{-5} | 9.34 |
| (5% level) | (0%, 55.32%) | (6.38%, 36.17%) | |
| (10% level) | (0%, 70.21%) | (12.77%, 51.06%) | |
| Mid Cap | -0.0015 | 0.0002 | 7.22 |
| (5% level) | (0%, 72.09%) | (25.58%, 32.56%) | |
| (10% level) | (0%, 79.07%) | (30.23%, 34.88%) | |

Panel B: Individual slope

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0084 | 0.0028 | 6.46 |
| (5% level) | (0%, 27.66%) | (8.51%, 12.77%) | |
| (10% level) | (0%, 29.78%) | (8.51%, 21.28%) | |
| Mid Cap | -0.0185 | 0.0016 | 6.98 |
| (5% level) | (0%, 48.83%) | (20.93%, 11.63%) | |
| (10% level) | (0%, 53.49%) | (20.93%, 16.28%) | |

Table 6: The predictive power of the bid-ask spread and market depth

This table presents results of investigating the predictive power of the bid-ask spread and market depth on future volatility. The results are obtained from the estimation of the following CGARCH models:

CGARCH model for the bid-ask spread:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SPREAD_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

CGARCH model for the market depth:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) DEPTH_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1}$$

where r_t is the seasonally adjusted return of the stock at the t th interval. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $SPREAD_{t-1}$ is the bid-ask spread, measured as the percentage of the difference between the best ask and best bid quote over the bid-ask midpoint, at the end of interval $t-1$. $DEPTH_{t-1}$ is the market depth, measured as the total number of shares at the best bid and ask quote, at the end of interval $t-1$. NT_{t-1} and ATS_{t-1} are the total number of trades and the average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for the CGARCH model. The CGARCH models are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A and B. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10%, respectively.

Panel A: Bid-ask spread

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | 0.5277 | -0.0738 | 8.79 |
| (5% level) | (31.92%, 0%) | (2.13%, 10.64%) | |
| (10% level) | (34.04%, 0%) | (6.38%, 19.15%) | |
| Mid Cap | 0.3647 | -0.0140 | 7.93 |
| (5% level) | (37.21%, 0%) | (18.61%, 20.93%) | |
| (10% level) | (41.86%, 0%) | (18.61%, 20.93%) | |

Panel B: Market depth

| | δ_1 | δ_2 | DoF |
|-------------|------------------------|------------------------|-------|
| Large Cap | -1.4×10^{-6} | -3.97×10^{-7} | 12.11 |
| (5% level) | (0%, 27.66%) | (2.13%, 12.77%) | |
| (10% level) | (0%, 27.66%) | (4.25%, 12.77%) | |
| Mid Cap | -1.62×10^{-6} | -6.88×10^{-7} | 15.39 |
| (5% level) | (0%, 41.86%) | (6.98%, 9.30%) | |
| (10% level) | (0%, 44.19%) | (11.63%, 9.30%) | |

Table 7: The predictive power of the order book slope, controlling for bid-ask spread and market depth

This table presents results of investigating the predictive power on future volatility of the limit order book slope, controlling for the impact of the bid-ask spread and market depth. The results are obtained from the estimation of the following CGARCH models:

CGARCH model for controlling the impact of the bid-ask spread:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})SLOPE_{t-1} + (\delta_3 + \delta_4 D_{post})SPREAD_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}$$

CGARCH model for controlling for the impact of the market depth:

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})SLOPE_{t-1} + (\delta_3 + \delta_4 D_{post})DEPTH_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}$$

where r_t is the seasonally adjusted return of the stock at the t th interval. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $SPREAD_{t-1}$ is the bid-ask spread, measured as the percentage of the difference between the best ask and best bid quote over the bid-ask midpoint, at the end of interval $t-1$. $DEPTH_{t-1}$ is the market depth, measured as the total number of shares at the best bid and ask quote, at the end of interval $t-1$. $SLOPE_{t-1}$, NT_{t-1} and ATS_{t-1} are the limit order book slope, the total number of trades and the average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for the CGARCH model. The CGARCH models are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A and B. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10%, respectively.

Panel A: Controlling for Bid-ask spread

| | δ_1 | δ_2 | δ_3 | δ_4 | DoF |
|-------------|--------------|------------------|--------------|------------------|------|
| Large Cap | -0.0278 | -0.0028 | -0.1382 | 0.0501 | 9.02 |
| (5% level) | (0%, 74.45%) | (8.51%, 25.53%) | (12.77%, 0%) | (8.51%, 10.64%) | |
| (10% level) | (0%, 85.10%) | (12.77%, 40.43%) | (17.02%, 0%) | (10.64%, 10.64%) | |
| Mid Cap | -0.0515 | -0.0039 | 0.2251 | -0.0947 | 8.39 |
| (5% level) | (0%, 79.07%) | (20.93%, 30.23%) | (25.58%, 0%) | (2.32%, 23.26%) | |
| (10% level) | (0%, 86.05%) | (23.26%, 34.88%) | (27.91%, 0%) | (6.98%, 23.26%) | |

Panel B: Controlling for Market depth

| | δ_1 | δ_2 | δ_3 | δ_4 | DoF |
|-------------|--------------|------------------|-----------------------|-----------------------|-------|
| Large Cap | -0.0166 | 0.0021 | -1.6×10^{-6} | 3.21×10^{-7} | 12.38 |
| (5% level) | (0%, 59.57%) | (19.15%, 12.77%) | (0%, 40.43%) | (8.51%, 12.77%) | |
| (10% level) | (0%, 82.98%) | (21.28%, 25.53%) | (0%, 42.55%) | (17.02%, 17.02%) | |
| Mid Cap | -0.0305 | 0.0015 | -2.1×10^{-6} | 2.22×10^{-8} | 12.42 |
| (5% level) | (0%, 76.75%) | (13.95%, 13.95%) | (0%, 55.81%) | (11.63%, 23.26%) | |
| (10% level) | (0%, 83.72%) | (16.28%, 20.93%) | (0%, 65.12%) | (11.63%, 23.26%) | |

Table 8: The predictive power of the order book slope based on five levels and up to 100 levels of the order book

This table presents results of investigating the predictive power of the limit order book slope, calculated based on the five best levels of the order book, or based on all orders in the order book up to 100 ticks away from the best quotes (up to 100 levels). We estimate the following CGARCH models for this examination

CGARCH model for the order book slope calculated from the best five levels of the order book

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})SLOPE5BEST_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1}$$

CGARCH model for the order book slope calculated from all orders up to 100 levels of the order book

$$r_t = \mu + r_{t-1} + \varepsilon_t,$$

$$\sigma_t^2 = q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}),$$

$$q_t = \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post})SLOPEALL_{t-1} + \phi_1 NT_{t-1} + \phi_2 ATS_{t-1},$$

where where r_t is the seasonally adjusted return of the stock at the t th interval. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $SLOPE5BEST_{t-1}$ is the order book slope, calculated from the five best levels of the order book, at the end of interval $t-1$. $SLOPEALL_{t-1}$ is the order book slope, calculated from all orders up to 100 levels of the order book, at the end of interval $t-1$. NT_{t-1} and ATS_{t-1} are the total number of trades and the average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for the CGARCH model. The CGARCH models are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A and B. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10% level, respectively.

Panel A: Using five levels of the order book

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0129 | 0.0003 | 5.59 |
| (5% level) | (0%, 63.83%) | (10.64%, 23.40%) | |
| (10% level) | (0%, 74.47%) | (10.64%, 29.78%) | |
| Mid Cap | -0.0289 | 0.0011 | 6.10 |
| (5% level) | (0%, 79.07%) | (25.58%, 23.26%) | |
| (10% level) | (0%, 83.72%) | (25.58%, 25.58%) | |

Panel B: Using all orders, up to 100 levels of the order book

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0391 | 0.0080 | 9.17 |
| (5% level) | (0%, 46.81%) | (12.77%, 34.04%) | |
| (10% level) | (0%, 53.19%) | (14.89%, 44.68%) | |
| Mid Cap | -0.0377 | 0.0045 | 7.74 |
| (5% level) | (0%, 62.79%) | (25.58%, 27.91%) | |
| (10% level) | (0%, 72.09%) | (30.23%, 34.88%) | |

Table 9: Robustness tests

This table presents results of robustness tests on the predictive power of the limit order book slope. We perform three different robustness tests. First, we utilize a different measurement of the limit order book slope, based on the Kalay et al. (2004). Second, we include hidden (undisclosed) orders in the calculation of the limit order book slope. Finally, we investigate the predictive power of the limit order book slope using one-hour frequency. We estimate the following CGARCH models for the abovementioned robustness tests

Robustness test 1: using Kalay et al. (2004) measure of the limit order book slope

$$\begin{aligned} r_t &= \mu + r_{t-1} + \varepsilon_t, \\ \sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\ q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPEKSW_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1} \end{aligned}$$

Robustness test 2: including hidden orders

$$\begin{aligned} r_t &= \mu + r_{t-1} + \varepsilon_t, \\ \sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\ q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPEHIDDEN_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1} \end{aligned}$$

Robustness test 3: using one hour frequency

$$\begin{aligned} r_{1hour,t} &= \mu + r_{1hour,t-1} + \varepsilon_t, \\ \sigma_t^2 &= q_t + \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}), \\ q_t &= \varpi + \rho q_{t-1} + \phi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) + (\delta_1 + \delta_2 D_{post}) SLOPE1HOUR_{t-1} + \varphi_1 NT_{t-1} + \varphi_2 ATS_{t-1} \end{aligned}$$

where r_t is the seasonally adjusted return of the stock at the t th interval, calculated using 30-minute frequency. $r_{1hour,t}$ is the seasonally adjusted return of the stock at the t th interval, calculated using one-hour frequency. σ_t^2 is the conditional variance of the error process ε_t and $h_t = \log(\sigma_t^2)$. $\sigma_t^2 - q_t$ is the transitory volatility component and q_t is the time varying permanent (long-run) volatility. $SLOPEKSW_{t-1}$ is the order book slope, calculated based on the methodology of Kalay et al. (2004), at the end of interval $t-1$. $SLOPEHIDDEN_{t-1}$ is the order book slope, calculated from normal and hidden (undisclosed) orders, at the end of interval $t-1$. $SLOPE1HOUR_{t-1}$ is the order book slope, calculated using one-hour frequency, at the end of interval $t-1$. NT_{t-1} and ATS_{t-1} are the total number of trades and the average trade size for interval $t-1$. D_{post} is a dummy variable that takes the value of one for the period from 28 November 2005 onwards and zero otherwise. “DoF” is the average of the Degree of Freedom for the CGARCH model. The CGARCH models are estimated using the quasi-maximum likelihood method, as described by Bollerslev and Wooldridge (1992). The mean estimates of the coefficients are reported in Panel A, B and C. The first (second) number inside the parentheses indicates the number of estimates that are positive (negative) and significant. “(5% level)” and “(10% level)” show significance at 5% and 10% level, respectively.

Panel A: Robustness test 1

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -4.3430 | -0.3012 | 6.43 |
| (5% level) | (0%, 74.47%) | (12.77%, 17.02%) | |
| (10% level) | (0%, 89.36%) | (19.15%, 29.79%) | |
| Mid Cap | -3.7808 | -0.0012 | 5.71 |
| (5% level) | (0%, 86.05%) | (20.93%, 23.26%) | |
| (10% level) | (0%, 90.70%) | (23.26%, 25.58%) | |

Panel B: Robustness test 2

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|-------|
| Large Cap | -0.0275 | 0.0005 | 12.43 |
| (5% level) | (0%, 85.10%) | (17.02%, 21.28%) | |
| (10% level) | (0%, 93.62%) | (19.15%, 29.79%) | |
| Mid Cap | -0.0421 | 0.0027 | 12.83 |
| (5% level) | (0%, 88.37%) | (23.26%, 27.91%) | |
| (10% level) | (0%, 93.02%) | (27.91%, 32.56%) | |

Panel C: Robustness test 3

| | δ_1 | δ_2 | DoF |
|-------------|--------------|------------------|------|
| Large Cap | -0.0117 | -0.0007 | 6.03 |
| (5% level) | (0%, 51.06%) | (6.38%, 17.02%) | |
| (10% level) | (0%, 59.57%) | (8.51%, 27.66%) | |
| Mid Cap | -0.0386 | -0.0013 | 6.30 |
| (5% level) | (0%, 55.82%) | (11.63%, 16.28%) | |
| (10% level) | (0%, 69.77%) | (13.95%, 30.23%) | |
