行政院國家科學委員會補助專題研究計畫成果報告

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西太平洋晚第三紀古海洋學研究
-ODP1125與1143岩心之氧碳同位素地層

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本成果報告包括以下應繳交之附件：

□赴國外出差或研習心得報告一份

□赴大陸地區出差或研習心得報告一份

∨□出席國際學術會議心得報告及發表之論文各一份

□國際合作研究計畫國外研究報告書一份

執行單位：國立台灣大學地質科學系

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一、中文摘要

本研究分析取自西南太平洋占松隆起北坡水深 1359 公尺的 ODP181 航次 1125 站位(42°33'S, 178°10'W)，最近 5 百萬年來 207 個海洋沈積物標本，取樣間距約平均每 2 萬 4 千年一個標本之三種有孔蟲殼體（*Globigerina bulloides*， *Globorotalia inflata*， *Uvigerina* spp.，分別棲息於混合層、溫躍層及海底底層）氧、碳同位素值變化趨勢。

在氧同位素值方面，三種有孔蟲顯現相同的變化趨勢：在 4.6 至 2.6 Ma，殼體氧同位素值較輕；而自 2.6 Ma 以後，呈逐漸變重現象。此結果與已知的中上新世暖期及晚上新世北半球冰川發育期頗為一致。

至於碳同位素值的變化，浮游與底棲有孔蟲各自記錄了大相逕庭的古水文變化。*G. bulloides* 和 *G inflata* 分別在 4.7-4.1 Ma 與 3.8-3.3 Ma 兩個時期變重以及在 4.1-3.8 Ma 期間與 3.3 Ma 之後變輕。意味前者上層海水存在豐富營養鹽、高生產力，因而造成殼體碳同位素值偏重；後者則處於低營養鹽、低生產力期。而底棲之 *Uvigerina* 則呈現逐漸變重的趨勢，顯示自上新世至更新世，南極中層水源區的生產力愈益增大，或北大西洋深層水流量有逐漸減緩的現象。

關鍵詞：氧碳同位素、西南太平洋、新第三紀

Abstract

The $\delta^{18}O$ and $\delta^{13}C$ values of three species (*Globigerina bulloides*, a mixed-layer dweller; *Globorotalia inflata*, a thermocline dweller; and *Uvigerina* spp., a group of benthic in-fauna) were determined in 207 samples at ~24 k.y. intervals through the last 5 m.y. at Ocean Drilling Program Leg 181, Site 1125 (42°33'S, 178°10'W, at 1359 m water depth) on the northern slope of Chatham Rise.

The $\delta^{18}O$ profiles of three foraminiferal species show a similar trend, with light values between 4.6 and 2.6 Ma, and increasing values after 2.6 Ma. The pattern is fairly consistent with the well-recognized "mid-Pliocene warmth" and "Northern Hemisphere glaciation": A warmer temperature during mid-Pliocene than today, and a gradually cooling trend since that time is recognized at the middle latitudes of the Southwest Pacific.

The $\delta^{13}C$ profile of *G. bulloides* displays significant variations through the Pliocene. The first interval of increasing trend existed in the time between 4.7 and 4.1 Ma. The first interval of decreasing trend occurred in the time between 4.1 and 3.8 Ma. After that decreasing, an increasing trend happened again in the period between 3.8 and 3.3 Ma. The last time interval after 3.3 Ma, another decreased trend shown again. The heavy $\delta^{13}C$ values indicate high nutrient and high productivity, and vice versa. The $\delta^{13}C$ profile of *G. inflata* show a similar trend to *G. bulloides*, and indicates that *G. inflata* lived in the water depth above the Antarctic Intermediate Water (AAIW) almost all the time during the Pliocene. The profile of the $\delta^{13}C$ value of *Uvigerina*, however, is less variable through time, and shows an increasing trend through early Pliocene. It suggests that the source of AAIW was enriched with increasing productivity and/or the North Atlantic Deep Water (NADW) production decreased from early Pliocene through late Pleistocene.

Keywords: Neogene, Southwest Pacific, Stable Isotopes

二、緣由與目的

Site 1125 (42°33'S, 178°10'W) of Ocean Drilling Program (ODP) Leg 181lies 610 km east of South Island of New Zealand, at 1359 m depth on the northern slope of Chatham Rise. The major goal's of Site 1125 were to retrieve an unaltered sequence of Neogene sediments from which to deduce the history of Antarctic Intermediate Water (AAIW) activity. A thick late Neogene sequence was drilled, which provides a record of AAIW paleohydrography, and of the changing paleoproductivity and position of the Subtropical Convergence (STC). Site 1125 presently lies at the base of AAIW. Material from Site 1125 was used for $\delta^{13}C$ analysis to determine whether during the late Neogene glaciations the site lay under severely nutrient-depleted AAIW or enriched Circumpolar Deep Water (CDW).

A general consensus has emerged that relative to the present, the early Pliocene (~5-3 Ma) was the most recent interval of sustained global warmth. Much of the evidence comes from the mid-Pliocene (~3 Ma), when high-latitude North and South Atlantic sea surface temperatures (SSTs) may have been as much as 8℃ and 2-3℃ higher, respectively, than today with little warming in the tropics (Billup et al., 1998). Another striking phenomenon of climate change is the late Pliocene (~2.4 Ma; Raymo, 1994) cooling of the Northern Hemisphere.

This paper examines foraminiferal isotopic data at Site 1125 on the northern slope of Chatham Rise with a sampling interval of about 24 k.y. intervals through the last 5 m.y. Stable isotopes for *Globigerina bulloides*, *Globorotalia inflata* and *Uvigerina* spp., which would represent the mixing-layer, thermocline and deep-water characters, respectively, were measured in the same samples. The evolutions of oxygen and carbon isotopic variations in the three water layers are emphasized in this paper.

Bulk sediment samples (10 cm^3), obtained from the hydraulic piston cores of Site 1125 at an averaged every 1 m between 0 and 214 meters of composite depth, were sampled. The samples were soaked, washed, wet sieved, and dried in an oven. Absolute ages are assigned to samples using the age models of Chen and Wei (2001, based upon magnetostratigraphy and calcareous nannofossil biostratigraphy). Stable isotopes were measured on three taxa of foraminifers, as described in the "Introduction" section.

Five to twelve Specimens of foraminifera in the 250-300□m size fraction were picked from sieved sediments for isotopic analysis. According to the cleaning procedure of Wei et al. (2000), foraminiferal samples were cleaned to eliminate contamination of adherent organic matters. The CO_2 gas generated in Kiel Device was immediately sent into the Finnigan MAT Delta^{plus} mass spectrometer housed in the Institute of Geosciences, National Taiwan University to determine its $\delta^{18}O$ and $\delta^{13}C$ values. All $\delta^{18}O$ and $\delta^{13}C$ values are reported relative to the Peedee belemnite (PDB) standard and the calibration to PDB has been done using NBS-19 Standard ($\delta^{18}O$ = -2.20‰, $\delta^{13}C$ = +1.95‰). External precision of the measurements was better than 0.08‰ for $\delta^{18}O$ and 0.04‰ for $\delta^{13}C$, as calculated through repeatedly routine analyses of the internal laboratory standard.

三、結論

The $\delta^{18}O$ profile of the three foraminiferal species show a similar trend, with light values between 4.6 and 2.6 Ma, and increasing values after 2.6 Ma. The pattern is consistent with the well-recognized "mid-Pliocene warmth" and "Northern Hemisphere glaciation". A warmer temperature during mid-Pliocene than today, and a gradually cooling trend since that time is recognized at the middle latitudes of the southwest Pacific.

The $\delta^{13}C$ profile of *G. bulloides* displays significant variations through the Pliocene. The first interval of increasing trend existed in the time between 4.7 and 4.1 Ma. The first interval of decreasing trend occurred in the time between 4.1 and 3.8 Ma. After that decreasing, an increasing trend happened again in the period between 3.8 and 3.3 Ma. The last time interval after 3.3 Ma, another decreased trend shown again. The heavy $\delta^{13}C$ value indicates high nutrient and high productivity, and vice versa. The $\delta^{13}C$ record of *G. inflata* shows a similar trend to *G. bulloides*, and indicates that *G. inflata* lived in the water depth above the AAIW almost all the time of the Pliocene. The pattern of the $\delta^{13}C$ values of *Uvigerina*, however, is less variable through time, and shows an increasing trend through the early Pliocene. It suggests that the AAIW increased its productivity and/or the North Atlantic Deep Water (NADW) production was decreasing from the early Pliocene through the late Pleistocene.

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出 席 國 際 會 議 報 告

報 告 人:李 孟 陽

一、參加會議經過

二○○○年美國地球物理聯合會係每年春秋兩季舉行的國際會議，本年度在舊金山召開爲期五日的秋季年會。與會各國地球科學工作者近八千名，會中發表論文近萬篇，係地球科學界之年度盛事。此次我國與會者近二十名，主要成員包括中央研究院地球科學研究所、台灣大學地質科學系、中央大學地球物理所，研究範疇涵蓋地震學、構造學、古海洋學、地球物理學、火山學、古地磁學等。

本人於本會議發表論文之題目爲"A Reassessment of Post-depositional remanent magnetization lock-in depth of the Brunhes/Matuyama reversal in deep-sea sediments."，係藉由深海岩心微雷公墨與地磁極反轉之地層關係，重新檢討深洋沉積物碎屑殘磁獲得之深度。此一研究將有助於瞭解碎屑殘磁形成之機制及過程，解釋深海岩心記錄之地磁場強度變化，及建立高分辨率岩心之對比基準。

二、與會心得

在集集地震發生後，我國地科界亦投注相當人力、物力於相關研究，本次會議特闢有集集地震的專題，約有五十篇左右的論文發表，

與會者皆有熱烈的討論。值得一題的是地震預報的可行性問題，日本是目前少數仍積極從事地震預測的國家，經過幾十年來的努力，目前的研究仍缺乏突破性進展，我國在九二一地震之後，如何擬定正確的方向，是亟待思考的。

三、建議

美國地球物理聯合會的分支，所轄學門包括太空科學、海洋科學、地球科學、大氣科學等領域，提供一個跨越學門藩籬、整合資源的機會。相較於國內各學門固步自封、各行其事，地球科學連合會的召開必將有助於喚起不同學門之間的對話，進而激盪出新的思惟、新的方向，學術水平亦當因此向上提升。

四、攜回資料名稱及內容

二〇〇〇年美國地球物理年會論文摘要（自購）：內容涵蓋本次會議發表論文之摘要，共計千餘篇。

Ice Ages and Astronomical Causes（自購）:內容系涵蓋古氣候重建資料、頻譜分析及冰期形成機制。

五、其他

A Reassessment of the Post-Depositional Remanent Magnetization Lock-in Depth of the Brunhes/Matuyama Reversal in Deep-Sea Sediments

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ABSTRACT

Detailed paleomagnetic records from Core MD972142 and MD972143 confirmed the global existence of double decreasing in paleointensity (DIP) close to the Brunhes/Matuyama (B/M) reversal, separated in time by approximatly 15 kyrs. The upper paleointensity decrease (DIP2) centered over the B/M transition was associated with the polarity reversal. After correcting the post-depositional remanence acquisition the mid-point of pre-transition paleointensity low (DIP1), accompanying a directional excursion recorded in some cores, is coincident in time with the Australasian microtektite event at 793 ka. In viewing the coincidence of timing between the Australasian impact and the precursor of the B/M reversal, we re-examined the hypothesis that large impacts might have triggered geomagnetic reversals.

To better estimate the lock-in depth of post-depositional remanent magnetization (PDRM) we have compiled stratigraphic data of eight deep-sea cores in which the occurrence of the Australasian microtektite layer and the B/M geomagnetic boundary are well constrained. Regression analysis of the depth offsets between the B/M reversal and the microtektite layers versus sedimentation rates suggests that the PDRM acquires at about 10 cm below the water/sediment interface. The result also indicates that the Australasian impact preceded the B/M magnetic reversal by ~15 kyrs, coinciding in timing with the precursor prior to the B/M transition. This result appears to support an efficient causal relationship between the huge impact and the geomagnetic excursion.

INTRODUCTION

Tektites are natural glasses formed by melting of upper crustal materials during the hypervelocity impact of an extraterrestrial object. The stratigraphic proximity of the Australasian and Ivory Coast microtektite layers, with the Brunhes/Matuyama boundary and the base of the Jaramillo subchron, respectively, has prompted the hypothesis that large impacts may trigger geomagnetic reversals (Glass and Heezen, 1967; Durrani and Khan, 1971; Glass et al., 1979). Based on the apparent association of specific impact events and geomagnetic reversals, Muller and Morris (1986) proposed a geophysical mechanism to explain how a bolide impact might lead to a geomagnetic reversal by means of rapid climate cooling. However, paleomagnetic studies showed the Ivory Coast microtektites were deposited ~8 kyr after the onset of the Jaramillo subchron (Schneider and Kent, 1990; Glass et al., 1991) and, therefore, precluded a possible causal relationship between these two events. As the Australasian microtektite preceded the Brunhes/Matuyama reversal by estimates of ~12 to 16 kyr (Burns, 1989; deMenocal et al., 1990; Schneider et al., 1992; Lee and Wei, 2000), these results also are inconsistent with simple geophysical models linking geomagnetic reversals with impact events.

Recently, detailed paleomagnetic records from the Pacific and Atlantic Oceans consistently found a decrease in paleointensity approximately 15 kyr prior to the Brunhes/Matuyama transition (Kent and Schneider, 1995; Hartl and Tauxe, 1996; Channell and Kleiven, 2000). In some of these records (e.g., ODP Site 769, Kent and Schneider, 1995; ODP Sites 609 and 804, Hartl and Tauxe, 1996), a directional excursion to nearly full normal polarity with a low paleointensity remains after (alternating field) demagnetization. The close temporal proximity of the pre-transition low to the B/M transition raised questions about its relationship to the reversal itself as well as to an apparently unrelated event - the Australasian impact, that just occurred before the reversal.

A through examination of the question hinges on how accurate one can define the temporal relationships among these events. To be sure, gauging the time offset between the Australasian impact and certain geomagnetic signals inherits uncertainty because of two factors: (1) the position of the reversal boundary was affected by the depth of post-depositional remanent magnetization (PDRM) (Irving, 1957; Irving and Major, 1964; Kent, 1973, Løvlie, 1976; Verosub, 1977), and (2) the original stratigraphic position of the microtektites was redistributed by bioturbation (Glass, 1969; Guinasso and Schink, 1975; Officer and Lynch, 1983). Such post-depositional effects can displace the position of the paleomagnetic signal downward below the position of a synchronous microtektite deposition. Previous estimates for the PDRM lock-in zone in deep-sea sediments ranged from a few centimeters to tens of centimeters below the sediment-water interface (Burns, 1989; Okada and Niitsuma, 1989; deMenocal, 1990; Tauxe et al., 1996). The uncertainty in the remanence acquisition depth (the estimated depth range over which the magnetization acquired) remains large and these prior results are not satisfactory for either examining the synchroneity of or determining the temporal relationship between the Australasian impact event and the precursor of the B/M reversal.

The purpose of the present study is to (1) establish detailed paleomagnetic records from two newly obtained deep-sea cores through the Brunhes/Matuyama reversal interval in association with well-defined Australasian microtektite layers, (2) reassess the lock-in depth of post-depositional remanence acquisition based upon a compilation of eight deep-sea cores, and (3) test the impact-reversal hypothesis by examining the stratigraphic and temporal relation between the Australasian impact event and the precursor of the B/M reversal.

MATERIALS AND METHODS

During Leg II of the IMAGES III Cruise in 1997, several giant piston cores were obtained within or close to the Australasian microtektite strewnfield (Figure 3-1). Among them, two cores, MD972142 and MD972143, penetrated the B/M boundary (Horng, 2000; Lee, 2000), and therefore, were selected to examine the temporal relationship between the Australasian microtektite event and the precursor of the B/M reversal. Core MD972142 (12° 41.33' N, 119° 27.90' E) was raised northwest of Palawan in the South China Sea at a water depth of 1557m. Core MD972143 (15° 52.26' N, 124° 38.96' E) was retrieved from the Benham Rise, east of Luzon Island in the West Philippine Sea at a water depth of 2989m. Both cores are situated well above the carbonate lysocline depth, which lies at about 3400m in this area (Berger and Johnson, 1976; Rottman, 1979; Berger et al., 1982).

Paleomagnetic samples were obtained with plastic cubes (~7 cm^3) roughly every 12 cm and 9 cm, respectively, throughout the core MD972143 and MD972142. The sampling interval was reduced to a minimum (~2cm/4cm) around the B/M boundary. Low-field magnetic susceptibility (χ) of discrete samples was measured with a Bartington MS2 system. Stepwise alternating field demagnetization of the natural remanent magnetization, with a 10mT increment up to 80 to 100mT, was performed within a shielded room. After each demagnetization step, remanent magnetization of the samples was measured on a 2G cryogenic magnetometer at the Institute of Earth Sciences, Academia Sinica.

In order to better define the occurrence of the Australasian microtektite layers, both cores were sampled continuously through the B/M boundary every 4 cm as documented in Lee and Wei (2000). We counted microtektites (>125μm in diameter) according to their characteristic shapes (Figure 3-2) and glassy appearance under a binocular stereomicroscope. The abundance curve of microtektites from both sites displayed a simple shape with a sharp lower boundary and a rapidly tapering upper boundary. To deconvolute the bioturbation effect, we followed Burns (1989) and Schneider et al. (1992) to calculate the weighed mean of the microtektite distribution and designated the peak value as the original stratigraphic level of the event (Guinasso and Schink, 1975). Accordingly, the depths of the microtektite layers reported in the following discussion are those corrected after the bioturbation effect was removed. Such correction displaces usually the peak horizon upward in respect to its apparent stratigraphic level by an average of 2 centimeters (Burns, 1989; Schneider et al., 1992, Lee and Wei, 2000).

RESULTS

Paleomagnetic Records of Core MD972142 and MD972143

For core MD972142, the normalized natural remanent magnetization (NRM) intensity profiles obtained in the 0-20 mT demagnetization range with normalizer (χ) are very similar (Figure 3-3). Of particular significance is the presence of two successive and remarked decreases in paleointensity, DIP1 and DIP2, as previously recognized and coined by Kent and Schneider (1995). The depth offset between the DIP1 and DIP2 is approximately 68 cm, corresponding to a time offset of 15.7 kyrs based on the mean sedimentation rate of ~4.3 cm/kyrs (Lee and Wei, 2000). The upper paleointensity decrease (DIP 2) centered over the B/M transition was associated with the polarity reversal at subdepth 3374 cm (Figure 3-3). Directional changes associated with the B/M transition are recorded between 3378 and 3350 cm, corresponding to a duration of 6.5 kyrs based on the mean sedimentation rate. This duration for the directional change is consistent with previous observations (e.g., Love and Mazaud, 1997) and with the estimated duration needed for diffusive decay of a dipole field in the inner core (Hollerback and Jones, 1993).

Below the polarity reversal, a narrow zone of excursional directions centered at about 3438 cm is associated within the DIP1 and remains after AF demagnetization. The microtektites are scattered in the upper part of DIP 1 between 3385 cm and 3445 cm (Figure 3-3). After correction for the bioturbation effect, the original microtektite deposition was estimated to be at 3425cm (Lee and Wei, 2000), which is about 51 cm below the DIP 2 and 13cm above the excursion of the DIP 1.

For core MD972143, the location of the B/M boundary is centered at 1559cm in association with the upper paleointensity dips (Figure 3-4). Of particular significance, again, is the presence of two distinct and consecutive decreases in paleointensity at 1559 cm and 1579 cm, separated by ~15kyrs. The older paleointensity dips occur at about 20cm below the B/M boundary in association with reversed polarity without a clear excursion. Previous studies showed that only a fraction of the records exhibit a directional excursion accompanying the DIP1. Hartl and Tauxe (1996) interpreted this as an unremoved viscous remanent magnetization (VRM), which was acquired under low strength of geomagnetic field.

After correction for bioturbation effect the original deposition of the microtektites was located at 1569cm, which is 10 cm below the B/M boundary at 1559 cm and 10 cm above the DIP 1 (Lee and Wei, 2000). As there shows no excursion accompanying the DIP 1, we calculated the stratigraphic offset between the

Australasian impact and the mid-point of the pre-transition paleointensity low in the following discussion.

Both records demonstrate that the occurrence of the Australasian microtektites is slightly above the position of the DIP 1. The depth offset between these two events is 13 cm for core MD972142 and 10 cm for MD972143, respectively. As the delayed remanence acquisition acts to lower the recorded paleomagnetic signals a small amount (lock-in depth) below the position of synchronous deposition, their "apparent" stratigraphic positions can not be used to determine the temporal relationship. To sustain a possible impact-reversal hypothesis, however, would be evidence of a clear temporal relationship demonstrating that impact precede magnetic reversal.

Assessment of the Post-Depositional Remanence Acquisition Depth

Determining the temporal relationship between the Australasian impact event and the precursor of the B/M reversal inherited uncertainty because microtektite particles and magnetic remanence acquisition have been both stratigraphically displaced by post-depositional processes. The post-depositional remanence acquisition has been suggested to proceed gradually below the water/sediment interface until consolidation processes have reduced the size of interstitial voids effectively to a point inhibiting further reorientation of magnetic grains. Investigation of this process in marine sediments has been conducted by comparing the stratigraphic relationships between the B/M geomagnetic boundary with synchronous microtektite layers (Burns, 1989), ash layers (Okada and Niitsuma, 1989), and oxygen isotopic events (deMenocal et al., 1990; Tauxe et al., 1996). However, as documented in these studies it has been a considerable controversy as to the depth range over which the magnetization is locked in. The wide range of the estimated lock-in depth casts certain difficult for examining the causal relation of the Australasian impact and the precursor of the B/M reversal.

As noted in the above section, the Australasian microtektites were deposited above the position of the precursor of the B/M reversal by 13 and 10 cm, respectively, for core MD972142 and MD972143. If the post-depositional remanent magnetization acquires within a few centimeters below the water/sediments interface (Tauxe et al., 1996), the precursor of the B/M reversal would precede the Australasian impact and preclude any causal relationship between these two events. On the other hand, if the remanence is locked in below the interface by a depth in the amount of 16 cm (deMenocal et al., 1990) or even more (Burns, 1989; Okada and Niitsuma, 1989), our records would indicate that the Australasian impact might have happened simultaneously with or just before the precursor of the B/M reversal. The validity of the impact-reversal hypothesis hinges upon which of the various estimates of the lock-in depth is appropriate.

In order to better determine the lock-in depth of post-depositional remanence acquisition, we compiled eight deep-sea core records in which the microtektite layers and the B/M boundary are well constrained (Table 3-1). The average sedimentation rates, ranging from ~1 cm/kyr to 8 cm/kyr, were calculated by dividing the published depths of the B/M boundary (in cm) at each core by 778 kyr as the age of the B/M reversal (Shackleton et al., 1990; Singer et al., 1996). Using the method first documented by Burns (1989) and other following studies, the PDRM acquisition depth and the age offset between the B/M reversal and the Australasian impact event can be determined by comparing stratigraphic relationships between the B/M boundaries and the microtektite layers at sites with different sedimentation rates.

In Figure 3-5, the regression analysis shows that the best-fitted line through the data points intercepts the y-axis at ~ -10 cm, which is considered to be the average remanence acquisition depth. Strong linearity ($r^2 > 0.9$) in the regression indicates that the lock-in depth is independent of the sedimentation rate, which is consistent with the prerequisite for using the linear regression method. Our estimate is comparable to the estimated average PDRM acquisition depth by deMenocal et al. (1990). A shift of the precursor of the B/M reversal ~10cm upward will result in the depth offset between these two events negligible from the perspective of experimental uncertainty and statistical error.

The slope of the line indicates that the age offset between the Australasian Impact and the B/M reversal is about 15 kyrs, coinciding in time with the offset between paleointensity decrease and the B/M transition (Kent and Schneidei, 1995; Hartl and Tauxe, 1996). Our estimate is also consistent with previous results that the Australasian microtektite layer was deposited before the Brunhes/Matuyama reversal by 12 to 16 kyrs (Burns, 1989; deMenocal et al., 1990; Schneider et al., 1992; Lee and Wei, 2000). On the basis of the stratigraphic and temporal coincidence, we suggest that the pre-transition paleointensity low was associated with the Australasian impact at 793 ka, given the mean age of 778 ka for the B/M reversal by Ar/Ar dating (Singer et al., 1996).

DISCUSSIONS

Detailed paleomagnetic records from core MD972142 and MD972143 confirmed the global existence of double-DIPs closer to the B/M reversal, separated in time by ~15 kyrs (Figure 3-6). The uppermost paleointensity decrease (DIP2) centered over the B/M transition was associated with the polarity reversal at 778 ka.

The mid-point of the pre-transition low (DIP1) accompanying excursional directions was correlated to the Australasian microtektite event at 793 ka. The association of the DIP1 with the Australasian impact and the temporal proximity to the B/M transition raised questions about its role in triggering the geomagnetic reversal/excursion. Is the pre-transition low a part of the reversal itself or an independent excursion event? Is the excursion initiated by processes that are intrinsic (self-reversal hypothesis) or extrinsic (impact-reversal hypothesis) to the geodynamo?

The Australasian Excursion: a Precursor to the B/M Reversal?

In some of the records, a directional excursion lasting less than 2 kyr in association with the pre-transition paleointensity low (DIP1) remained after demagnetization. The inconsistent occurrence of the directional excursion within DIP 1 can be accounted by two kinds of explanations: (1) the so-called excursions are simply unremoved overprints; or, on the other hand, secondary remanent magnetization, such as viscous remanent magnetization (VRM) (Hartl and Tauxe, 1996); (2) the directional changes lasted too short to be recorded in sites where sedimentation rates are low. With or without the excursion, nevertheless, it is still intriguing that the paleointensity of geomagnetic field dropped to one-fifth to one-tenth of the present-day field at this particular time interval.

A recent global compilation of relative paleointensity records over the past 800 kyr (Guyodo and Valet, 1999), the so-called "Sint-800" composite, appears to support the second interpretation. The Sint-800 demonstrates that pronounced paleointensity minima occurred simultaneously with known excursions in field directions during the Brunhes Chron. The double-DIPs closer to the B/M reversal are also observed at the older end of the composite record. It is believed that low intensities in association with incidents of geomagnetic excursion reveal inherent properties of the geodynamo (Gubbins, 1999). Such features have led Gubbins (1999) to propose that such magnetic excursions relate to processes in the Earth's core: excursions are resulted from reversal of geomagnetic field in the liquid outer core, but not in the solid inner core. Such changes of the magnetic field in the outer core are achieved by fluid flow with a timescale of only 500 yr or less, and the change occurs very rapidly compared to the changes in the inner core by diffusion. If so, many such excursions are not observed in sedimentary records simply because they do not last long enough, while in other records their geomagnetic signals may be distorted or lost by post-depositional alteration.

Post-depositional remanence lock-in process occurs over a range in depth. The depth below the water/sediment interface at which at least 50% of the magnetization has been locked defines the lock-in depth of post-depositional remanence acquisition. The final lock-in depth depends on quite a few factors such as bioturbation, particle size/shape, and degree of compaction. Given this array of complicating factors, a reliable high-resolution geomagnetic record from the deep-sea core must meet the following criteria: 1) the lock-in process must have been the same throughout the sedimentation processes, 2) the sediment and magnetic source must have been relatively stable, and 3) the magnetization must have remained unaltered since it was locked in. Most sedimentary sequences do not satisfy these conditions so as to bias the fidelity of short-term events in deep-sea sedimentary record. Furthermore, short-term excursions are difficult to recognize in sediments because the geomagnetic field tends to return to its initial polarity state rather than to the opposite polarity in the presence of a weak magnetic field. Theoretical simulations suggested that excursional directions are more prone to be affected by smoothing processes induced by post-depositional remanent magnetization than transitional directions (Quidelleur and Valet, 1994). In deep-sea sediments, such a smoothing effect acts to depress paleomagnetic secular variations for features of less than 2 kyrs in duration (Lund and Keigwin, 1994). Consequently, we would not expect to obtain a full track of excursional directions in all deep-sea records. Sedimentary sequences with higher sedimentation rates tend to retain excursions, such as ODP 769 with SAR of 8cm/kyrs and ODP 609 with SAR of 5cm/kyrs as documented by Hartl and Tauxe (1996), therefore, only a fraction of deep-sea records exhibit directional excursions after demagnetization. This explains also why MD972142 (a high sedimentation rate core) shows partial reversal of the magnetic field, but not in low sedimentation rate core of MD972143. Interestingly enough, the directional excursion together with DIP 1 coincides perfectly with the Australasian impact event. We propose to name the DIP1 directional change as "the Australasian excursion" (Figure 3-6). This excursion preceded the B/M reversal by ~15 kyr, which is too long to be explained by the duration of well-documented B/M transition. Accordingly, we don't consider the Australasian excursion as the precursor of the B/M reversal.

The Australasian Impact: A Trigger of the Geomagnetic Excursion?

The magnitude of the Australasian impact was arguably the largest impact in the past several tens of millions of years. Microtektites belonging to the Australasian strewn field have been found in deep-sea cores throughout much of the Indian Ocean, the western Pacific Ocean and marginal seas (Glass and Wu, 1993; Glass and Pizzuto, 1994; Lee and Wei, 2000). Recently, microtektites identified for the first time on land from the Luochuan loess (Li et al., 1993; Zhou and Shackleton,

1999) signify a northward extension of the Australasian strewn field, covering at least 15% of the Earth's surface. Despite its relative young age and the large size of the strewn field, no source crater of the Australasian microtektites has been discovered. Based on the geographic extent of the Australasian strewn field (Blum et al., 1992; Koeberl, 1994) and the spatial variations of the microtektite thickness (Glass and Pizzuto, 1994; Lee and Wei, 2000), the diameter of the source crater producing the Australasian tektites was estimated to be about 100 km.

The terrestrial impact events are extremely difficult to recognize from geologic record and to extract sufficient information for examining a possible causal relationship between a bolide impact and a geomagnetic anomaly. So far, only 16 known occurrences of impact-related materials were recognized in the stratigraphic record (Grieve, 1997), including the best-documented K-T event and the four known tektite strewnfields. As the stratigraphic proximity of the Australasian microtektite layer with the B/M boundary, Glass and Heezen (1967) first implied a possible causal relationship between the bolide impact and the geomagnetic reversal. However, our detailed paleomagnetic studies indicate that the Australasian impact occurred in association with the Australasian excursion at 793 ka, which preceded the B/M reversal by ~15 kyr. The 15-kyr duration is too long to account for a polarity transition (deMenocal et al., 1990; Schneider et al., 1993), thus, the impact itself may not be responsible for the B/M transition. Instead, the apparent coincidence between the Australasian microtektite and the geomagnetic excursion led us to reassess the possibility of a causal relationship between these two events, particularly, would it be possible that the Australasian impact triggered magnetic excursion, rather than a reversal?

Conventionally, excursions are loosely defined as directional departures when the change of the virtual geomagnetic pole (VGP) is larger than those seen in secular variations by showing a shift in VGP larger than 45° (Verosub, 1977). Based on the global occurrence of excursions and their temporal characteristics (Langereis et al., 1997; Lund, 1998), Gubbins (1999) proposed that excursions are events in which the geomagnetic field reverses in the liquid outer core but not in the solid inner core. Changes of the magnetic field in the outer core are achieved by fluid flow, while diffusion plays only a secondary role, and therefore the change is fast compared to the diffusion process. In general, the magnetic inertia imposed by the inner core delays full reversal for several thousand years, during which the original polarity may establish itself in the outer core. In fact, excursions reflect activities of the geodynamo, they should not be treated as abandoned reversals or a pair of reversals.

In contrast, it is necessary to have a complete diffusion into the inner core before a permanent magnetic reversal can be established. The requirement for the magnetic field to diffuse into the inner core provides a significant moderation of the reversal process (Hollerbach and Jones, 1993). The reversals can be viewed as results of final modulation of the inner core by diffusion. It is very unlikely that the inner core might be directly or indirectly perturbed by a bolide impact. On the other hand, several geophysical mechanisms have been proposed to initiate geomagnetic reversals by means of a series of chain reactions to transfer impact-induced perturbations to the core-mantle boundary (Muller and Morris, 1986; Pal and Creer, 1986; Burek and Wänke, 1988). It is possible that dynamic processes in the lower mantle can interact with the outer core (e.g., Glatzmaier et al., 1999) and trigger excursions in geomagnetic field. Such a scenario is supported by our records: The coincidence in time between the Australasian impact event and the Australasian excursion suggests a causal relationship. Recent advances in geodynamo theory and numerical simulation preclude the possibility of the impact-reversal linkage. Instead, we suggest that a hypervelocity impact might possibly trigger only an excursion for its dynamic plausibility.

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Table 3-1 Site, coordinates, depth of the Brunhes/Matuyama boundary (BMB), the microtektite peak, and the corrected depth of microtektite occurrence, and sedimentation rate (SAR) in eight selected deep-sea cores in the Australasian strewnfield.

Core/Site	Latitude	Longitude	BMB (cm)	Microtektite (cm)	Corr-µtektite (cm)	SAR (cm/kyr)	Reference
ODP 769	8.79 N	121.22 E	6227	6331	6329	8.0	Schneider et al.(1992)
ODP 767	4.79 N	123.50 E	4880	4963	4961	6.3	Schneider et al.(1992)
MD972142	12.69 N	119.56 E	3374	3425	3425	4.3	Lee and Wei (2000)
MD972143	15.87 N	124.65 E	1559	1571	1569	2.0	Lee and Wei (2000)
ODP 758	5.38 N	90.36 E	1065	1091	1095	1.4	Smit et al. (1991)
V28-238	1.02 N	160.48 E	1200	1214	1208	1.5	Shackleton and Opdyke (1973)
17957	10.90 N	115.31 E	795	805	807	1.0	Jian et al. (2000)
V28-239	3.25 N	159.18 E	726	730	728	0.9	Shackleton and Opdyke (1976)

Figure Caption:

Figure 3-1 Geographic extent of Australasian strewnfield defined by deep-sea cores (open circles) and land section (solid circle) where microtektites were found. Solid triangles represent cores where magneto-, oxygen isotopic and microtektite stratigraphy was documented. Open triangles represent cores where double-DIPs were reported.

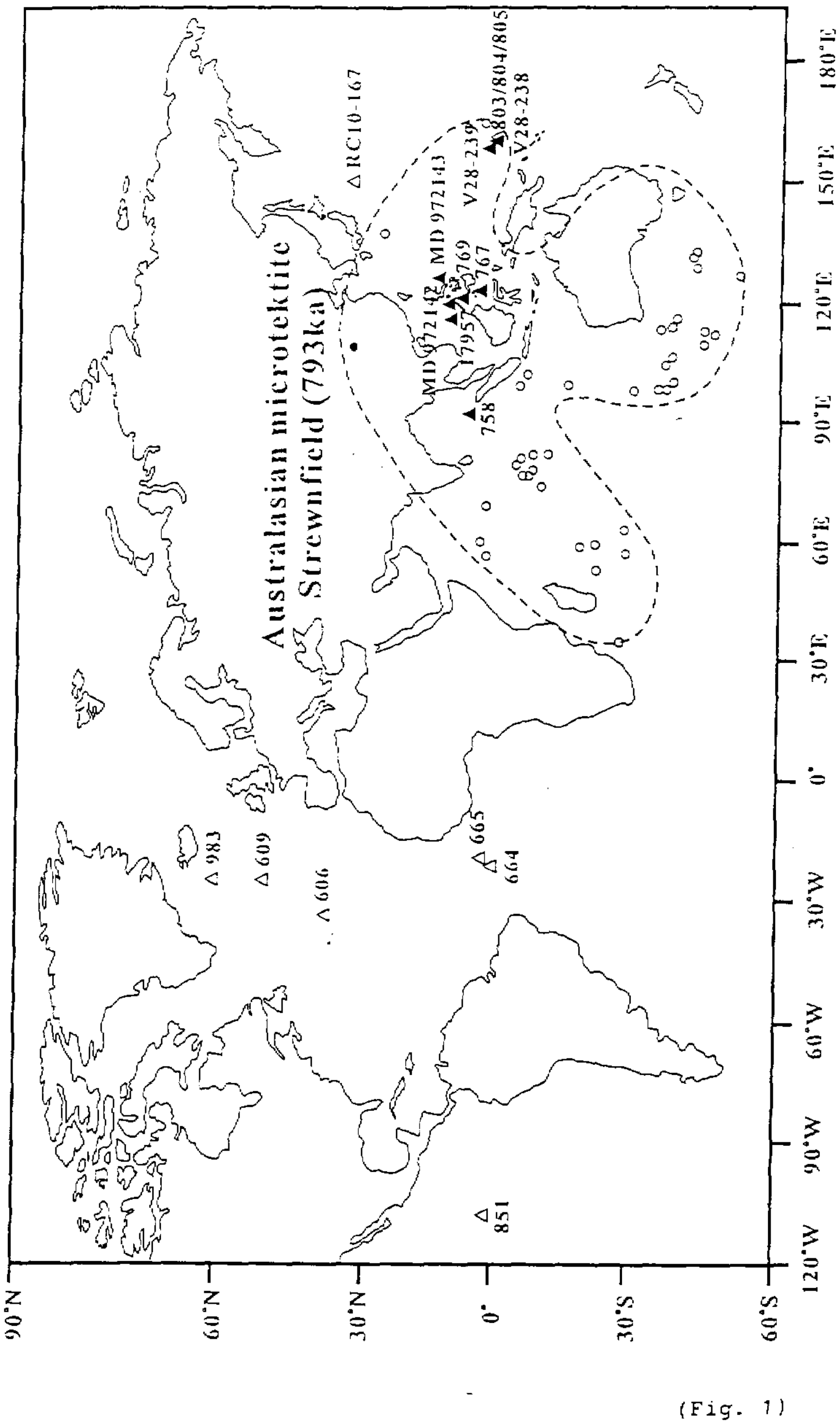
Figure 3-2 Scanning electron microscope photomicrographs of microtektites illustrating various shapes and surface textures observed in Core MD972142 (a-b) and Core MD972143 (c-f). a) smooth spheres; b) smooth dumbbell; c) droplet with curled-up tail; d) sphere with etched flowlines; e) spheroid with etched flowlines; f) etched sphere showing interior hallow cavities.

Figure 3-3 Paleomagnetic stratigraphy from core MD972142. Thick dash line indicates the corrected peak abundance of microtektites at 3425cm.

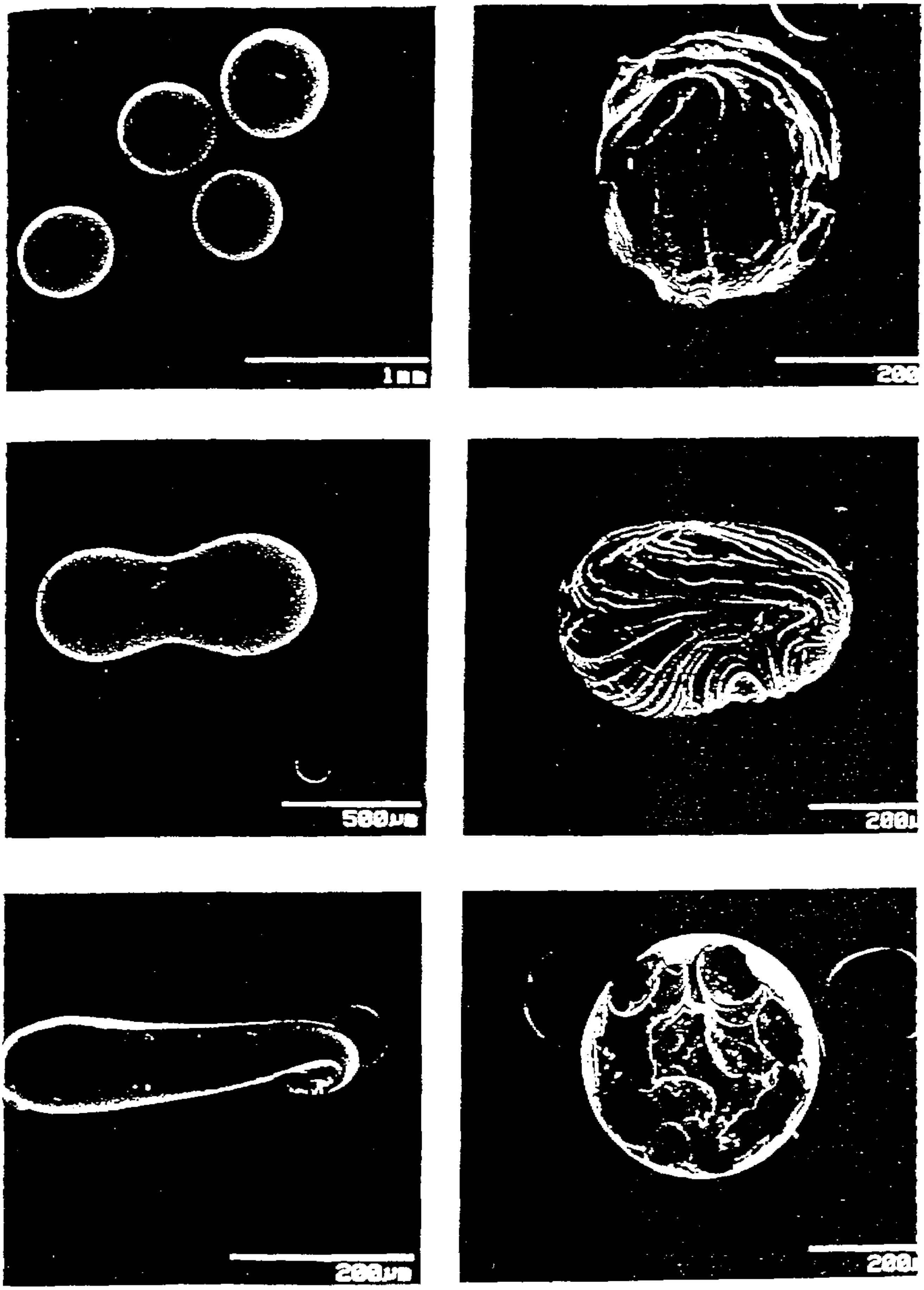
Figure 3-4 Paleomagnetic stratigraphy from core MD972143. Thick dash line indicates the correlated peak abundance of microtektites at 1569cm.

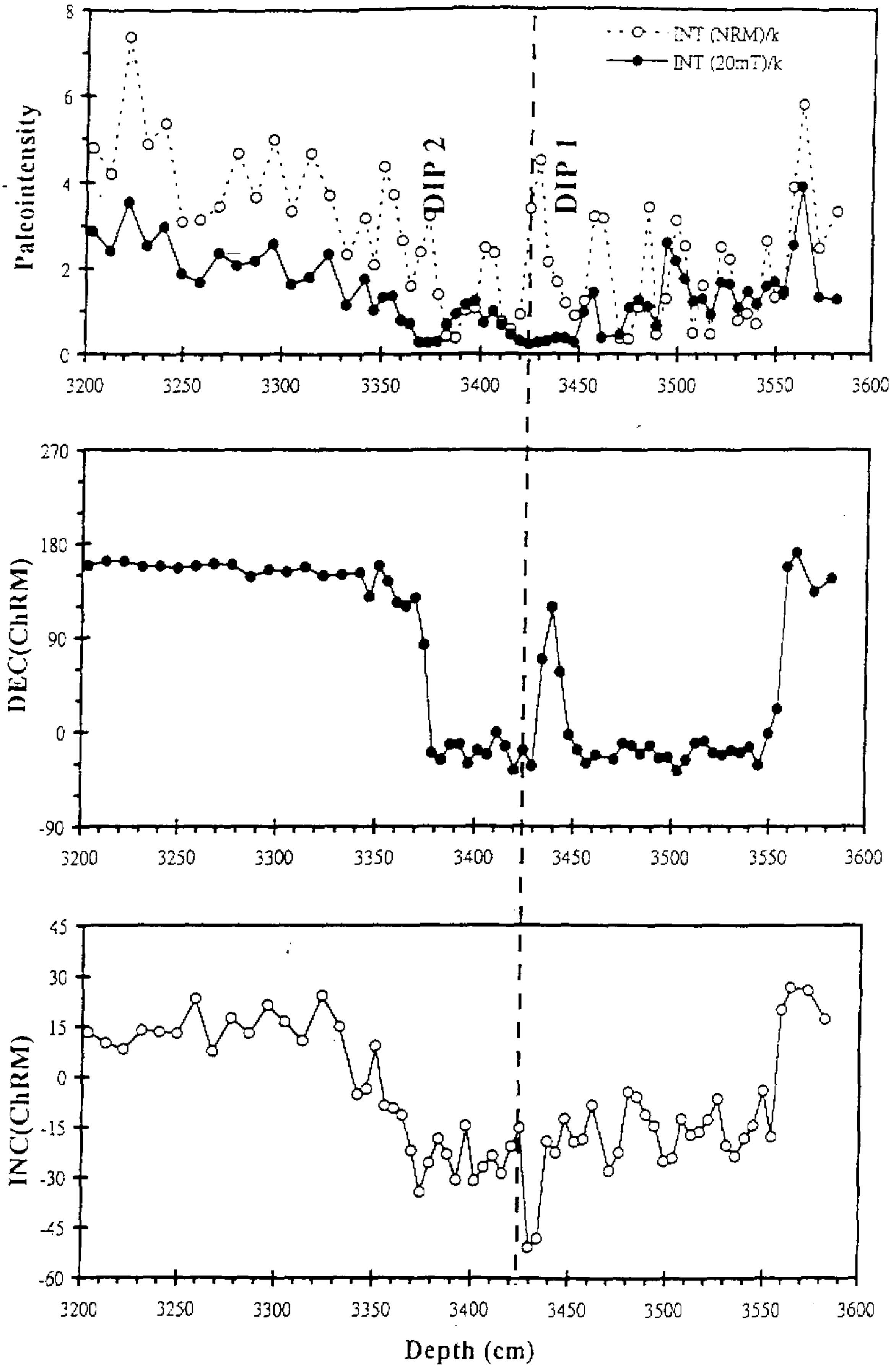
Figure 3-5 Plot of sedimentation rates versus depth offsets in eight selected cores (solid squares) within the Australasian strewnfield. The depth offset (ΔZ) between the Brunhes/Matuyama boundary and the microtektite layer is determined after the microtektite layer has been corrected for the bioturbation effect. For a comparison, previous data used for estimating the PDRM lock-in depth by Burns's (1989) from deep-sea cores with low sedimentation rates are shown in open circles.

Figure 3-6 Pictograph of the temporal relationships between various paleomagnetic events and the Australasian impact around the Brunhes/Matuyama reversal.


Australasian microtektite
Strewnfield (793ka)
Δ RC10-167
MD 972143
MD 972142
1795
769
767
758
803/804/805
V28-239
V28-238
Δ 983
Δ 609
Δ 606
Δ 665
664
Δ 851
90°N
60°N
30°N
0°
30°S
60°S
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°E

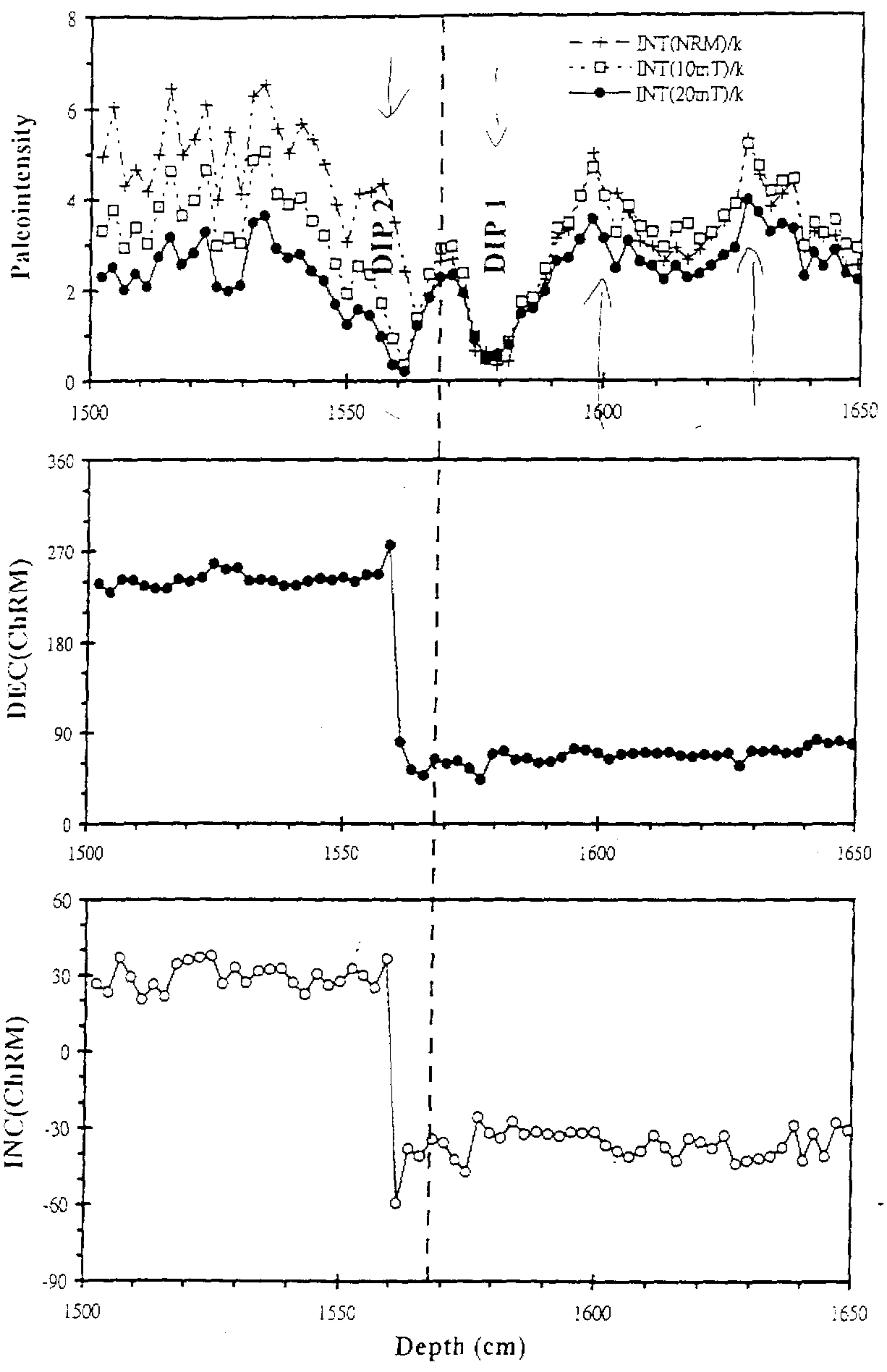
(Fig. 1)


1mm
200
500μm
200μ
200μm
200μ



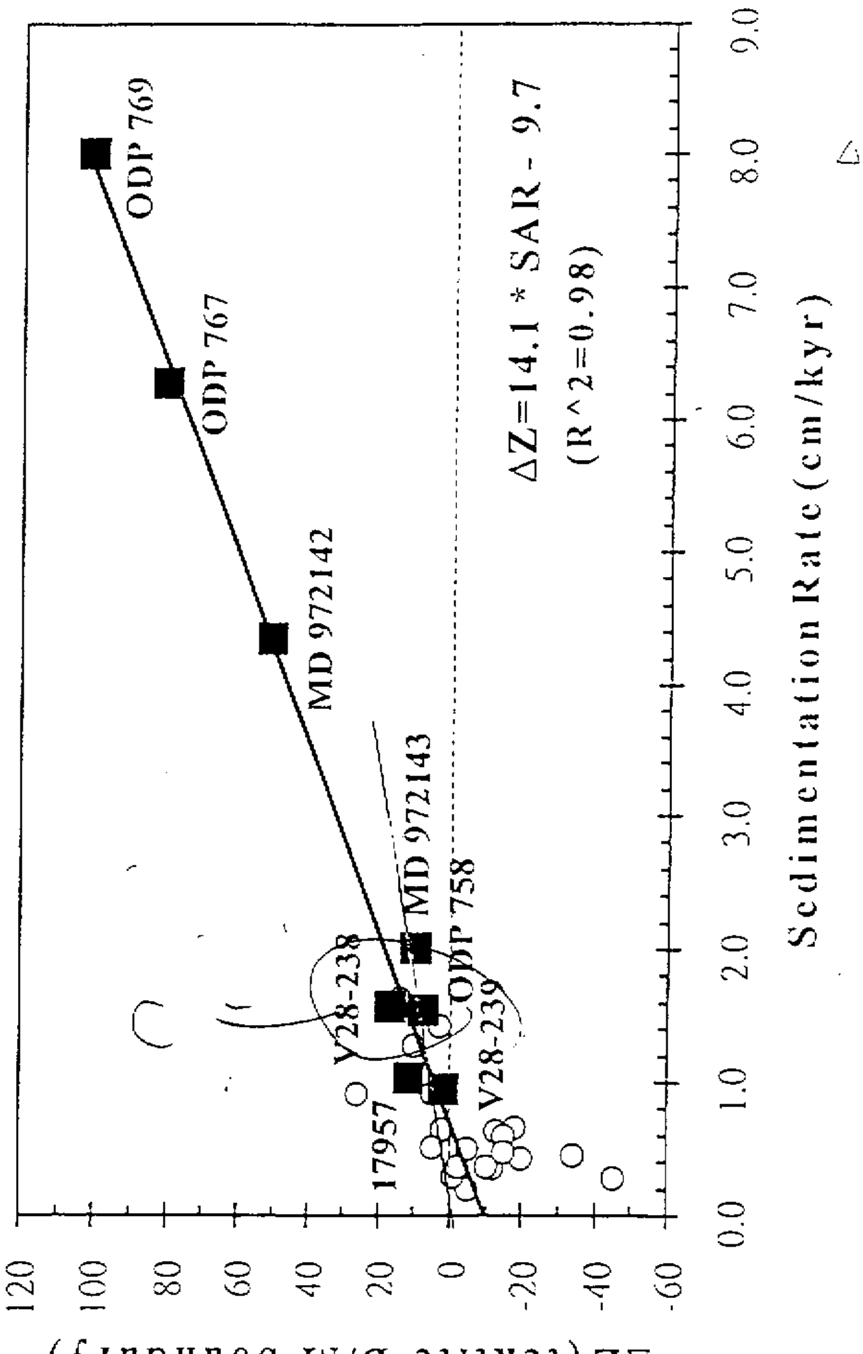
INT (NRM)/k
INT (20mT)/k
DIP 2
DIP 1
Paleointensity
DEC(ChRM)
INC(ChRM)
Depth (cm)

(Fig. 3)

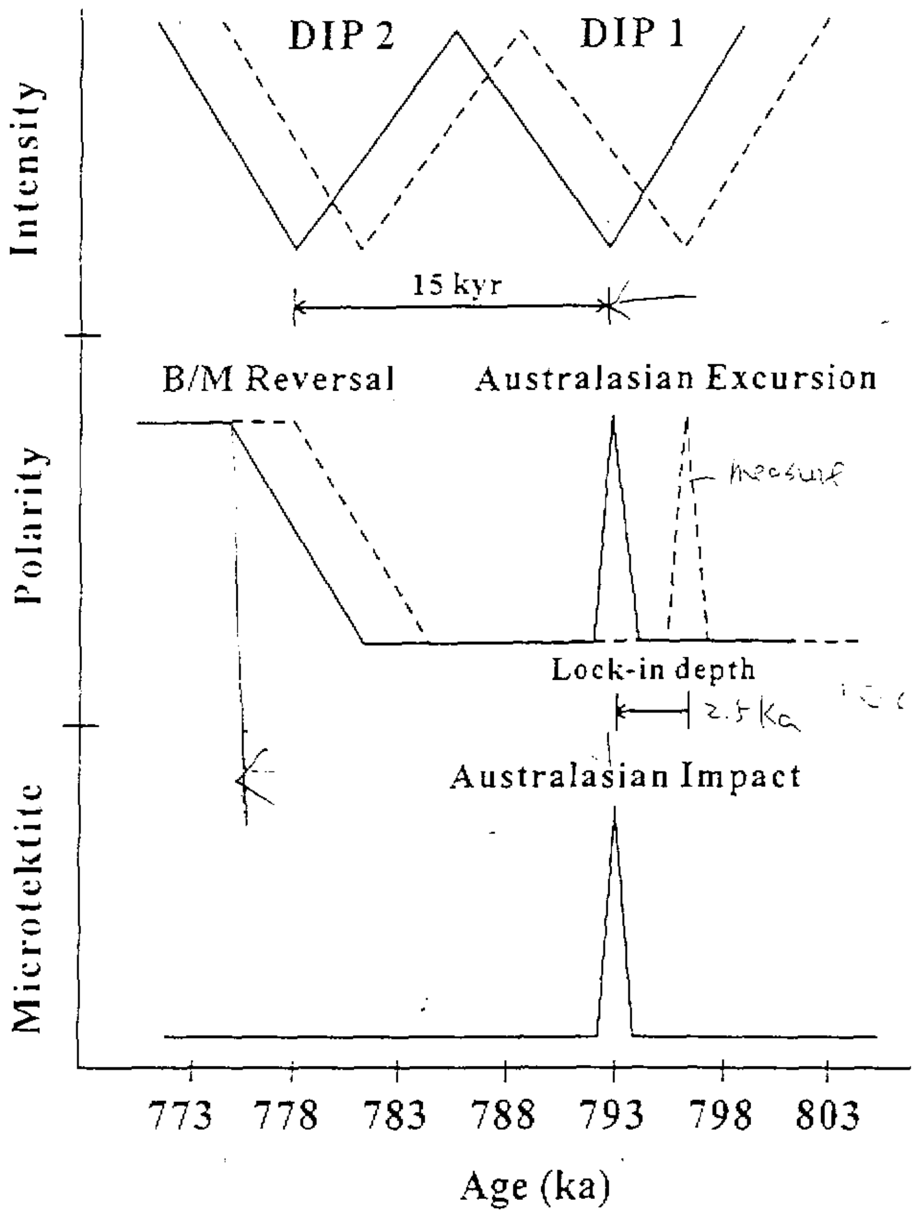


INT(NRM)/k
INT(10mT)/k
INT(20mT)/k
Paleointensity
DIP 2
DIP 1
DEC(ChRM)
INC(ChRM)
Depth (cm)

(Fig.4)


ODP 769
ODP 767
MD 972142
MD 972143
ODP 758
V28-238
V28-239
17957
ΔZ=14.1 * SAR - 9.7
(R^2=0.98)
Sedimentation Rate (cm/kyr)
ΔZ (tektite-B/M boundary)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
120
100
80
60
40
20
0
-20
-40
-60

(Fig. 5)


DIP 2
DIP 1
Intensity
15 kyr
B/M Reversal
Australasian Excursion
Polarity
Lock-in depth
Australasian Impact
Microtektite
773
778
783
788
793
798
803
Age (ka)

(Fig. 6)