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Re-assessing the Upper Permian Stratigraphic Succession of the Northern Sydney Basin, Australia, by CA-IDTIMS

Angelos G. Maravelis [1,*], Jake Breckenridge [2], Kevin Ruming [3], Erin Holmes [3], Yuri Amelin [4] and William J. Collins [5]

1 Department of Geology, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
2 School of Environmental and Life Sciences, University of Newcastle, Callaghan 2308, Australia; Jake.Breckenridge@uon.edu.au
3 Geological Survey of NSW, Department of Industry, Division of Resources and Energy, Maitland 2320, Australia; kevin.ruming@planning.nsw.gov.au (K.R.); admin@coalfieldgeologycouncilnsw.org (E.H.)
4 Research School of Earth Sciences, The Australian National University, Building 142, 1 Mills Road, Acton, Canberra 2601, Australia; yuri.amelin@anu.edu.au
5 Faculty of Science and Engineering, School of Earth and Planetary Sciences (EPS), Curtin University, GPO Box U1987, Perth 6845, Australia; William.Collins@curtin.edu.au
* Correspondence: angmar@geo.auth.gr

Received: 22 October 2020; Accepted: 18 November 2020; Published: 22 November 2020

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Abstract: High precision Chemical abrasion-isotope dilution thermal ionisation mass spectrometry (CA-IDTIMS) U-Pb zircon results from tuff marker beds that are interstratified within the Upper Permian deposits of the northern Sydney Basin add constraints on the timing of sediment deposition, and afford a better understanding of the regional stratigraphy. The results indicate a magmatic influence during the deposition of the sediments, with episodic events spanning at least from 255.65 ± 0.08 to 255.08 ± 0.09 Ma. The zircon data suggest that the studied sedimentary rocks and tuffs have accumulated simultaneously over a short time interval, which contrasts with current stratigraphic models that suggest a much greater period of deposition and stratigraphic thickness. Therefore, an updated stratigraphic correlation of the basin is suggested, which combines the presently defined Lambton, Adamstown, and Boolaroo sub-groups into a single Lambton sub-group. This updated correlation framework is stratigraphically and geochronologically constrained and provides a more precise exploration model for the northern Sydney Basin. This case study highlights the valuable contribution of the CA-IDTIMS method in intrabasinal correlations of sedimentary successions, when integrated with a robust sedimentological framework, to minimize the stratigraphic uncertainties.

Keywords: CA-IDTIMS zircon dating; stratigraphic correlation; Permian; Sydney Basin; Australia

1. Introduction

Tuff beds interstratified in the sedimentary successions are common and are often employed as marker horizons to add tighter constraints on the stratigraphic evolution of sedimentary basins. Chemical abrasion-isotope dilution thermal ionisation mass spectrometry (CA-IDTIMS) data from such beds have been recently utilised as the most precise radio-isotopic dating data for zircon analysis [1,2]. This method has the ability to provide dates with an accuracy of ~100,000 years [3], making it a particularly useful tool for intrabasinal correlations [4,5]. The application of CA-IDTIMS method has also been proven very useful in obtaining numerical constraints on biostratigraphic schemes [6], refining the temporal framework of mass extinction events and major climatic changes [7], and determining the initiation of major plate tectonics configurations [8,9]. Furthermore, this methodology can be applied for the evaluation of depositional models within sedimentary basins. Even though such models are critical for the exploration of natural reserves, the research that utilizes CA-IDTIMS data to calibrate such models is limited [4,6].

The Permian and Triassic sedimentary basins of Australia are stratigraphically challenging, as a result of lateral facies variations over short distances, and late-stage block faulting, which make lithostratigraphic correlations difficult [6,10]. One of these basins, the Sydney Basin, is situated in New South Wales, southeast Australia, bounded by the Lachlan Orogen to the southwest and the New England Orogen to the northeast [11]. The basin is one of the largest coal producing regions in the world and a suitable case study to evaluate the existing stratigraphic models with newly acquired CA-IDTIMS data.

This research focuses on the Upper Permian sedimentary rocks (Newcastle Coal Measures) that outcrop in the Northern Sydney Basin (referred henceforth as NSB, Figures 1 and 2). These deposits host major coal reserves in the NSB and reveal the need for such research because the existing stratigraphic models are controversial. These deposits are traditionally thought to belong to three distinct sub-groups (Lambton, Adamstown and Boolaroo sub-groups, Figure 2) and were accumulated during several periods of regression and transgression [12–14]. It has also been suggested that these sub-groups include several tuff beds that are younger from north to south [15–17], as shown in Figure 2. However, recent sedimentological and sequence stratigraphic analysis suggests that at least some of these tuffs are positioned at the same stratigraphic level [18].

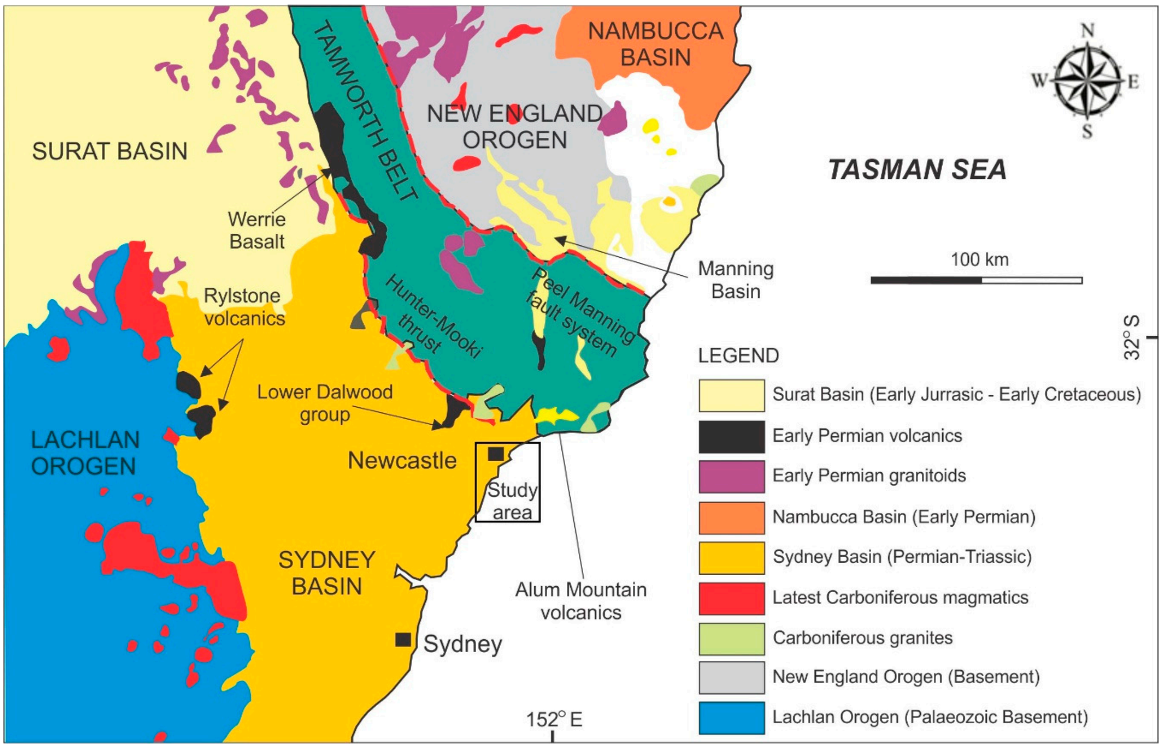

Figure 1. Geological map of the study area (Sydney Basin) and surrounding regions including the New England and Lachlan Orogens and adjacent sedimentary basins [19,20].

Northern Sydney Basin

Boolaroo sub-group	Fassifern Coal	251 Ma
	Belmont Conglomerate	
	Upper Pilot Coal	
	Mt. Hutton Tuff	
	Mt. Hutton Coal	
	Lower Pilot Coal	
	Hartely Hill Coal	
Adamstown sub-group	Warners Bay Tuff	
	Australasian Coal	
	Charlestown Conglomerate	
	Stockrington Tuff	
	Montrose Coal	
	Whitebridge Conglomerate	
	Wave Hill Tuff	
	Wave Hill Coal	
	Tingira Conglomerate	
	Edgeworth Tuff	
	Upper Fern Valley Coal	
	Redhead Conglomerate	
	Lower Fern Valley Coal	
	Merewether Conglomerate	
	Unnamed Tuff (in Kotara formation)	
Lambton sub-group	Victoria Tunnel Coal	
	Nobbys Tuff	
	Nobbys Coal	
	Signal Hill Member	
	Young Wallsend Coal	
	Cockle Creek Conglomerate Member	
	Yard Coal	
	Ferndale Conglomerate	
	Borehole Coal	
	West Borehole coal	
Tomago Coal Measures	Waratah Sandstone	255 Ma

Figure 2. Lithostratigraphic chart of the Northern Sydney Basin illustrating the different sub-groups that form the studied succession [15,21]. The Lambton, Adamstown and Boolaroo sub-groups make up the Newcastle Coal Measures. Each sub-group is internally sub-divided into lithological units that are defined as conglomerates (e.g., Ferndale, Merewether, Redhead and Belmond conglomerate), tuffs (e.g., Nobbys, Unnamed, Edgeworth and Mt. Hutton tuffs) and coal seam (e.g., Borehole, Yard, Nobbys, Upper Ferm and Lower Pilot coal).

To resolve the problem of whether the three sub-groups (Boolaroo, Adamstown, and Lambton) are all of the same stratigraphic succession or not, a high-precision zircon dating program was undertaken, focussed on tuff horizons that directly underlie major units in each subgroup. If the original stratigraphic nomenclature is correct, the tuff ages should become progressively older in the deeper part of the succession. Alternatively, if the sequence stratigraphic model of Breckenridge et al. [18] is correct, the tuffs should all be the same age, within error.

The objectives of this investigation are: (1) to test existing stratigraphic models in the NSB and highlight the value of CA-IDTIMS methodology in such research, (2) to correlate the several sub-group boundaries in order to document stratigraphic correlations, and (3) to clarify the lithostratigraphic nomenclature of the Newcastle Coal Measures in the NSB.

2. Geological Setting

The Early Permian to Middle Triassic Sydney Basin represents a component of a larger NNW trending, asymmetric retroarc foreland basin known as the Bowen-Gunnedah-Sydney Basin, which developed between the Lachlan Orogen to the southwest and the New England Orogen to the northeast [22]. The sedimentary fill of the basin overlies a basement of Ordovician, Silurian, and Devonian metamorphic rocks, as well as Devonian and Carboniferous plutons [23,24]. During the Late Carboniferous to Early Permian, the displacement of an active magmatic arc through crustal transtension caused intrusions of S-type granitoids and co-magmatic ignimbrites in the New England Orogen [25]. The New England Orogen was then uplifted during the early stages of the Hunter-Bowen Orogeny [26,27], possibly associated with right-lateral shearing during the initial stages of orocline development [28].

The Sydney Basin initiated during the Early Permian with rifting of the eroded Lachlan and New England Orogens [29], along with subsidence associated with cooling of the magmatic arc [30]. The eastwards migration of the subduction zone initiated widespread crustal extension and was responsible for the evolution of the East Australian Rift System that extended approximately 5000 km from northern Queensland, through New South Wales to Tasmania [31–34]. This process caused the intrusion of marine waters into the Sydney Basin and accumulation of alternating shallow-marine and alluvial sedimentary successions [35–37]. In the Late Permian, the geometric and kinematic characteristics of major folds and thrust systems in the Sydney Basin and New England Orogen indicate west-directed thrusting as the basin evolved from a continental rift system into a foreland basin [26,29,38].

The sedimentary rocks in the NSB are sourced from the New England Orogen and are bounded by the NW trending Hunter-Mooki fault system [39]. Major regression during the Late Permian, as a result of the uplift of the New England Orogen led to the prevalence of the fluvio-deltaic conditions that produced the extensive coal deposits of the Newcastle Coal Measures [18,40–42]. During the Late Permian-Early Triassic, the renewal of regional E-W compressional regime further deformed the region, and the Tamworth Terrane was thrust onto the Bowen-Gunnedah-Sydney Basin, generating favorable conditions for alluvial sedimentation [43,44]. During the Middle to Late Triassic, the SB was dissected by fold and thrust belts in response to westward migrating thrust fronts with associated crustal shortening [45]. This deformation was responsible for the termination of deposition in the SB during the Middle-Triassic time [12].

3. Field Characteristics, Petrography and Geochemistry

In terms of the depositional environments and stratigraphic evolution, the sedimentary succession has been described and interpreted, suggesting deposition within a fluvio-deltaic system [18,35–37,40–42]. Most of the deposits correspond to delta-plain depositional environment, followed by fluvial deposits. The studied tuffs occur in the deltaic system (Figure 3). Breckenridge et al. [18] documented an upward transition from delta-front to delta-plain and fluvial deposits that is accompanied by a coarsening-upward trend. This study also indicates that delta-plain distributary channels with lateral accretion elements are overlain by fluvial channels with downcurrent accretion elements. These characteristics, along with the absence of strata that document an increase in water depth, suggest progradation and aggradation of the deltaic system [18].

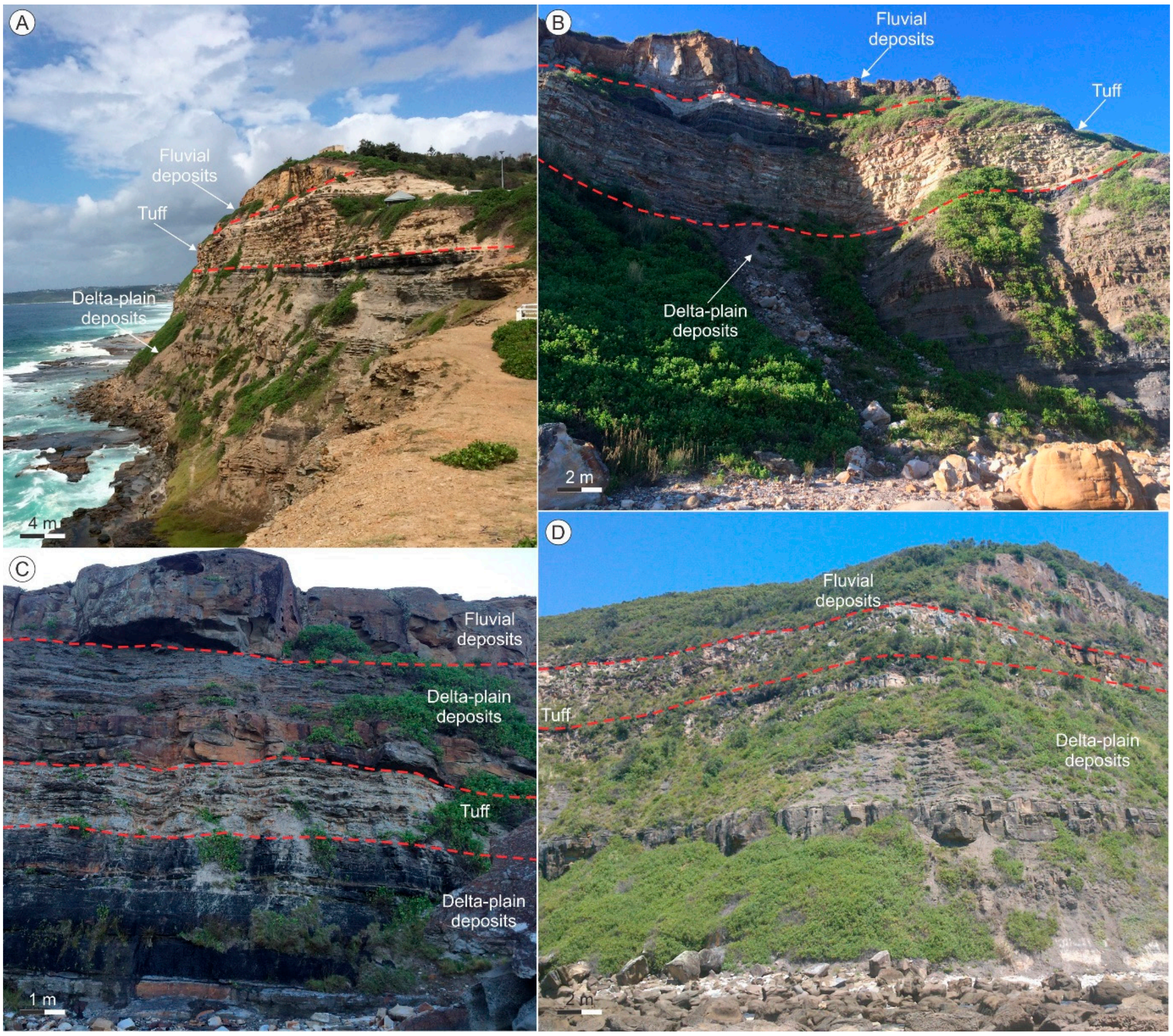

Figure 3. Outcrop photographs of the sedimentary succession in the NSB. Note the upwards shift in the environments of deposition, from deltaic to fluvial. (**A**) Bar Beach. (**B**) Merewether Beach. (**C**) Dudley North. (**D**) Dudley South. Note also the presence of thick and laterally continuous tuff deposits at the boundary between the underlying deltaic and the overlying fluvial deposits.

The petrographic and geochemical features of the tuffs have been documented by Kramer et al. [46]. Petrographic analysis suggests that they are composed of vitric, crystal, and lithic fragments, but the lithic component occurs in a small number of samples. The crystals are represented principally by quartz, plagioclase and biotite. K-feldspar is rare and Ti-rich biotite occurs in most of the samples. Opaque minerals are an uncommon phase and when present is represented by magnetite. Zircon and apatite are observed in the studied tuffs. Lithic fragments are represented by the recrystallised groundmass of dacitic rocks, with often plagioclase phenocrysts set in a fine-grained groundmass. The geochemical data revealed that the tuffs exhibit LREE-enrichment (La/Yb = 4.05 to 11.37), flat-HREE chondrite normalized patterns, high values of immobile elements (Hf, Th, Ta, Nb, and Zr) and depletion of Ti and P in the rock/primordial mantle patterns. These features suggest an origin from rhyodacitic to dacitic, continental arc, calc-alkaline magmas [46].

4. Materials and Methods

Five tuff samples were collected from the Upper Permian Newcastle Coal measures and analyzed for CA-IDTIMS dating. From north to south, the samples were collected from the Nobbys heads, Dudley north and Swansea heads and belong to the three sub-groups (Lambton, Adamstown, and

Boolaroo respectively, Figures 2 and 4). The sample locations were chosen because they coincide with tuff stratigraphic marker beds that have been identified (Nobbys, Unnamed, and Mt. Hutton Tuffs respectively) in the literature [12,15,16,46], as shown in Figure 2. The tuff samples were taken from the basal section of tuff beds to avoid the impact of the settling of zircons during deposition [47].

Zircons were separated using standard methods of crushing, magnetic separation and heavy liquid separation [48]. Zircons are then selected under microscopic conditions and then subject to chemical abrasion method described by [49]. Zircon samples were placed in a furnace at 900 °C for 48 hours in quartz beakers to anneal the zircon grains. Single zircon grains were transferred into 3 mL Teflon perfluoroalkoxy (PFA) beakers, washed with HNO_3 twice, and placed into 300 µL Teflon PFA microcapsules. Crystals were then leached in 29 M HF with trace amounts of HNO_3 for 15 hours at 190 °C within the microcapsules before being removed and returned to the Teflon PFA beakers. HF is then removed, with grains washed in ultra-pure H_2O and then immersion in HNO_3 whilst being ultrasonically cleaned for 1 hour followed by another hour of being heated at 80 °C on a hotplate. HNO_3 is removed and grains are rinsed in ultra-pure H_2O before being reloaded into the same Teflon PFA microcapsules (microcapsules were rinsed and fluxed with HCL) and spiked with the EARTHTIME [50,51] mixed ^{205}Pb-^{233}U-^{235}U tracer solution (ET535). Chemically abraded grains were then dissolved in Parr vessels in 120 µL of 29 M HF with trace amounts of HNO_3 at 220 °C for 48 hours before being dried in fluorides and then redissolved in 6 M HCL at 180 °C overnight. U and Pb were removed from the zircon matrix using an HCl-based anion-exchange chromatographic procedure [52], washed and dried with 2 µL diluted H_3PO_4.

Pb and U were placed on a single out gassed Re filament in 2 µL of a silica-gel/phosphoric acid mixture [53]. U and Pb isotope measurements were performed on an Isoprobe-T multi collector thermal ionization mass spectrometer (TIMS) equipped with an ion-counting Daly detector at the Australian National University, Canberra. U-Pb dates and uncertainties for each analysis were calculated using the algorithms of [54] and dates were corrected for initial ^{230}Th disequilibrium using a Th/U (magma) of 3 [55].

5. U-Pb Geochronology Results

Zircons from five tuff samples were collected from three locations (Nobbys Head, Dudley north and Swansea Heads) and were processed for CA-IDTIMS dating (Figure 4). The size of the zircons is usually ~150 µm (Figure 5) and the timing of the main volcanic events has been determined from the weighted mean dates (Supplementary Table S1). The Th/U ratios of the analysed zircons are high and are consistent with a magmatic origin [56].

The samples NBT-1 and NBT-2 were collected from the Nobbys Head (Figure 6), from the tuff known in the literature as the Nobbys tuff in the Lambton sub-group (Figure 4). The outcrop is characterized by the continuous accumulation of tuff deposits, with no intercalation of other deposits (coal and/or other siliciclastics). Both samples were collected from the same outcrop, with one sample being collected from the basal part (NBT-1) and one from a higher stratigraphic level (NBT-2). The sample NBT-1 recorded an age of crystallisation at 255.10 ± 0.11 Ma, based on 5 of 7 grains as youngest most coherent group (Figure 6). The two youngest grains were rejected because their obtained ages were not within most coherent group (possibly because of residual lead loss) and exhibited large error bars (Supplementary Table S1). The sample NBT-2 provides two possible interpretations: one younger age at 254.82 ± 0.05 Ma (based on 2 of 8 grains as youngest group), and another slightly older at 255.19 ± 0.15 Ma (based on 6 of 8 grains as second youngest group, Figure 6). One zircon was rejected because the age was not within most coherent group (Supplementary Table S1). It is suggested here that the older age at 255.19 ± 0.15 Ma is the most plausible age of crystallisation for the sample NBT-2. The reason is that it is based on a much larger number of zircons that belong to the same most coherent group and display small mean squared weighted deviation (MSWD = 0.3, Figure 6). This approach suggests that the ages of NBT-1 and NBT-2 are still within error of one another.

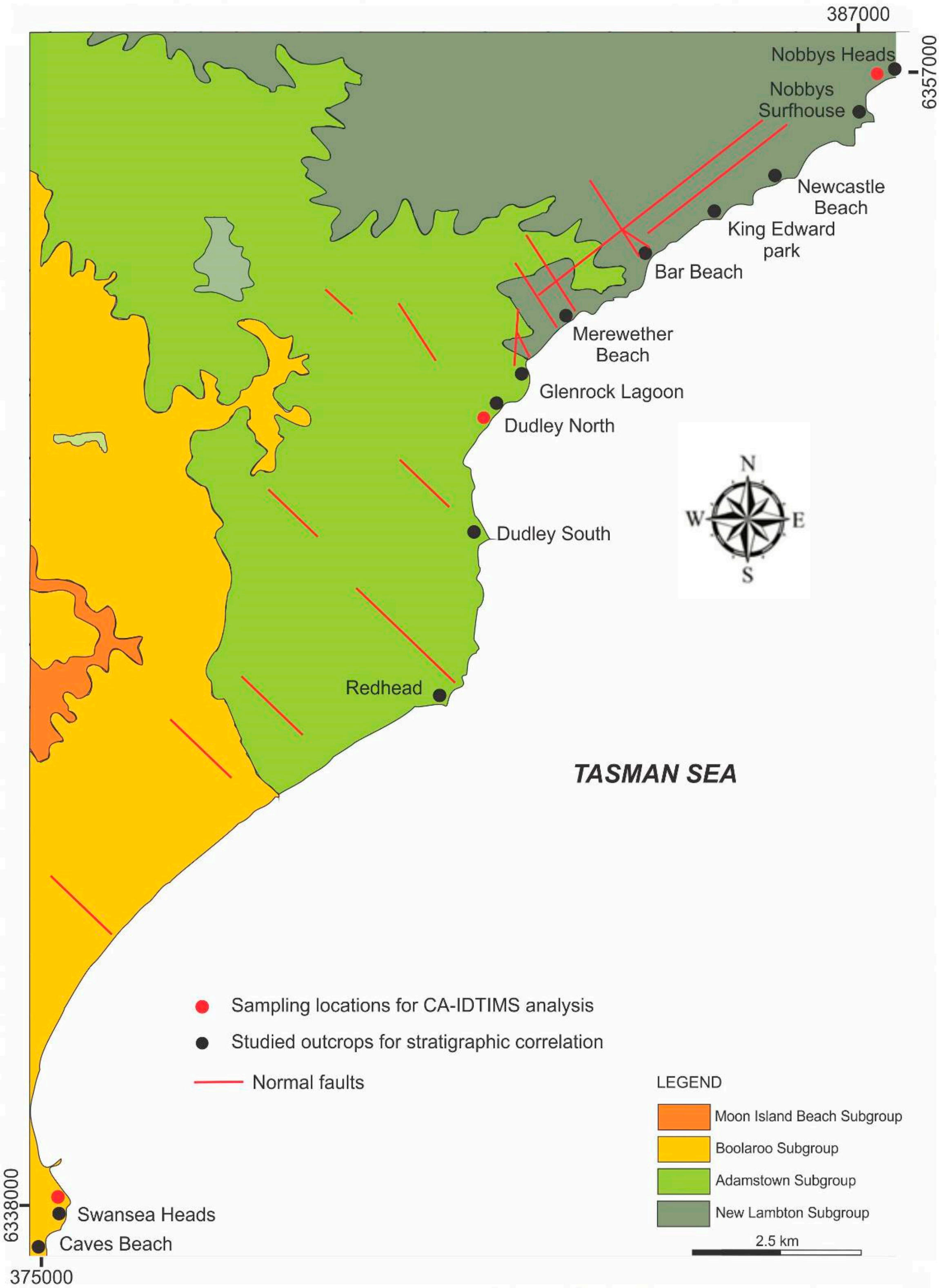

Figure 4. Map of the study region illustrating the lateral extension of the different sub-groups. Black dots refer to the selected locations for geochemical analysis, red dots to the locations for CA-IDTIMS analysis.

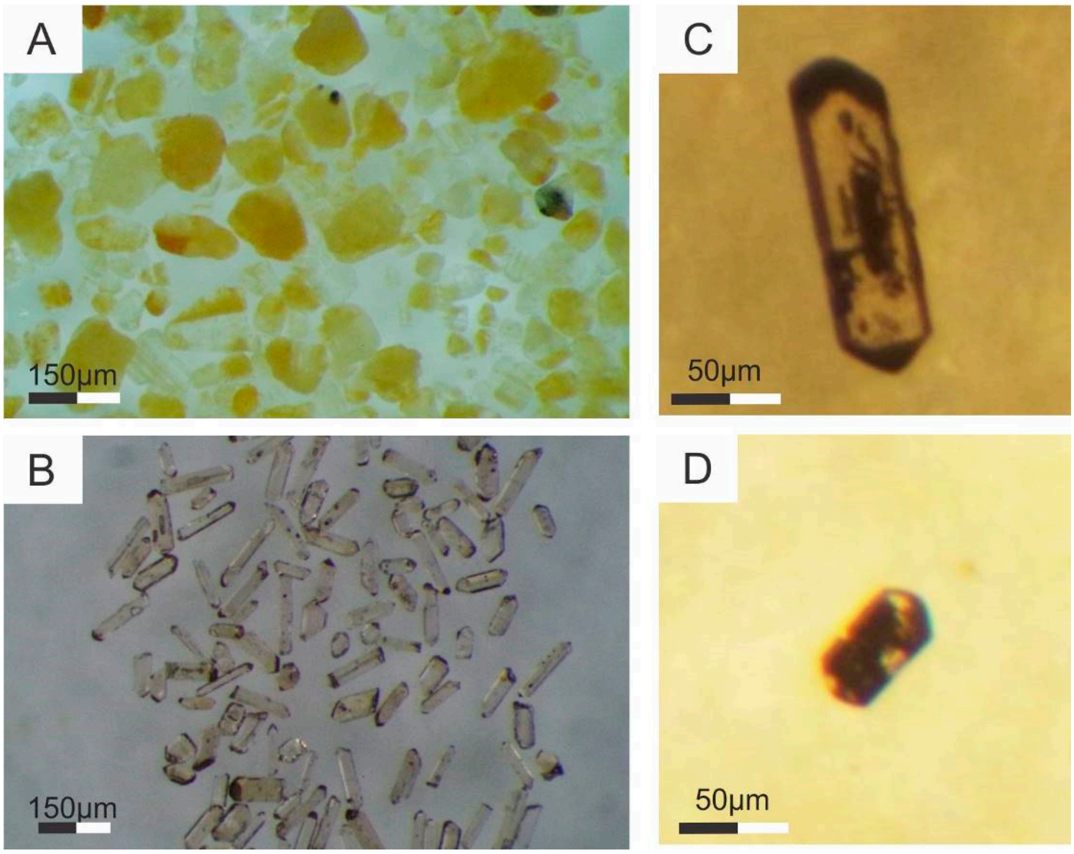

Figure 5. (**A**,**B**). Images of representative analysed zircons from the examined tuff samples. (**C**,**D**). Close up view of a long and a short prismatic zircon.

The samples DBN-1 and DBN-2 were collected from the Dudley north (Figure 4). They belong to the tuffs listed in the literature as the Nobbys tuff within the Lambton sub-group (DBN-1) and from the "Unidentified" tuff in the Adamstown sub-group (within the Kotara Formation, DBN-2). The tuff beds are 2–6 m thick and are separated by thick (3–5 m) coal deposits, known as the Nobbys Coal Seam (Figure 7). Both samples were collected from the same outcrop (Figure 4), with one sample being taken from the lower tuff bed (under coal seam, DBN-1) and the other from the stratigraphically higher tuff bed (over coal seam DBN-2). Therefore, DBN-1 should be older than DBN-2. DBN-1 records two ages of crystallisation: (1) one at 255.65 ± 0.16 Ma with the MSWD >1 (based on 7 of 10 grains, Figure 7), and (2) another at 255.59 ± 0.10 Ma with the MSWD = 0.22 (based on 5 of 10 grains, Figure 7). The reason for rejecting some of the zircon grains is that they obtained ages that were not within the youngest most coherent group. Both ages could explain the stratigraphic position of this sample (if they are older than DBN-2), but based on the level of coherency, the age at 255.59 ± 0.10 Ma is regarded here as the most suitable age of crystallisation for the sample DBN-1 (belongs to the youngest most coherent group and exhibits low MSWD). Based on 4 of 10 grains that belong to the youngest, most coherent group, the sample DBN-2 recorded an age of crystallisation at 255.08 ± 0.09 Ma (MSWD = 0.22, Figure 7). The reasons for rejecting the remaining zircon grains are: (1) the small Pb*/Pb_c ratio (the ratio was too small to be measured correctly), or (2) the obtained ages that were not within the youngest, most coherent group.

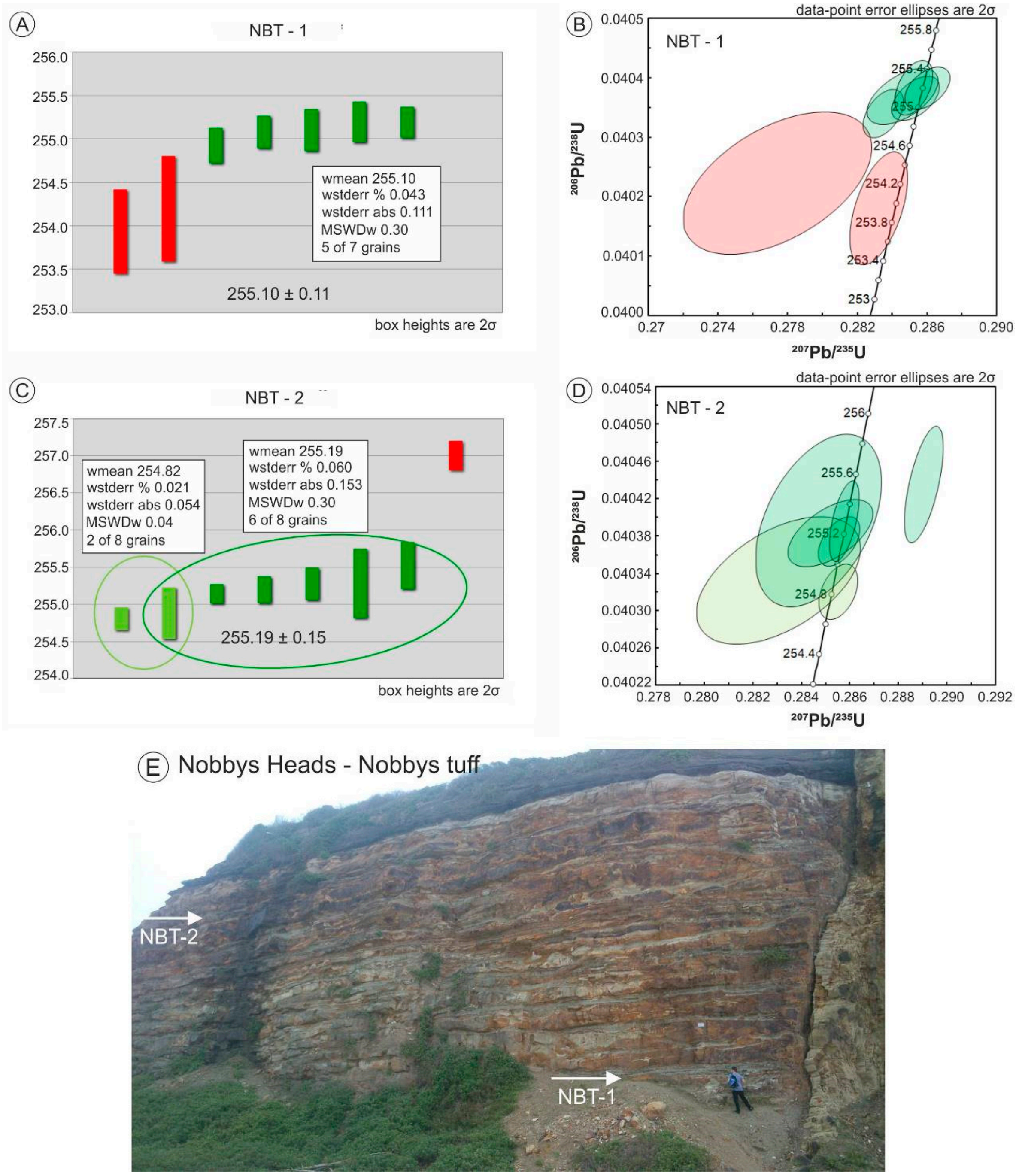

Figure 6. Weighted mean U-Pb CA-IDTIMS results of the selected samples in the study region (northern Sydney Basin). (**A**–**D**). Obtained zircon ages and Concordia plots of the tuff marker beds exposed at Nobbys heads. (**E**) Outcrop photograph of the studied location illustrating the stratigraphic position of the selected tuff samples. Person for scale is 180 cm tall. Plots illustrate individual zircons (green) used in weighted mean calculation and rejected zircon ages (red). Uncertainties are 2σ internal.

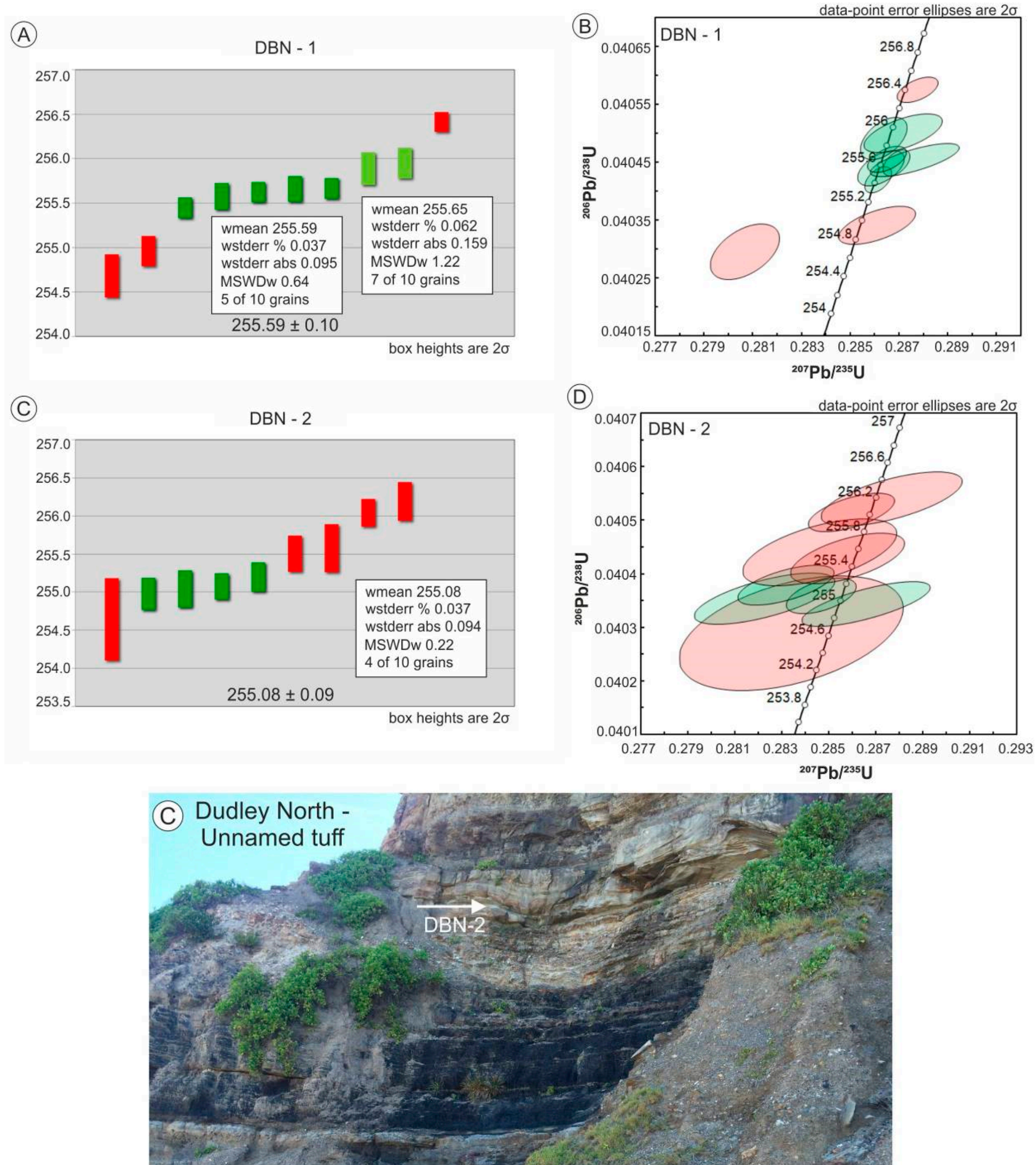

Figure 7. Weighted mean U-Pb CA-IDTIMS results of the selected samples in the study region (northern Sydney Basin). (**A**–**D**). Obtained zircon ages and Concordia plots of the tuff marker beds exposed at Dudley north. (**E**) Outcrop photograph of the studied location illustrating the stratigraphic position of the selected tuff samples. Plots illustrate individual zircons (green) used in weighted mean calculation and rejected zircon ages (red). Uncertainties are 2σ internal.

The sample from the Swansea heads (DMDCK II) is from the Mt. Hutton tuff in the Boolaroo sub-group (Figure 4). The sample was collected from the bottom of the tuff bed, above the coal seam known as the Lower Pilot Seam (Figure 8). The Sample DMDCK II records an age of crystallisation at 255.65 ± 0.08 Ma, based on 3 of 8 grains that are the youngest most coherent group (MSWD = 0.22, Figure 8). The remaining zircons were rejected because they revealed ages that were not within youngest most coherent group, most likely as the result of residual lead loss (Supplementary Table S1).

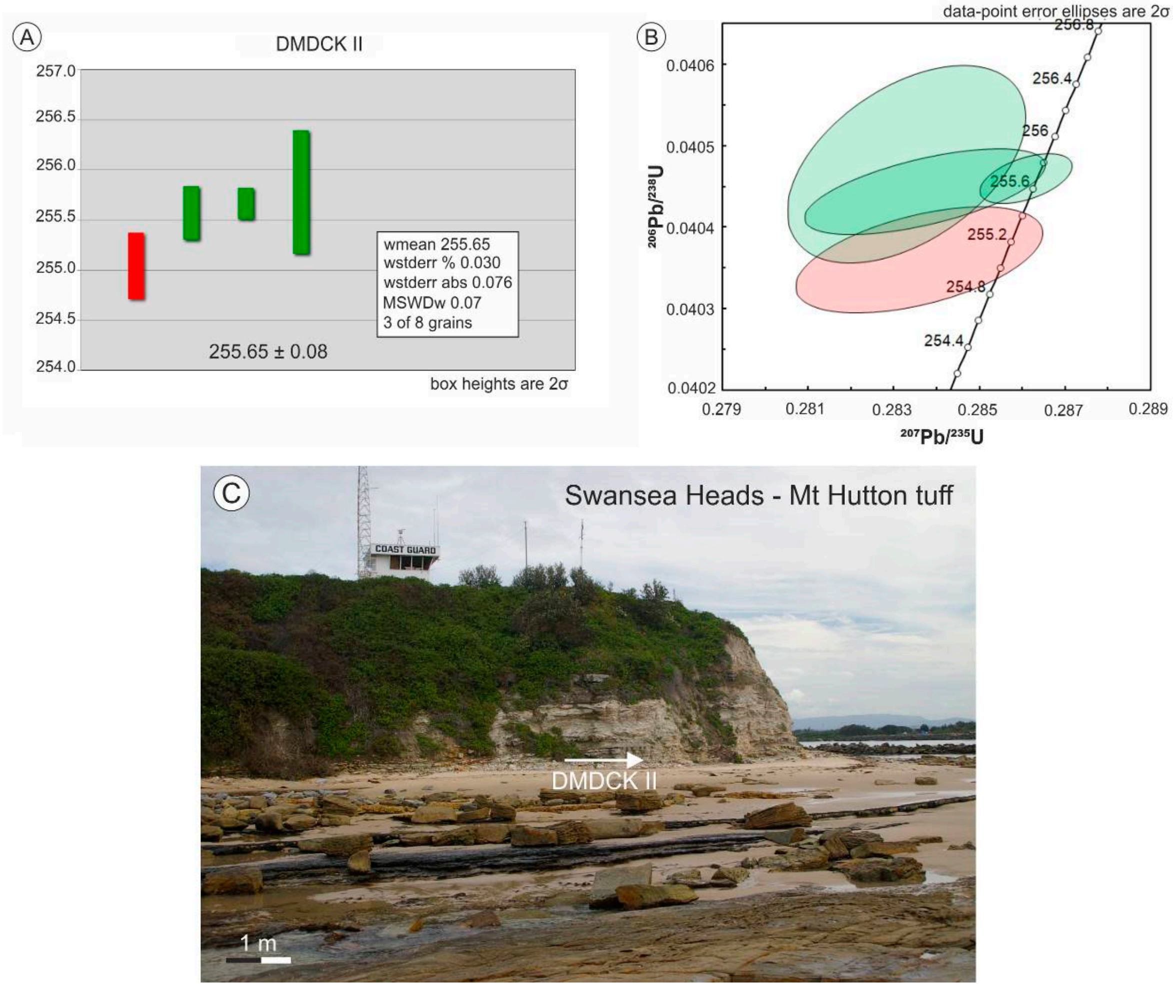

Figure 8. Weighted mean U-Pb CA-IDTIMS results of the selected samples in the study region (northern Sydney Basin). (**A**,**B**). Obtained zircon ages and Concordia plots of the tuff marker beds exposed at Swansea heads. (**C**) Outcrop photograph of the studied location illustrating the stratigraphic position of the selected tuff sample. Plots illustrate individual zircons (green) used in weighted mean calculation and rejected zircon ages (red). Uncertainties are 2σ internal.

The comparison of the obtained ages with the stratigraphic level of the studied tuff deposits is a valid method to estimate whether or not the volcanism is time equivalent to sedimentation of the surrounding sedimentary rocks [57]. The samples DBN-1 and DBN-2 have been collected from the same outcrop (Nobbys beach), similarly to samples DBN-1 and DBN-2 (Dudley north). At Nobbys beach, the ages are within error indicating deposition at similar stratigraphic levels and/or high sedimentation rates (compared to the precision of the analysis). Both parameters may be responsible for this trend at Nobbys beach because the samples are stratigraphically closely spaced and within a discrete thick tuff unit that can explain high sedimentation rates (Figure 6). At Dudley north, the ages become younger upwards, indicating that they are reliable and represent the depositional age of the sediments (sedimentation and volcanism are time-equivalent). The short time differences between the samples (<1 Myr) suggests deposition from a single eruption (Duddley) and eruptive episodes (Dudley north). The samples DBN-1 (Dudley north) and DMDCK II (Swansea heads) exhibit ages that are within statistical error. They are slightly older than the samples NBT-1, NBT-2 (Nobbys heads) and DBN-2 (Dudley north) that also exhibit ages that are within statistical error. The age data indicate the existence of one tuff unit and that the studied sections are time equivalent. Therefore, they can all be correlated because they contain deposits of the same age. The minor age variations between some of the studied tuff samples can be reasonably explained by the field characteristics of the tuff unit and exposed sedimentary record. In particular, the tuff unit is not entirely exposed in all outcrops and the exact stratigraphic position of the samples is slightly variable (sample collection from the base of the tuff unit was impossible at Nobbys beach). The samples (DBN-1 and DMDCK II) that were collected from lower stratigraphic levels (below the NBT-1, NBT-2, and DBN-2) yielded the older zircon ages.

6. Discussion

6.1. The Role of CA-IDTIMS Method in Stratigraphic Correlations

The contribution of CA-IDTIMS method to link the isotopic dates to the palynostratigraphic schemes in sedimentary successions has been recognized previously [1,4–6].

In eastern Australia, CA-IDTIMS data have been employed in order to evaluate the proposed palynostratigraphic schemes and add tighter constraints on the regional stratigraphy and basin analysis [6]. Specifically, high-precision U-Pb zircon dating of tuff beds documented discrepancies in intrabasinal correlations of the Permian successions of the Sydney, Bowen, Gunnedah, and Canning Basins, resulting in a revised calibration of the Permian palynostratigraphy in Australia [6]. The CA-IDTIMS data, combined with palynological evidence evaluated the correlation of the palynozones defined in eastern Australia to the global timescale. This integration of data overcame the degree of uncertainty that exhibit the previous palynostratigraphic zonations, which relied on the sparse presence of ammonoids and conodonts in Western Australia [21]. Further, the Carboniferous-Permian Lodève and Graissessac basins of southern France offer case studies to perform climate reconstructions using of CA-IDTIMS data [4]. New, high-precision U-Pb zircon data for tuffaceous beds in these basins led to a revised chronostratigraphic framework for the Permian basins of eastern Euramerica and a re-evaluation of climatic conditions across the Carboniferous-Permian boundary throughout Pangea. The Permian tuff beds in the periphery of the Okhotsk Massif, N-E Russia were selected for radioisotopic calibration of the Middle Permian sedimentary rocks in which they are bracketed [1]. The CA-IDTIMS results changed the duration of the Kungurian Stage from ~10 Myr to ~6.0–6.5 Myr. Further, this research suggests a possible correlation with alpine glacial events in the Eastern Australia, associated with the disappearance of ammonoids and conodonts in high-latitudes regions, as a consequence of dramatic decrease in the temperature. The data from the Okhotsk Massif add tighter constraints to the palynological zonation and link the biostratigraphic zonation of N-E Russia with the International Geologic Time Scale.

Even though many of the studies that employ CA-IDTIMS results are also well-constrained with regional lithostratigraphic and biostratigraphic frameworks, the implications of such absolute age data on potential challenging proposed frameworks of the same basin are not common. The present study employs CA-IDTIMS results to evaluate the different proposed correlation schemes for the Upper Permian deposits in the NSB. These schemes include: (1) deposition of numerous thick tuff marker beds that are younger from north to south. If correct, these beds occur in three distinguished sub-groups and have been mainly accumulated in a continental (fluvial) environment of deposition [12–14,17,58]. (2) Deposition of most of these tuff beds at the same stratigraphic level, in a single regressive fluvio-deltaic system. If correct, these beds are time-equivalent and laterally extensive from north to south. They occur within the deltaic setting and close to the fluvio-deltaic boundary, as proposed by Brekenridge et al. [18].

To gain a better understanding about the stratigraphic framework of the NSB, it is important to integrate field evidence with absolute age data. Even though such data are scarce, recently acquired U-Pb zircon results taken from other parts of the NSB that are not within the study area, revealed inconsistencies between the absolute ages and the existing lithostratigraphic correlations [59]. As a certain example, CA-IDTIMS data of tuff marker beds indicate that the Nobbys tuff in the Newcastle Coal Measures are of similar age with tuff beds that are considered to belong to older deposits [59]. These CA-IDTIMS data come from widely spaced exploration wells and lack of a tight stratigraphic framework. Therefore, the exact stratigraphic position of the analysed tuffs is uncertain [59]. Nevertheless, these discrepancies highlight that the presently used nomenclature and stratigraphy should be reconsidered, and this need is further supported by the new U-Pb zircon data presented here. According to the existing stratigraphic subdivisions, the tuffs that analysed in this study should become younger to the south because they are reported to occur in successively younger subgroups of the Newcastle coal measures [12–14,17,58]. However, the results indicate that the tuff marker beds (Nobbys, Unnamed and Mt. Hutton Tuffs) are time-equivalent and agree with the proposed sequence-stratigraphic model of [18]. The results indicate one short magmatic period during the accumulation of the sediments, with episodic events spanning at least from 255.65 ± 0.08 to 255.08 ± 0.09 Ma (Figures 6–8). The reported differences between the obtained absolute ages and the presently used lithostratigraphic framework suggest that the current lithostratigraphy within the NSB should be revised.

6.2. Proposed Revision of the Upper Permian NSB Stratigraphy

The review and revision of the presently used lithostratigraphic nomenclature and sedimentary units of the Upper Permian deposits of the NSB is necessary scientifically because field data, along with CA-IDTIMS results, indicate significant ambiguities between the zircon ages and the existing stratigraphic framework. In the currently defined litho-stratigraphic scheme the three sub-groups that make up the studied succession are further divided in several individual units. These units are chiefly lithologically based (sandy and conglomeratic units, coal seams, and tuff beds), and are not defined based on robust facies analysis and interpretations about the depositional environments. This approach leads to a large number of sub-divisions, making the current models confusing (Figure 2). The U-Pb results agree with the sequence-stratigraphic model of Breckenridge et al. [18], which analysed and interpreted the sedimentary facies, re-interpreting key diagnostic surfaces and defining sequence stratigraphic boundaries (Figure 9). In contrast to the current model, Breckenridge et al. [18] suggest that the tuff beds have been deposited largely contemporaneously, and the actual stratigraphic record is much thinner, implying stratigraphic repetition in the existing correlation scheme.

This study presents a proposed revision of the Upper Permian deposits of the NSB that shifts away from previous published models, amalgamating the total number of sub-groups and various lithostratigraphic units within the Newcastle coal measures. The new model is based on the absolute ages and stratigraphic evolution of the different depositional environments. The sequence stratigraphic and geochronological data suggest that the Lambton, Adamstown and Boolaroo sub-groups could be merged into Lambton sub-group. The reason for this is that these sub-groups represent the lateral evolution of the same depositional system that was accumulated at the same time and outcrops across the study region (Figure 9). It is also proposed that the lithostratigraphic units that belong to Adamstown and Boolaroo sub-groups could be abandoned, whereas those of the Lambton sub-group could remain constant and representative of the Newcastle coal measures in the NSB (Figure 10). The new proposed stratigraphic framework suggests that the Lambton sub-group includes all the thick coal deposits that are well-established in the literature (Borehole, Yard, Young Wallsend, Nobbys, and Victoria Tunnel coals). These deposits are interbedded with conglomeratic and sandy sedimentary rocks and are accumulated in a delta-plain environment of deposition [18] Figure 10. The boundary between the Lambton and the overlying Moon Island Beach sub-groups is suggested to be placed at the top of the Victoria Tunnel coal, at the boundary between delta-plain deposits (Lambton sub-group) and fluvial (lower part of Moon Island Beach sub-group) sedimentary rocks (Figures 9 and 10).

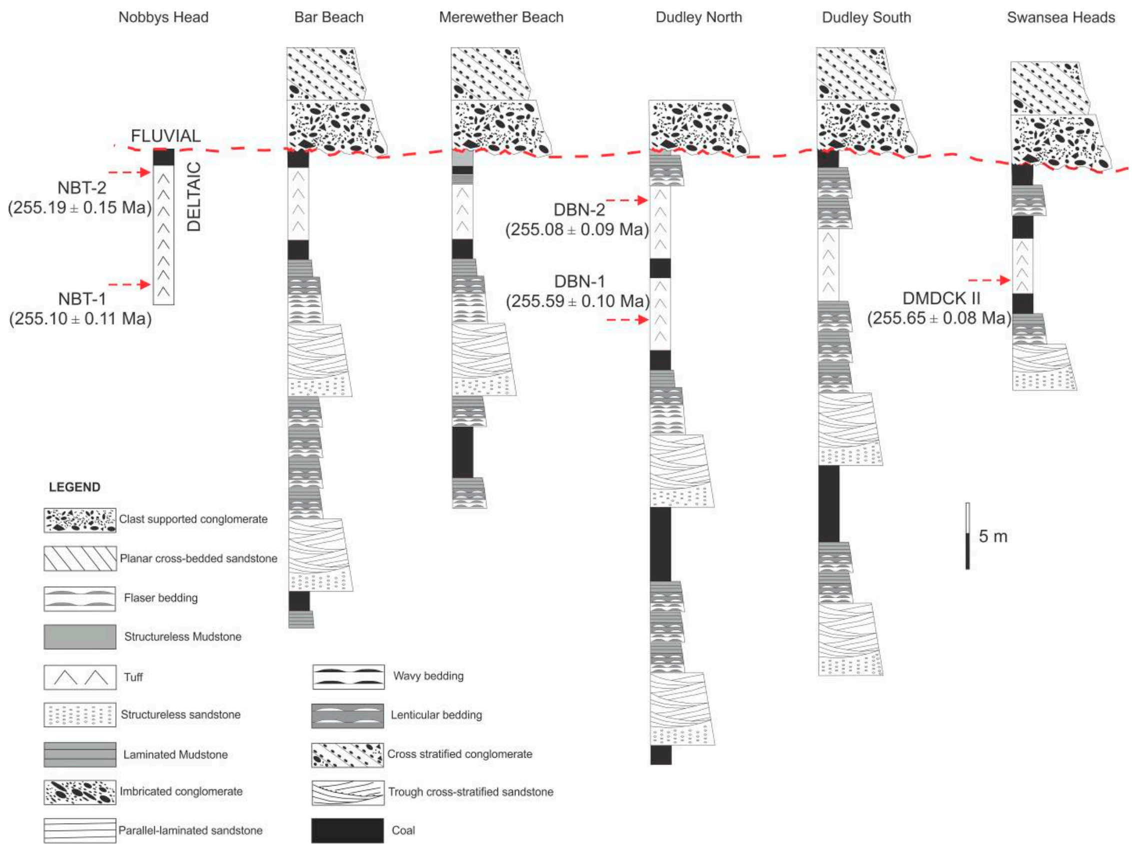

Figure 9. Synthetic stratigraphic cross section of the studied region that presents the spatial and temporal evolution of different depositional environments [18]. The construction of the cross section is based on stratigraphic and geochronological (CA-IDTIMS) evidence. Note the shoaling-upward trend as documented by the transition of tidally influenced delta-plain sediments to fluvial deposits. Red lines indicate interpreted boundaries between depositional settings.

This review and revision are also important economically because the NSB has been exploited for high quality and quantity of coal resources [60]. The basin also exhibits high exploitation potential for coal seam gas and hydrocarbons [61–63]. The two scenarios have also applications to exploration geology because applying the suitable stratigraphic scenario is vital to minimize the risk of subsurface exploration and development activities and avoid potentially wasted exploration expenses. Both of them are tied to the better prediction of coal and coal seam gas, however the current scenario suggests a much larger number of coal seams that the model presented in this study (Figure 10). This difference is important and should be taken into serious consideration when prospecting for coal reserves in NSB because specific prospecting activities (e.g., seismic surveys, land acquisition and/or drilling) would be expensive. The model presented here provides a better constrained stratigraphic framework, elaborating CA-IDTIMS and stratigraphic results that could be useful for the industry to draw different exploration strategies.

The revised model condenses the current stratigraphy in two sub-groups: the Lambton sub-group that holds the deltaic setting and the Moon Island Beach sub-group that represents (at least at its basal part) the fluvial portion of the succession. Further investigation is required to precisely determine the depositional environments that make up the remaining part of the Moon Island Beach sub-group.

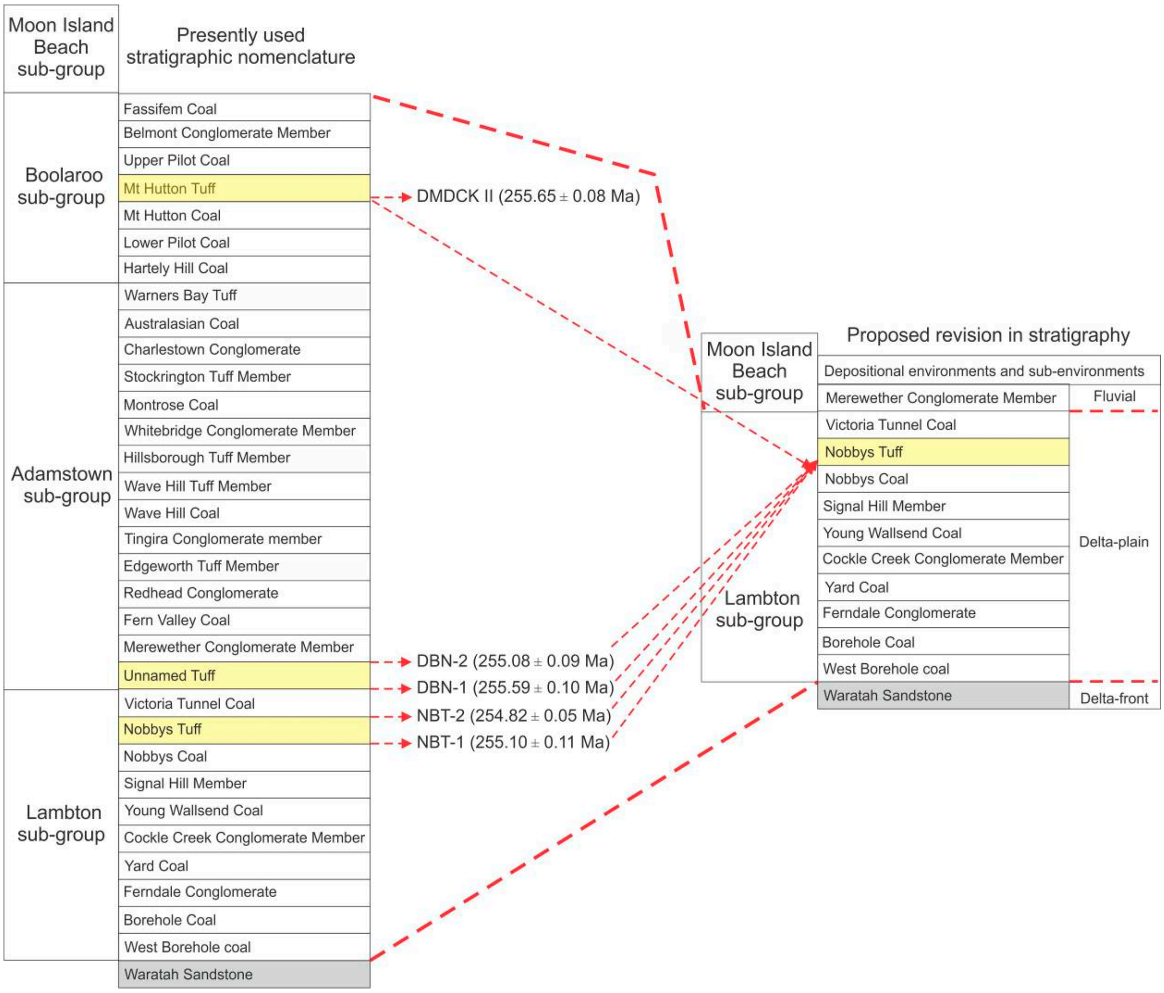

Figure 10. Comparable diagrams illustrating the differences between the current and the proposed revision of the stratigraphic framework in the NSB. Results from CA-IDTIMS dating and information about the depositional environments are included. The revised model amalgamates the regional stratigraphy and proposes the existence of two sub-groups: the Lambton sub-group that is represented by the deltaic setting, and the Moon Island Beach sub-group that includes (at least at its basal part) the fluvial portion of the succession. Further research is needed to accurately define the depositional settings that make up the remaining part of the Moon Island Beach sub-group.

7. Conclusions

The well-exposed Upper Permian sedimentary rocks of the NSB offer a case study to better understand the paleoenvironmental development of the basin through geochronological studies, integrated with a robust stratigraphic framework. New CA-IDTIMS data of zircons sourced from tuffaceous strata from important tuff marker beds provided precise radio-isotopic ages, allowing for valuable interpretations about the timing relationships and intrabasinal correlations within the NSB (Newcastle coal Measures).

The zircon results indicate that the studied sedimentary rocks are of the same age, in contrast to previous considerations that supported a southwards younging of the deposits and several repetitions of coastal plain and fluvial sediments along the study region. These zircon results agree with recent sequence-stratigraphic analysis that proposes simultaneous deposition of sediments in a large fluvio-deltaic depositional environment exposed along the study area. Thus, it is proposed a new stratigraphic correlation scheme that is based on both depositional and geochronological consistency. This scheme amalgamates the regional stratigraphy and proposes that the Newcastle Coal Measures could be better considered to belong to two sub-groups: the Lambton (delta-plain deposits) and the overlaying Moon Island Beach (fluvial deposits) sub-groups. This scheme could have major implications for the industry and triggers updated exploration strategies. This case study also indicates that the integration of CA-IDTIMS results with comprehensive stratigraphic data can shed light on stratigraphic uncertainties that commonly occur in sedimentary basins.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/10/11/474/s1, Table S1: CA-IDTIMS results, selected zircons and U-Th-Pb isotopic data of the studied samples.

Author Contributions: The original draft was written by A.G.M. and J.B. and then modified after discussions with W.J.C. and K.R. The figures have been compiled and drafted by A.G.M. and J.B. Resources and funding were provided by K.R. and E.H. Data analysis was performed by Y.A. All authors have read and agreed to the published version of the manuscript

Funding: This research was funded by Geological Survey of New South Wales (GSNSW), through the research project Stratigraphic Correlation: Nobbys Tuff-Althorpe Claystone.

Acknowledgments: This research was sponsored by the Geological Survey of New South Wales (GSNSW), through the research project Stratigraphic Correlation: Nobbys Tuff-Althorpe Claystone. The authors wish to acknowledge the journal editor and two anonymous reviewers for their constructive reviews that improved quality of the manuscript. Bill Landenberger is thanked for constructive and valuable discussions about the basin-fill conditions in the northern Sydney Basin.

Conflicts of Interest: The authors declare no conflict of interest.

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