Advancing tephrochronology as a global dating tool:
applications in volcanology, archaeology, and palaeoclimatology

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Abstract

Layers of far-travelled volcanic ash (tephra) from explosive volcanic eruptions provide stratigraphic and numerical dating horizons in sedimentary and volcanic sequences. Such tephra layers may be dispersed over tens to thousands of kilometres from source, reaching far beyond individual volcanic regions. Tephrochronology is consequently a truly global dating tool, with applications increasingly widespread across a range of Quaternary and geoscience disciplines. This special issue of the International Focus Group on Tephrochronology and Volcanism (INTAV) showcases some of the many recent advances in tephrochronology, from methodological developments to diverse applications across volcanological, archaeological, and palaeoclimatological research.

Tephrochronology as a global dating tool

The main value of tephra layers as geochronological units lies in their capacity to act both as dated age markers (tephrochronology) and event-stratigraphic horizons (tephrostratigraphy) for the correlation of widespread sedimentary or volcanic archives. Furthermore, provided that the geochemical and taphonomical integrity of a tephra layer can be demonstrated, there is no maximum age limit to tephrochronology. Few other dating methods are so versatile or robust.

The basis of tephrochronology is the identification of an individual tephra layer and its reliable correlation between deposits found in proximal settings and/or distal sedimentary archives. Ideally, but not always (see Lane et al., 2012), a tephra layer is correlated to a dated individual eruption event. Identification relies upon a combination of physical, mineralogical, or geochemical properties, derived from field and/or laboratory observations or measurements, together with observed stratigraphic and age relationships (e.g. Lowe, 2011; Lowe and Alloway, 2015). Chemical analyses of individual glass shards are especially important for the characterisation of both tephra layers and cryptotephra deposits, especially at distal locations where no other phases (such as minerals) are normally available. The ideal of a unique chemical “fingerprint” for every eruptive has been shown in some cases not to hold (e.g. Lane et al., 2012; Lind et al., 2016). However, this may not prove to be a major limitation where the general chronostratigraphic framework of the tephra is known and can be used to add further constraints on correlation (e.g. Lane et al., 2012). There has recently been a range of new developments in tephra characterisation techniques, such as glass and mineral characterisation methods (e.g. Matsu’ura et al., 2011; Hall and Hayward, 2014; Marcaida et al., 2014; Pearce, 2014; Pearce et al., 2014a; D’Antonio et al., 2016), improved multi-element datasets (e.g. Tomlinson et al., 2015), statistical methods for distinguishing multivariate datasets (e.g. Pouget et al., 2014; Blegen et al., 2015; Bronk Ramsey et al., 2015; Petrelli et al., *this issue*), new methods for visual assessment of tephra depositional processes and taphonomy (e.g. Griggs et al., 2014, 2015; Hopkins et al., 2015; Zawalna-Geer et al., 2016), and means to extract maximum information from even the finest cryptotephra deposits (e.g. Blockley et al., 2005; Lane et al., 2014; Iverson et al., *this issue*). These advances now mean that many of the most widespread and/or well-studied tephra or cryptotephra deposits can now be confidently identified and utilised as stratigraphic, and potentially chronological, horizons.

Tephra layers predating historic records may be directly dated by a number of means. In many cases dating is carried out on the mineral or glass components of a deposit, including application of the isothermal-plateau fission-track (ITPFT) dating technique to some of the furthest travelled glass-rich tephra layers (Westgate et al., 2013; Lowe and Alloway, 2015). The most widely applied methods that utilise mineral (crystal) phases include K-Ar and Ar-Ar dating, which typically are undertaken on potassic feldspars, biotite, and hornblende (Deino, 2012; Morgan et al., 2017). However, U-series methods, including (U/Th)/He, ^{238}U/^{230}Th, and U/Pb for dating primary zircon crystals (Danišík et al., 2012, *this issue*; Howe et al., 2015; Ito et al., *this issue*), are growing in use.

Indirect dating of tephra layers, via dating of their host sediments, often enables age-estimates for those layers that do not preserve sufficient or appropriate datable minerals or glass to be obtained (Lowe and Alloway, 2015). Such dating includes most commonly radiocarbon dating of organic materials, together with luminescence dating or palaeomagnetic correlations of inorganic units. Extremely precise ages can also be established in varved sediments or annual layers of ice (e.g. Abbott and Davies, 2012; Staff et al., 2013; Lane et al., 2015), as well as by dendrochronology when material is buried by tephra falls or flows (e.g. Hogg et al., 2012; Friedrich et al., 2014). Any age estimate for a tephra can in turn be transferred to all sequences that contain the same horizon – the raison d'être of tephrochronology (*sensu stricto*). Both traditional and Bayesian age-modelling tools now place tephra connections as a key means to enhance regional palaeoenvironmental, volcanological, and archaeological chronologies by combining age-information across far-reaching tephrostratigraphic frameworks or "lattices" (e.g. Blockley et al., 2008; Smith et al., 2013; Bronk Ramsey et al., 2015; Lowe et al., 2015; Schmid et al., *this issue*).

Extensive reviews of the theory and applications of tephrochronology and tephrostratigraphy have been published in the last years, which record and reflect the huge growth in tephra research over the past few decades (e.g. Lowe, 2011; Lowe et al., 2015) (Fig. 1A). The breadth of applications, both across disciplines and geographical regions, has been markedly increased since the development of methods for detecting and analysing cryptotephra (e.g. Turney et al., 1997; Blockley et al., 2005) (Fig. 1B). Derived from the Greek word *kryptein*, meaning 'to hide', cryptotephra deposits usually comprise fine-ash-sized glass shards preserved in sedimentary sequences (including ice), or in soils/paleosols, that are insufficiently concentrated to be visible as a layer to the naked eye (Lowe and Hunt, 2001; Davies, 2015; Ponomareva et al., 2015). In some cases, cryptotephra are manifested as crystal (mineral) concentrations rather than, or in addition to, sparse glass shard concentrations (e.g. Hogg and McCraw, 1983; Lowe, 2011; Matsu'ura et al., 2011, 2012, 2014).

Although the key role of visible tephra layers in constructing chronostratigraphic frameworks for palaeoenvironmental successions is well established globally (e.g. Blockley et al. 2012; Davies et al., 2012; Lowe et al., 2013; Moriwaki et al., 2016), cryptotephra studies have - greatly extended the use of tephrochronology in building age models for palaeoenvironmental sequences in Europe and the North Atlantic regions, where they are identified as a critical tool in the correlation of ice core, marine, and terrestrial archives by the INTIMATE network (INTegration of Ice core, MArine and TErrestrial records, http://intimate.nbi.ku.dk/; Blockley et al., 2014; Davies et al., 2014; Lowe et al., 2015). Cryptotephra research is now being carried out across all continents (Fig. 2), and indeed oceans, as exemplified by some of the papers in this volume (e.g. Martin-Jones et al., *this issue*; Matsu'ura et al., *this issue;* Smith et al., *this issue*; Sun et al., *this issue*). One very significant finding resulting from the rise in cryptotephra research is the tracing of tephra deposits that have been dispersed across continental distances (Fig. 2). These occurrences vastly extend the use of these deposits as tephrostratigraphic marker layers, because important palaeoclimatic archives can be aligned with certainty at the time of tephra deposition (e.g. Lane et al., 2013; Jensen et al., 2014; Pyne-O'Donnell et al., 2016; van der Bilt et al., *in press*). It has now been shown that glass shards chemically correlated with known (well-characterised) tephra layers from Japan, North America, and Iceland can all be found in the Greenland ice-core records (Bourne et al., 2016). In Antarctic ice cores, tephra layers have been found mainly from eruptions of Antarctic volcanoes, although some glass shards have been tentatively correlated to volcanoes in South America and the South Atlantic (Kurbatov et al., 2006; Narcisi et al., 2010, 2012). The degree of connectivity starting to be observed in the North Hemisphere (Fig. 2), where cryptotephra research is commonplace, will inevitably increase, and with further studies, tropical and Southern Hemisphere records will surely also begin to join up. The potential for a unified global tephrostratigraphy, however, is likely still a long way off, as there remain many areas, even in proximal volcanic zones, where detailed tephrostratigraphies for the recent past are still in early development or refinement (e.g. Fontijn et al., 2014; Watson et al., 2015; Damaschke et al., 2017; Johannsson et al., *this issue*).

Distal tephra applications now extend additionally into archaeology (Riede and Thastrup, 2013; Lane et al., 2014; Alloway et al., 2017; Schmid et al., *this issue*), volcanology (Shane et al., 2013; Rawson et al., 2016, Smith et al., 2016), and geohazard research (Swindles et al., 2011; Magill et al., 2015; Bourne et al., 2016), where detailed eruption histories are filling the gaps in our knowledge of the frequencies and controls on Quaternary volcanism in less-studied areas (e.g. Martin-Jones et al., *this issue*). Studies bringing together proximal and distal (often crypto-) tephra datasets to increase our breadth of understanding and generate robust datasets for correlation, are essential to the advance of tephrochronology as a global dating tool. We believe that the diversity of papers in this issue is a good reflection of the work ongoing towards this goal by members of the INTAV community.

Research goals of the International Focus Group on Tephrochronology and Volcanism

This special issue, in part, is derived from work supported and promoted by The International Focus Group on Tephrochronology and Volcanism (INTAV). The important and far-reaching role of tephrochronology as a Quaternary correlational and dating method is recognised by the Stratigraphy and Chronology Commission (SACCOM) of the International Union for Quaternary Research (INQUA), which has supported INTAV as an International Focus Group since 2007. During the last 10 years, INTAV has provided a format for collaboration and open discussion between tephrochronologists from around the world, who undertake research across a wide range of disciplines including volcanology, archaeology, palaeoclimatology, and geohazard studies (e.g. Swindles et al., 2011; Biass et al., 2014). INTAV has led numerous tephra conferences between the 4-yearly INQUA congresses, often followed by the publication of tephro-centric proceedings (e.g. Froese et al., 2008; Lowe et al., 2011a). INTAV members have also undertaken specific projects, such as developing inter-laboratory standardisation guidelines (e.g. Kuehn et al., 2011). Consequently, tephrochronology (*sensu lato*) is one of the clearest examples of inter-environmental and inter-discipline working that exists today in the Quaternary and geoscience communities.

Tephra-related focus groups have in fact existed within INQUA since 1961 under various names including the Commission on Tephrochronology (COT) and Subcommission on Tephrochronology and Volcanism (SCOTAV), as summarised in Suzuki et al. (2011). In a community effort to keep on "*Advancing Tephrochronology"* into the future, INTAV members collaborate within core projects supported by the INQUA commissions as well as those supported by sister organisations including Past Global Changes (PAGES) and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI). A long-term aim is the enhancement of tephrochronology as a global research tool and its application in multiple Quaternary disciplines including geochronology and volcanology. At the same time, INTAV proposes to maintain and extend the capability of the discipline and to promote its value to the wider community, both scientific and general. These aims have been encapsulated by two overarching projects led by INTAV, including the now-completed INTREPID project "Enhancing tephrochronology as a global research tool through improved fingerprinting and correlation techniques and uncertainty modelling" (Lowe et al., 2011b; Lowe, 2015) and, since 2015, the EXTRAS project: "EXTending tephRAS as a global geoscientific research tool stratigraphically, spatially, analytically, and temporally within the Quaternary". EXTRAS is being targeted through seven core objectives (see http://www.comp.tmu.ac.jp/tephra/intavtmu/link.html).

With sadness we record that there have been special colleagues and friends lost to the community over the last few years. At INQUA in Nagoya we marked the passing of Dr Stephen Stokes (1964-2014, formerly University of Oxford) and Dr Solène Pouget (1987-2015, University of Buffalo), and most recently (July 2016) we heard of the sad loss of Professor Valerie Hall (1946-2016, Queens University Belfast). Valerie was an inspiring friend, colleague, and mentor to many tephra researchers during her career. Valerie's contributions to the discipline, and those of Stephen and Solène, will not be forgotten, and we are pleased to include an obituary for Valerie in the opening pages of this special issue (Plunkett et al., *this issue*).

Themes in this issue

Eleven new research articles report on progress made across the tephrochronological community as part of the EXTRAS project. The issue follows on from two excellent conference sessions held in Nagoya at the nineteenth INQUA Congress, in the boreal summer of 2015:

Session SO4: "Tephras and cryptotephras and their use in studies of natural hazards and archaeology", convened by Takehiko Suzuki and Christine Lane; and

Session SO5: "Studies on tephras and cryptotephras and their use as isochrons in palaeoenvironmental and palaeoclimatic reconstructions", convened by David Lowe and Victoria Smith.

In total, close to 50 papers were presented in these sessions and a number of them led directly to contributions in this special issue. In line with the objectives of the EXTRAS project, the papers address a range of topics, covering methodological developments to novel applications, across the disciplines of palaeoclimatology, archaeology, and volcanology. Reflecting the significant growth of distal-tephra and cryptotephra research, in particular within palaeoclimatological studies, we include six papers that demonstrate progress at the far frontiers of this area of the discipline. We have arranged the volume into two themes reflecting advances in methodologies and in building regional tephrostratigraphic frameworks that help to facilitate or enhance volcanological, palaeoclimatological, archaeological research.

Theme 1. Advancing methodologies

Our first two papers deal with advances in methods for the direct dating of tephra samples, a topic critical not only for the reconstruction of volcanic eruption histories and to underpin estimations of volcanic hazard, but also to provide well-dated isochrons essential for the application of tephrochronology (*sensu stricto*). Ito et al. (*this issue*) demonstrate the application of laser-ablation, inductively-coupled plasma mass spectrometry (LA-ICP-MS) for conducting *in situ* zircon U-Pb dating. Their findings highlight some of the inherent challenges of this method, whilst providing precise age estimates for key Early to Middle Pleistocene tephra isochrons found across the Boso Peninsula in Japan. Danišík et al. (*this issue*) also address the challenges of U/Pb and (U-Th)/He dating of zircons in tephra, reviewing the progress made using combined U-Th-disequilibrium/U-Pb and (U-Th)/He approaches in dating zircons as young as 2.5 ka and as old as 1.5 Ma. The demonstrated advances in "zircon disequilibrium dating" place the method alongside other more established techniques, such as K-Ar, Ar-Ar and fission track dating, as a key tool for the direct dating of volcanic and pyroclastic deposits.

Large compositional datasets are central to tephrochronology, with geochemical correlations between proximal and distal tephra layers based upon single-grain major through to trace element analyses of glass and/or mineral phases (Lowe, 2011; Tomlinson et al., 2015). One significant area of debate in recent years has been the most appropriate methods for analyses of geochemical data for correlation purposes. Many researchers generally use combinations of binary scatter plots and spider diagrams to discriminate between data or propose correlations. Others have developed further statistical approaches, such as simple correlation coefficients or multivariate methods using discriminant function analysis, principal component analyses, and kernel density estimates (Begét et al., 1991; Pollard et al., 2006; Pouget et al., 2014; Ramsey et al., 2015). Petrelli et al. (*this issue*) explore a novel machine-learning approach for statistical discrimination between Pleistocene Italian tephra. Machine learning is a term derived from the computing literature that refers to statistical methods such as cluster analysis or discriminant analysis. It has been used quite extensively in the geosciences and wider literature for classifying and correlating compositional data and this paper attempts to develop the technique for the purposes of distal tephra correlations. Interestingly, the authors are able to provide new insights into the tephra record of the early Pleistocene Caio section in central Italy, as well as exploring several issues discussed in recent reviews of statistical analyses of tephra, such as the unit sum problem, as discussed by Aitchison (1992) and Pollard et al. (2006). Petrelli et al. provide links to the relevant PYTHON codes to allow other uses to test this developing tool against a range of data sets. This approach may have the potential to become a key tool for future analyses of tephra correlations.

One of the greatest challenges in cryptotephra research is achieving robust compositional characterisation of the most distal cryptotephra deposits, which are typically represented by low concentrations of fine-grained glass shards. Working with invaluable cryptotephra deposits in Antarctic ice cores, Iverson et al. (*this issue*) explore a set of methods for the isolation, preparation, SEM imaging, and geochemical analysis of the often tiny, and frequently scarce, glass shards. They demonstrate that there is value gained from using SEM on un-polished shards < 10 µm in diameter, to measure accurate, albeit less precise, compositions when WDS-EPMA is no longer achievable. The approaches they outline to mount glass shards using computer hard-disk platters follows on from earlier work by Kuehn and Froese (2010). However, they additionally present a flexible work-flow that is adaptable to both visible and cryptotephra samples and should be of benefit to cryptotephra research within a range of sedimentary environments, not just in ice.

Theme 2. Enhancing regional tephrostratigraphies

An important part of tephra research is the continuing improvement of regional tephrostratigraphic frameworks, which are critical datasets (shared by via publication or within databases) for dating and correlating tephra layers across a range of studies. Such improvements may be made via the addition of new sites with detailed tephra records, by exploration of tephra compositions, through new discoveries of tephra in less-explored regions or through the compilation and application of a tephrostratigraphic framework relevant to a particular research question. The papers within this section cover all of these aspects and highlight some of the most recent and exciting advances in regional tephrostratigraphies. For example, a new dataset of more than 250 Icelandic Viking-age archaeological sites containing tephra layers has been compiled and analysed by Schmid et al. (*this issue*). Sediment accumulation rates, established from ice-core, lacustrine, and aeolian records, together with written records, are used to constrain the ages of 18 key tephra horizons found across Iceland, and beyond. Central to this chronostratigraphy is the first century AD Landnám tephra layer, which is used to define periods of colonisation in Iceland, anchoring the archaeological record within a secure tephrochronological framework.

Timms et al. (*this issue*) present a Lateglacial to Early Holocene tephrostratigraphic record for Quoyloo Meadow in Orkney, demonstrating the value of the cryptotephra approach to dating terrestrial archives far from volcanic regions. Centred in the North Atlantic region, where systematic cryptotephra research, as we now know it, was pioneered (Dugmore, 1989; Turney et al., 1997; Turney, 1998), the authors are able to build a chronology for their record using precisely-dated Icelandic cryptotephra isochrons, then, in turn, improve the age-estimates for less well-studied tephra deposits. Their careful methodology revealed a number of previously un-reported cryptotephra deposits. It is clear that even in regions with established tephrostratigraphic frameworks (Fig. 2; Blockley et al., 2014), detailed cryptotephra studies continue to add to the eruption record and provide new isochrons for the correlation of palaeoclimatological and archaeological sequences.

New cryptotephra discoveries are also presented by Smith et al. (*this issue*), who have located far-travelled mid-Holocene age tephra glass shards in low concentrations within the sediments of Lake Keilambete in Victoria, Australia. Initial evaluations indicate the presence of both local basaltic cryptotephras, probably derived from South Australia's mid-Holocene-age volcanoes of Mt Gambier and/or Mt Shank, and possibly rhyolitic tephra that may have travelled from much farther afield (i.e. from beyond Australia). This research paves the way for further cryptotephra research in Australia, where only isolated discoveries have been made to date (e.g. Lowe, 2008; Coulter et al., 2009) and no connected tephrostratigraphic framework exists.

Two further articles also explore the potential for distal tephrochronology within geographical regions, or time-frames, where these methods have not yet been widely applied. Martin-Jones et al. (*this issue*) present the first steps toward a Holocene tephrostratigraphy for the Afar region, Ethiopia, where little is known about the eruption record of currently active volcanoes. There is huge potential in this region for improving the chronologies of palaeoclimate archives and for informing geohazard assessment. Similarly, Sun et al. (*this issue*) define a new tephra isochron in China and report the first glass and mineral compositional data for the little studied Arxan-Chaihe volcanic field.

Johannsson et al. (*this issue*) combines distal tephrostratigraphic techniques with proximal datasets to investigate the Holocene record of Faial and San Migeul islands in the Azores. Using major and minor element analyses, they characterised glass-shard compositions of tephra from the volcanoes of Capelinhos, Fogo, Sete Cidades and Furnas. Their findings reveal the source of previously unprovenanced distal cryptotephra deposits found in Ireland and Morocco, and thus add another volcanic centre source into the tephrostratigraphic framework of Europe and the North Atlantic (Fig. 2).

The final article, by Matsu'ura et al. (*this issue*), addresses much longer, and older, tephrostratigraphies, focussed on a marine sequence in the northwest Pacific Ocean. They present a re-evaluated Middle Pleistocene age model combining tephrostratigraphy and cryptotephrostratigraphy with biostratigraphic datasets. In this study, two cryptotephra deposits were found that are indistinguishable by the major- and trace-element compositions of glass shards. They correlated them to known tephra deposits from Japan on the basis of their stratigraphic positions, demonstrating the significance of stratigraphic relationships for extended sequences in areas that frequently receive fall-out tephra, such as northwest Pacific Ocean area.

Finally, we would like to highlight that more than half of the papers in this volume are led by early career researchers (ECRs). This representation is testament to the excellent support and opportunities provided by the INQUA–INTAV community to ECRs through attendance and participation in workshops, conferences, and field trips, as well as the opportunities for collaboration within an open and active international network. For further details of INTAV research and activities, and to sign up to join in, the reader is referred to the IFG website (http://www.comp.tmu.ac.jp/tephra/intavtmu/top.html) and entries on INQUA's recently-established ECR blog site (http://inqua.org/blog/2016/07/21/intav/).

Acknowledgements

The guest editors thank the INQUA Nagoya organising committee for supporting the tephra-themed sessions at the congress in 2015, as well as Youping Hou (Elsevier), Rainer Grün (*QG* Editor), and Daniel Lovegrove (*QG* Manager), for their encouragement and assistance in compiling this volume. This special issue was a great community effort, and therefore we thank the contributing authors and also the reviewers of the papers, many of whom are acknowledged by name, except where they chose to remain anonymous. Cheryl Ward is thanked for assistance with Fig. 1. INTAV is especially grateful to Brad Pillans and Phil Gibbard who, as successive presidents of the Stratigraphy and Chronology Commission (SACCOM) of INQUA from 2007 through to 2015, strongly supported INTAV and its activities in that period. Similar support is being received from Mauro Coltorti (the current president of SACCOM), other commission presidents, and the INQUA Executive 2015-2019. This introductory article, and the other papers in the issue, are outputs of INTAV's EXTRAS project "EXTending tephRAS as a global geoscientific research tool stratigraphically, spatially, analytically, and temporally within the Quaternary".

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Figure captions

Fig. 1. Numbers of papers involving the terms (A) tephra, as published from 1985 to 2016, and (B) cryptotephra, as published from 2004 to 2016. In both cases, the numbers relate to searches of Scopus using ‘tephra’ or cryptotephra’ in “all fields” (i.e. including title, keywords, and abstracts). Peak numbers are indicated for each dataset.

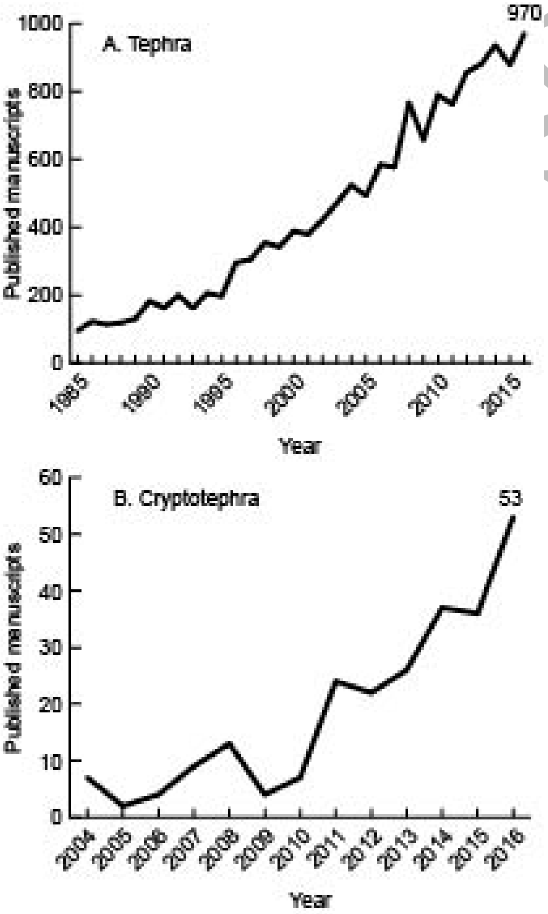

Fig. 2. Global tephra research areas and locations of studies within this volume (stars). Boxes indicate established regional tephrostratigraphic records, where tephra isochrons are widely used for palaeoenvironmental, archaeological, and volcanological research. Key example studies are referenced. Coloured envelopes enclose areas where tephra deposits have been found and geochemically correlated across more than one continent (compiled from references within: Sun et al., 2014; McLean et al., 2016 (ME); Jensen et al., 2014 (WRA); Mackay et al., 2016 (KS$_1$); van der Bilt et al., in press; Kyle et al., 2011 (KS$_2$); Zdanowicz et al., 1999 (MZ); Lane et al., 2012 (VA); Bourne et al., 2016 (To-H); Tomlinson et al., 2012 (CI); Lane et al., 2013, Pearce et al., 2014b, Song et al., 2000 (YTT)). Grey Earth basemap from NaturalEarthData.com.