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Intermontane basins and bimodal volcanism at the onset of the Sveconorwegian Orogeny, southern Norway

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Keywords: Sveconorwegian orogeny; detrital zircon; intermontane basin; bimodal volcanism

Abstract

The greenschist-facies late Mesoproterozoic Bandak succession in southern Norway consists of interlayered quartzites and meta-volcanic rocks with well preserved depositional and structural relations, which when combined provide important information on the late Mesoproterozoic continental margin of Baltica prior to the assembly of the supercontinent Rodinia. The timing of deposition of the Bandak succession is constrained by previously published tuff ages and new detrital zircon analyses reported here. The lower units of the Bandak succession (the Ofte and Røynstaul formations) display diverse detrital zircon age spectra implying derivation from a wide array of sources. The Morgedal and Gjuve formations have unimodal U-Pb age spectra, suggesting input from a single source and probably accumulation in restricted basins. The overlying Eidsborg Formation displays a wide range of detrital zircon age peaks indicative of input from more varied source regions. Hf and O isotopes in detrital zircons of the Bandak succession indicate derivation from typical Fennoscandian basement rocks with the youngest dominant population (~1150 Ma) having been derived from sources formed by remelting of the pre-Sveconorwegian juvenile Gothian basement. Whole rock geochemistry and Nd isotopic signatures further imply that the rhyolite of the Dalaå Formation was formed from anatexis of c. 1500 Ma crust. In contrast, mafic volcanic rocks indicate a mantle source that had been previously enriched through subduction, and variable contamination from older continental crust, or melts derived from it (i.e. the Dalaå Formation). The mafic lithologies reveal decreasing amounts of crustal contamination higher in the section, compatible with increasing amounts of extension and a thinner crustal column.

Age, sedimentological, and geochemical data for the volcanosedimentary units in the Bandak succession record an episode of intracontinental extension, associated with formation of a series of intermontane basins. We hypothesize that these localized basins were formed at different stages of extensional collapse following a pulse of regional orogenesis. The Ofte and Røynstaul formations accumulated during rifting and were followed by bimodal volcanism within the Morgedal, Dalaå, and Gjuve formations. The Eidsborg Formation, at the top of the succession, records post-extension transgressive sedimentation. This tectonic scenario represents a pre-Sveconorwegian stage of orogenesis that can be related to convergent margin processes. The surface expression of crustal growth during this time is relatively small; however, the volume of a postulated mafic underplate that accreted and intruded the lower crust in the Telemark region at this time is unknown. Crustal growth during syn-convergent extension in a retro-arc region may be significant if volumes of accreted mafic underplate are large.

Keywords: Sveconorwegian orogeny, detrital zircons, intermontane basins, bimodal volcanism

1. Introduction

The late Mesoproterozoic to early Neoproterozoic eras (1.3 to 0.9 Ga) are characterized globally as a time of intense orogenic activity related to the assembly of the supercontinent Rodinia (e.g., Hoffman, 1991; Li et al., 2008). The magmatism related to this time period is seen on every continent and it is dominated by bimodal mafic and felsic volcanic rocks and anorthosite-mangerite-charnockite-granite suites (Emslie and Hunt, 1990; Higgins and van Breemen, 1992; Fitzsimons, 2000; Keppie et al., 2001; Bingen et al., 2003; Fioretti et al., 2005). Although much of the magmatism preserved in this orogenic episode formed during the last stages of orogenesis (~1.05-0.92 Ga), the magmatic record of the earliest stages constrains geodynamic processes during the initial stages of continental assembly. In southern Norway, the geological record from the 1.3-1.1 Ga period is dominated by widespread magmatism and sedimentation speculatively associated with a convergent margin located along the southwest margin of Fennoscandia (Fig. 1; Brewer et al., 2004; Roberts et al., 2011).

This study explores the development of basins associated with the bimodal magmatism and related tectonism as recorded in 1.2-1.1 Ga sedimentary and volcanic rocks of the Telemark region of southern Norway. The Bandak succession in the central Telemark region is selected for this study because it corresponds to both a key time interval, i.e. the 1.48-1.15 Ga ‘inter-orogenic’ period immediately preceding the Sveconorwegian Orogeny (Åhäll and Connelly, 1998; Bingen et al., 2003; Bingen et al., 2008; Slagstad et al., 2013), and preserves high quality depositional relations between units thereby providing the opportunity for an integrated sedimentological, magmatic, and tectonic model. We report new U-Pb, Hf, and O data from detrital zircons throughout the Bandak succession, and whole-rock geochemistry of interlayered bimodal volcanic rocks. These data constrain the depositional timing of sedimentary units and petrogenesis of the volcanic rocks, and enable comparison with younger geologic analogues to augment understanding of late Mesoproterozoic geodynamics.

2. Geologic Setting

The Fennoscandian Shield is composed of an Archean core in the northeast that is rimmed to the south and west by progressively younger Proterozoic crustal domains (Gaál & Gorbatschev, 1987; Bingen et al., 2008). The youngest of these comprise the 1140-920 Ma Sveconorwegian province (Fig. 1), which has been divided into five ‘terranes’, separated by approximately orogen-parallel shear zones (Bingen et al., 2008). In the tectonic framework of Bingen et al. (2008) these terranes are considered to be both parautochthonous (Eastern Segment) and allochthonous (Idefjorden, Kongsberg, Bamble and Telemarkia terranes). The most westerly and youngest is the Telemarkia terrane;

some workers divide this into two crustal ‘blocks’, Hardangervidda-Rogaland and Telemark (Andersen, 2005), whereas others define four sectors (Hardangervidda, Suldal, Rogaland, and Telemark; Bingen et al., 2005; Fig. 1). In either case, the Telemarkia terrane displays crust formation ages between 1.52 and 1.48 Ga (Bingen et al., 2005; Roberts et al., 2013). Within the Telemark sector (see Fig. 1) there is a ~10 km thick succession of sedimentary and volcanic rocks referred to as the Telemarksuiten or Telemark supracrustals (e.g. Dons, 1960; 1972; Sigmond, 1978) that can be separated into several temporally distinct volcanic and sedimentary basins ranging from ~1.5 to 1.1 Ga in age (e.g. Bingen et al., 2002, 2003; Brewer et al., 2004; Laajoki et al., 2002; Bingen et al., 2008; Pedersen et al., 2009; Roberts et al., 2011). A number of terminologies and groupings have been proposed for this suite of supracrustal rocks, and here we follow the terminology of Laajoki et al. (2002). In the centre of the Telemark sector, the supracrustal rocks have been divided into the Rjukan, Vindeggen, Oftefjell, and Høydalsmo groups and the overlying Eidsborg Formation, each separated by major angular unconformities (see Dons, 2004; Laajoki et al., 2002; Laajoki and Lamminen, 2006; Köykkä, 2010; Lamminen et al., 2011). The Rjukan and Vindeggen groups were deposited prior to ~1350 Ma, whereas the other units were deposited between ~1170 Ma and ~1000 Ma.

The Bandak succession (Fig. 2) is a ~4 km thick volcanosedimentary succession inferred to have accumulated in a non-marine extensional basin (Menuge and Brewer, 1996; Köykkä and Laajoki, 2009). The oldest unit is the Oftefjell Group, divided into the uppermost Ofte Formation and basal Svinsaga Formation separated by three intervening felsic volcanic units (termed Ljosdalsvatnet, Ofte porphyry 2, and Ofte porphyry 3; Laajoki et al., 2002). This group is bounded by regional angular unconformity surfaces (Laajoki and Lamminen, 2006). The overlying Høydalsmo Group consists of the Røynstaul, Morgedal, Dalaå, and Gjuve formations (Brewer et al., 2002; Laajoki et al., 2002). The Røynstaul Formation is composed of ~500 m of sedimentary and volcanic rocks, dominated by quartzite and metabasalt with minor metaconglomerate and metafelsic volcanic rocks (Laajoki and Lamminen, 2006). The Morgedal and Gjuve formations define a thick sequence of sub-aerial metabasalt flows with minor intercalations of quartzite; flow margins are often highly altered, containing abundant epidote and chlorite (Brewer et al., 2002). The metafelsic volcanic unit of the Dalåii Formation separates the Morgedal and Gjuve formations and is comprised of both welded and non-welded tuffs (Brewer et al., 2002). The base of the youngest unit, the Eidsborg Formation is typified by a metaconglomerate on an angular unconformity (Lamminen et al., 2011) and is predominantly of quartzite with some metaconglomeratic intercalations. The base of the Eidsborg Formation is deposited variably on the Gjuve Formation, but also on the Rjukan and Vindeggen groups to the north and east of the region around Lake Bandak. This implies that the previous units were partially exhumed prior to deposition of the Eidsborg Formation (Lamminen et al., 2011), which is a likely correlative with the Heddal Group to the Kalhovd Formation to the northeast and northwest, respectively (Bingen et al., 2003; Lamminen et al., 2011).

During the Sveconorwegian Orogeny, the Bandak succession was variably metamorphosed to greenschist facies. Brewer and Atkin (1987) identified three phases of

Sveconorwegian metamorphism affecting these rocks: 1) greenschist facies regional metamorphism associated with the development of crenulation cleavage in mafic volcanic rocks; 2) localized contact metamorphism associated with the intrusion of post-kinematic granites; and 3) late stage veining. These workers also report geochemical data and note that rare earth elements display coherent patterns, implying that these elements have likely remained relatively immobile during metamorphism.

3. Methods

3.1 Whole-rock Geochemistry

Whole-rock major and trace element analyses were conducted on 20 samples from metabasaltic rocks within the Morgedal and Gjuve formations by X-ray flourescence (XRF) and (ICP-MS) at the University of St Andrews using a Spectro X-Lab XRF and a Thermo X Series II Quadrupole ICP-MS. See supplementary text (S1) for full methods.

3.2 Zircon U-Pb Geochronology and Hf, O Isotopic Analysis

Eight ~3 kg quartzite samples were collected from the Ofte, Røynstaul, Morgedal, Gjuve, and Eidsborg formations (samples CS12-17, -18, -19, -20, -22, -23, -24, -25; see Table S1 for sample locations and descriptions). U-Pb analyses were conducted using a Nu Instruments Attom single-collector inductively coupled plasma mass spectrometer (ICP-MS) and a New Wave Research UP193 solid-state laser ablation system. Near concordant (> 95 % concordance) U-Pb zircon ablation sites from samples CS12-17, -18, -23, -24, and -25 were then re-analyzed to measure their Lu-Hf isotopic compositions using a Thermo Scientific Neptune Plus MC-ICP-MS coupled to a New Wave Research

UP193FX excimer laser ablation system at the NERC Isotope Geoscience Laboratories (NIGL). Prior to U-Pb and Hf analyses, samples CS12-17, -23, -24, and -25 were analyzed for O isotopes using a Cameca IMS-1270 ion microprobe at the Edinburgh Ion Microprobe Facility (EIMF), University of Edinburgh. See supplementary text (S1) for complete methods.

4. Results

4.1 Whole-rock Geochemistry

Brewer et al. (2002) reported whole-rock geochemical data on mafic and felsic rocks of the Bandak succession and these data are compiled with the results from this study (Fig. 3; Table S2). Major element data are adjusted to an anhydrous basis by normalization to the loss on ignition values. The SiO_2 contents of these rocks range from 42.7 to 73.5 wt. %. The meta-basaltic samples contain 42.7-52.0 wt. % SiO_2, whereas the meta-dacites and rhyolites contain 71.8-73.5 wt. % SiO_2, highlighting the bimodal composition of this suite apart from two intermediate samples (Figs 3A, 3B).

The mafic rocks have moderate TiO_2 values (1.3-3.9 wt.%) and Al_2O_3 (13-17.2 wt. %), elevated Mg numbers (Mg#, 0.25-0.49), minor light REE enrichment (La/Yb_N, 1.3-3.5), and high ferromagnesian trace element contents (Co, 48-94 ppm; Cr, 93-168 ppm; Ni, 18-181 ppm; 108 ppm average). Samples lack a strong Eu anomaly and in some cases have a positive Eu anomaly (Eu/Eu*, 0.65-1.09) and exhibit a strong depletion in Nb relative to La (Nb/La_N: 0.3-0.6) (Fig. 3F). All mafic samples are also enriched in other highly incompatible mobile elements (Rb, Ba, Th, U).

The felsic samples of the Dalaå Formation reported by Brewer et al. (2002) have moderate concentrations of large ion lithophile elements (LILEs) (Ba, 751-1054 ppm; Sr, 86-157 ppm), and enrichment of light REEs. There is a slight enrichment in light REEs and highly refracted heavy REEs (Ce/Yb_n = 4.0-5.8; Gd/Nd_n = 0.42-0.49), as well as strongly negative Eu anomalies (Eu/Eu*, 0.7-0.78).

4.2 U-Pb Geochronology

Results and instrumentation parameters of U-Pb geochronology are presented in Figures 4 to 6 and Table S3. Samples were collected along two transects through the supracrustal rocks from the towns of Åmot to Øyfjell (Groven transect) and Vrådal to Vråliosen (Vrådal transect) (see Figure 2). Along the Groven transect, samples were collected from the Ofte, Røynstaul, and Eidsborg formations. Along the Vrådal transect, samples were collected from the Røynstaul, Morgedal, and Eidsborg formations. An additional sample from the Gjuve Formation was collected from a road cut along E134.

4.2.1 Ofte Formation

Zircons from sample CS12-17 are mainly colorless to ochre with moderate degrees of rounding and a range in size from 80-300 µm (Fig. 4). This sample has a dominant age population at 1550 Ma with subordinate populations at 1210 Ma and 2080 Ma ($^{207}Pb/^{206}Pb$ age) (Figs. 5 and 6). Although only 42 of the 68 analyses were < 5 % discordant, all analyses have the same age distribution as the concordant subset.

4.2.2 Røynstaul Formation

Zircons from sample CS12-22 are euhedral to well rounded, range from brown to pale orange in color, and are 30-300 µm in size (Fig. 4). Most of the analyses in this sample are discordant (62/84 are > 5 % discordant) but with dominant peak at 1500 Ma. Sample CS12-19 has a zircon age distribution composed of one dominant population at 1500 Ma together with three subordinate peaks at 1175, 1350, and 1830 Ma and a single concordant 2694 Ma age (Figs. 5 and 6). U concentrations of zircons in CS12-22 range from 320 ppm to 8070 ppm (2630 ppm average) and 24 ppm to 1235 ppm (260 ppm average) in CS12-19 and the zircons with higher U contents trending to higher discordance.

4.2.3 Morgedal Formation

Sample CS12-23 comes from a fluvial sandstone interbedded in a dominantly basaltic unit. Zircons from this samples are mainly colorless with moderate degrees of rounding and sphericity and a range in size from 40-300 µm (Fig. 4). U-Pb analyses from this sample have a concordant age distribution with a single dominant population at 1200 Ma, and subordinate populations of 1130 and 1170 Ma with a single 1500 Ma age (Figs. 5 and 6). In this sample only 29 of the 55 analyses were < 5 % discordant, and older ages tend to be from discordant analyses.

4.2.4 Gjuve Formation

Like the Morgedal Formation, sample CS12-20 of the Gjuve Formation is from a fluvial sandstone interbedded with basalt. Zircons from this sample are euhedral and range from colorless to yellow and are 60-250 µm in size (Fig. 4). The zircon age distribution within this sample has one dominant population at 1155 Ma and several older Proterozoic ages (Figs. 5 and 6). There is also little difference between all of the analyses (n = 134) and the concordant subset (< 5 % discordant; n = 63).

4.2.5 Eidsborg Formation

Zircons in each of the three samples collected from the Eidsborg Formation are colorless to ochre in color, range from euhedral to well rounded with several angular fragments, and are 30-300 μm in size (Fig. 4). The concordant (< 5 % discordant) age distribution from the basal Eidsborg Formation along the Vrådal transect has one dominant age peak at 1180 Ma and several scattered Proterozoic ages whereas the upper Eidsborg Formation from the Vrådal transect has a similar dominant concordant age peak at 1160 Ma with a number of additional smaller peaks at 1500, 1620, and 1830 Ma and two concordant Archean ages. Similar to the upper Eidsborg Formation from the Vrådal transect, the Eidsborg Formation from the Groven transect hosts a major peak at 1150 Ma with subordinate peaks at 1340, 1520, 1680, and 1780 Ma, and four ages older than 2000 Ma. Discordant populations (> 5 % discordant) from the three samples exhibit similar distributions.

4.3 Zircon Hf and O Isotopes

The results and instrumentation parameters of the zircon Hf and O isotope analyses are presented in Figures 7 and 8 and Tables S4 and S5. Within the eight samples, there are three discrete pre-1250 Ma populations that have a similar range of εHf values (1250 to 1450 Ma: εHf (average ± 2σ) = 2.5 ± 9.1; 1450 to 1600 Ma: εHf = 3.2 ± 6.6; 1600 to

1950 Ma: εHf = 2.0 ± 4.4). Analyses with ^{207}Pb/^{206}Pb ages younger than 1250 Ma have εHf values that fall into two distinct fields. Samples collected north of Lake Bandak (CS12-17, -18, -19, -20) have lower Hf isotopes ratios (εHf = 2.8 ± 4), whereas those samples ~25 km south of Lake Bandak (CS12-23 and -24) have higher values (εHf = 7.4 ± 1.6) with the exception of the four analyses in this age range of sample CS12-25 (Fig. 7).

Zircons from a subset of four samples (CS12-17, -23, -24, -25) were analyzed for ∂^{18}O (Fig. 8). Analyses with U-Pb ages displaying >5% discordant were rejected as Valley et al. (2003) demonstrated a significant shift in ∂^{18}O values with increasing discordance. Accepted analyses have ∂^{18}O values that range between 12.2 and 4.0 ‰. Each of the samples display a general decrease in ∂^{18}O values in zircons from ~2.0 Ga to 1.1 Ga. The spread of ∂^{18}O values within the 1.25-1.1 Ga age peak form a vertical array between 8.0 and 4.7 (average = 6.56 ± 1.8 ‰, 2σ).

5. Discussion

5.1 Petrogenesis of Volcanic Rocks in the Morgedal and Gjuve formations

The Telemark supracrustal succession has been metamorphosed to greenschist facies and thus the primary geochemical compositions are liable to subsequent mobilization. Large ion lithophile elements (e.g. Rb, Ba, K, Sr) are generally considered mobile under metamorphic conditions whereas rare earth elements and high field strength elements (e.g. Th, Nb, Ti, Zr, Y) are considered the least mobile or immobile (Rollinson, 1993).

Given these issues, only those elements generally considered immobile are used in the geochemical diagrams of Figure 3.

The bimodal volcanic rocks of the Morgedal, Dalaå, and Gjuve formations (Figs. 3A) are classified as within-plate basalts and dacites/rhyolites (Figs. 3B, 3C; Pearce and Norry, 1979). The basaltic rocks of the Bandak succession have elevated Th/Yb ratios implying derivation from a mantle source that has been previously enriched through subduction processes (Fig. 3D). Light REE enrichment (e.g. La/Yb) and negative Eu anomalies (Fig. 3E) are consistent with some degree of crustal assimilation between this enriched mantle-derived material and basement rocks, as indicated by the Nd isotope data. The felsic Dalaå Formation rhyolite has a Nd isotopic signature (εNd = 0.2; Brewer et al., 2002) that indicates it was derived from crustal anatexis of the underlying Rjukan Group, or at least basement of similar age, rather than a mantle origin (Fig. 3G). The Nd isotopic signatures also show that the basalt of the Morgedal and Gjuve formations was sourced from depleted mantle with varying degrees of contamination derived either from the continental basement and/or an enriched mantle (εNd = 2.6-5.1; Brewer et al., 2002).

5.2 Depositional Ages and Provenance of the Bandak succession

Maximum depositional ages for each of the samples were determined using the youngest, least discordant analyses from each sample. The Ljosdalsvatnet rhyolite was emplaced at 1155 ± 3 Ma (Laajoki et al., 2002); it directly underlies the Ofte Formation and thus provides a maximum depositional age for that formation, which is in broad agreement with the two youngest detrital zircon ages of 1197 ± 17 Ma (these are 1.0 % discordant; Fig. 9) The maximum depositional age of the Røynstaul and Morgedal formations is constrained by the age of the overlying Dalaå Formation (1150 ± 4 Ma; Laajoki et al., 2002). The maximum depositional ages for the Gjuve and Eidsborg formations are constrained by four zircons within the Eidsborg Formation that range in age from 1130 ± 23 Ma to 1118 ± 17 Ma (all less than 1% discordant). This limits the deposition of the Bandak succession to a relatively short interval of time. These data show that the time represented between the sub-Røynstaul unconformity and the Eidsborg Formation is ~35 Ma. Further, our results confirm and refine the oft-cited maximum depositional age for the Eidsborg Formation of 1118 ± 38 Ma (from de Haas et al., 1999).

The minimum depositional age of the Bandak succession is defined by the intrusive relationship of the post-tectonic granitoids found throughout the region. Within the vicinity of this study, those bodies include the Vrådal (964 ± 18 Ma; Andersen et al., 2007), Bessefjell (940 ± 19 Ma; Andersen et al., 2002), and Vehuskjerringa plutons (932 ± 2 Ma; Andersen et al., 2007), which together provide a minimum age of around 950 Ma.

5.3 Detrital Zircon Age Spectra Results

To illustrate the interrelated character of the detrital zircon age spectra, we employ multi-dimensional scaling to visualize the pairwise “dissimilarities” of these age distributions (as discussed by Vermeesch, 2013) (Fig. 10). When comparing several age spectra, it often becomes difficult to visualize their similarity/dissimilarity objectively. Furthermore, it is equally difficult to utilize numerical statistics to obtain a sense of how a specific age spectrum relates to a group of other samples. Multi-dimensional scaling overcomes these issues while maintaining statistical objectivity. The two statistical tests employed here to measure the statistical dissimilarity are the Kolmogorov-Smirnov test and Cramér-von Mises criterion. The Kologorov-Smirnov statistic is quantified as the maximum distance between the cumulative distribution function of two samples, whereas the Cramér-von Mises criterion measures the area between the cumulative distribution function of two samples. These statistics are calculated for each pair of samples and are plotted in multi-dimensional space (see Vermeesch, 2013). In Figure 10 the Kolmogorov-Smirnov test and Cramér-von Mises criterion maps show three statistically significant groups of age spectra, these correspond to unimodal distributions dominated by Sveconorwegian (1140-900 Ma; Bingen et al., 2008) zircons (CS12-20, -23, -24), or multimodal distributions dominated either by Sveconorwegian (CS12-18, -25) or ~1.5 Ga zircons (CS12-17, -19, -22).

The 1550-1500 Ma age peak in the Ofte and Røynstaul formations (Fig. 6) is probably related to the 1512-1502 Ma volcanic rocks of the Rjukan Group and associated intrusives (Dahlgren et al., 1990; Bingen et al., 2005), as they are found throughout the region (see also Lamminen et al., 2011). The greater spread of detrital zircon ages may be due to local differences in the age of the Rjukan Group, or may reflect sourcing from further afield as the rest of the Telemarkian basement has an age spread of ~1.55-1.48 Ga (Bingen et al., 2005; Pedersen et al., 2009; Roberts et al., 2013). The only nearby potential source for the ~1360 Ma age peak is the Sandvik diabase (Corfu and Laajoki, 2008; 1347 ± 4 Ma). Although the age of this body indicates nearby activity of similar age, its small subaerial footprint and composition make it unlikely to be the actual source. A potential correlative in the Sveconorwegian province is the Kungsbacka granite suite

(~1.34-1.30 Ga; Austin Hegardt et al., 2007) in the Idefjorden terrane. Thus, either the provenance of the Ofte and Røynstaul formations is distant (> 300 km), or the ~1.35 Ga source rocks have been removed by tectonic processes, or they are yet to be exposed or discovered. Additionally, the Røynstaul Formation from the Groven transect has a significant proportion of ~1850 to 1650 Ma zircons that are presumably derived from the Transcandinavian Igneous Belt (~1.85-1.66 Ga; Bingen and Solli, 2009).

Above the Røynstaul Formation, the Morgedal, Gjuve, and basal Eidsborg rocks are dominated by nearly unimodal age distributions between ~1200 Ma and 1155 Ma. Although there are several large A-type granitic bodies within 100 km from the locality of this study (see Bingen et al., 2003), the unimodal age spectra imply these zircons were derived from nearby sources, likely from the nearby felsic rocks associated with the Dalaå (1150 ± 4 Ma), Ljosdalvatnet (1155 ± 3 Ma), Brunkeberg (1155 ± 3 Ma), and Skogsaa (1145 ± 4 Ma) porphyries (Laajoki et al., 2002). Although these volcanic rocks provide a potential source for the youngest detrital zircons in the Bandak succession, it is important to note the 1180 Ma age peak seen in the Eidsborg Formation is enigmatic.

The Eidsborg Formation (samples CS12-18, -25) has a diverse array of zircon ages. The provenance likely included similar sources to the underlying units, which are dominated by ~1150 Ma aged zircons and attributed to early Sveconorwegian magmatism. The ~1340 Ma age peak is also present along with older age peaks at 1500-1520 Ma, 1620-1680 Ma, and 1780-1830 Ma, reflecting Telemarkian, Gothian and Transcandinavian Igneous Belt sources, respectively (Bingen & Solli, 2009).

We interpret the transition from the multimodal to unimodal and back to multimodal age distributions within the Bandak succession as a significant provenance shift reflecting evolution of the basin and its distributary province (Fig. 11). The multimodal patterns within the Ofte and Røynstaul formations are evidence that during early Bandak sedimentation, sediment transport systems were relatively extensive. Following this, the unimodal pattern signifies the establishment of individual depocentres in discreet extensional basins. Further, the attendant eruption of large volumes of bimodal magmatism likewise imply significant thinning of the crust (Brewer et al., 2002). As extension and volcanism decreased, detritus again began to be derived from a diverse spectrum of sources recreating the multimodal age distributions seen in the uppermost portion of the Bandak succession in the Eidsborg Formation (Fig. 11).

Zircon Hf isotopes also discriminate between various source regions. The 1.1 to 1.25 Ma detrital zircons fall into two fields in U-Pb/Hf space (Fig. 7). The samples from along Vrådal have higher Hf (εHf = 7.4 ± 0.8), whereas those from north of Lake Bandak have lower Hf (εHf = 2.8 ± 2) (Fig. 7). This implies that: (i) these two depocentres were receiving similar age detritus but derived from different source rocks via discrete drainage systems (see also Lamminen et al., 2011); and (ii) the average Hf isotopic composition of the Lake Vrådal region are more depleted than those north of Lake Bandak. However, the wide spread in published zircon Hf values from the Telemark region do not provide the resolution necessary to discriminate specific sources for the detrital zircons in this study (see Andersen et al., 2002; Andersen et al., 2007; Andersen et al., 2009; Pedersen et al., 2009; Lamminen and Köykkä, 2010; Bingen et al., 2011;

Petersson et al., 2014). Furthermore, oxygen isotopes in the Sveconorwegian-age zircons analyzed show that the host magmas were derived from a source that had assimilated an appreciable amount of supracrustal material driving their compositional trends to higher ∂^{18}O values (Fig. 8). Importantly, the O isotopic signature of the Sveocnorwegian-age zircons have the same range of values as those from the older basement rocks which potentially represent the source from which the Sveconorwegian-age zircon-forming magmas were derived.

5.4 Implications for Tectonic Models

Several distinct phases of Mesoproterozoic intra-continental extension and associated bimodal volcanism are present in southern Norway: for example, the ~1.26-1.21 Ga Sæsvatn-Valldal Group (Bingen et al., 2002; Brewer et al., 2004), ~1.23 Ga Grøssæ-Totak belt (Sigmond, 1978; Roberts et al., 2011), < 1.12 Ga Ofte, Morgedal, and Gjuve formations (Brewer et al., 2002; Laajoki et al., 2002; Bingen et al., 2003, herein), and the <1.22 Ga Byglandsfjorden supracrustals (Pedersen et al., 2009) in the poorly known Setesdalen region. In the Telemark region, exposure of normal faults associated with regional extension is generally limited, although individual basins are characterized by thick metaconglomerates that imply derivation from high relief, local sources possibly associated with fault-bounded depositional basins (Lamminen et al., 2011).

The presence of angular unconformities beneath the Røynstaul and Eidsborg formations are thought to represent episodes of basin inversion followed by subsidence and further sediment accumulation (Laajoki and Corfu, 2007; Lamminen et al., 2011); however, the presence of angular unconformities can also be explained by intra-basinal fault block rotation (e.g. Zhongquan et al., 2004; Hogan et al., 2011). Nevertheless, the evolution of similarly evolving volcanosedimentary basins with a range of ages (i.e. <1.27 Ga Saesvatn-Valldal, <1.24 Ga Grøsse-Totak, <1.22 Ga Byglandsfjorden, <1.16 Ga Bandak (Brewer et al., 2004; Roberts et al., 2011; Pedersen et al., 2009), suggests a period of crustal extension and basin formation.

The eruption and deposition of the volcanic and sedimentary rocks associated with the 1.26-1.16 Ga episode of intracontinental extension in southern Norway has been linked to a long-lived process involving mafic underplating, crustal melting, and formation of extensional basins inboard of an active convergent margin (Figure 12; Brewer, et al., 2004; Roberts et al., 2011). This is consistent with geodynamic models that join the leading margins of Fennoscandia, Laurentia, and Amazonia as part of a long-lived (> 600 Ma) retreating accretionary margin (Zhao et al., 2004; Whitmeyer and Karlstrom, 2007; Johansson, 2009; Condie, 2013; Roberts, 2013). Although 1.3-1.1 Ga continental arc material is not preserved, it is likely much of the hinterland of this orogenic episode was removed by subduction erosion or tectonic translation during the subsequent accretionary and/or collisional margin episodes (Roberts et al., 2011). Furthermore, although much (if not all) of the new arc crust was removed by subduction erosion, and despite the relatively minor surface expression of new and reworked crust in the here postulate retro-arc region, significant volumes of crust may have been added during the process of mafic underplating in the lower crust. In the model presented above, the Bandak succession represents the last recorded stage of this behind-arc continental extension, and is a pre-Sveconorwegian feature that can be related to convergent-margin processes.

Conclusions

From the data presented in this study, along with data previously published we find that:

1) At the base of the Bandak succession, the deposition age of the Ofte Formation is constrained by the intrusion of the Ljosdalsvatnet porphyry at 1155 ± 3. The Eidsborg Formation at the top has a maximum depositional age of 1118 ± 17 Ma.

2) The provenance of the Bandak succession in Telemark is characterized by three phases of deposition. The Ofte and Røynstaul formations were derived from sources contributing a wide range of detrital zircon ages. The overlying Mordegal, Dalaå, and Gjuve formations are dominated by bimodal volcanic rock with intercalations of sedimentary rocks with unimodal detrital zircon age spectra attributed to being locally derived and spatially linked to proximal bedrock; these mark the initiation of extensional tectonics. Lastly, the Eidsborg Formation signals the end of extension and deposition of sediments derived from more distal non-local sources.

3) Hf and O isotopes in zircon further subdivide the region of provenance for these units as having more enriched Hf and crustal O signatures north of Lake Bandak and depleted Hf and crustal O signatures to those along Lake Vrådal.

4) The basalt flows within the Morgedal and Gjuve formations were derived from a mantle previously enriched through subduction, with decreasing crustal contamination upsection.

5) The surface expression of crustal growth in the Telemark Region between ~1.3 Ga and ~1.1 Ga is relatively small; however, mafic underplating and lower crustal impregnation may add large volumes to the crustal column.

Acknowledgements

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Figures

1. Map of SW Fennoscandia showing the main Proterozoic lithotectonic units (after Bingen et al., 2005). Sectors within the Telemarkia terrane are *h*: Hardangervidda, *s*: Suldal, *r*: Rogaland-Vest Agder, and *t*: Telemark which is bisected by the Mandal-Ustaoset shear zone (*m*-*u*).

2. Simplified geologic map and stratigraphy of the southern part of the Telemark supracrustals near Lake Bandak (after Dons, 2004). Stratigraphic scheme follows Laajoki and Lamminen (2006).

3. Whole-rock geochemical diagrams for bimodal volcanic lithologies within the Høydalsmo Group. Data are compiled from this study and Brewer et al. (2002), Brewer & Atkin (1987), and Brewer (1985). Major element weight percentages are adjusted to an anhydrous basis. A) SiO_2 (wt%) vs. Nb/Y (ppm) after Winchester and Floyd (1977); B) Y + Nb vs. Rb (ppm) after Pearce et al. (1984); VAG: volcanic arc granite, ORG: ocean-ridge granite, WPG: within-plate granite, syn-COLG: syn-collisional granite; C) Zr vs. Zr/Y (ppm) after Pearce and Norry (1979); VAB: volcanic arc basalt, MORB: mid-ocean ridge basalt, WPB/OIB: within-plate basalt/ocean island basalt; D) Nb/Yb vs. Th/Yb (ppm) after Pearce et al. (1995); N-MORB: normal mid-ocean ridge basalt, E-MORB: enriched mid-ocean ridge basalt, OIB: ocean island basalt; E) La (ppm) vs. La/Yb_N; F) La/Yb_N vs Eu/Eu*; chondrite normalized after McDonough and Sun (1995); $Eu^* = Eu_N/((Sm_N+Gd_N)/2)$; UCC: upper continental crust composition after Rudnick and Gao (2003); NMORB: normal mid-ocean ridge basalt composition after Sun & McDonough (1989); G. Kernel density estimation (KDE; see Vermeesch, 2012) of Nd depleted mantle model ages (TDM) of (from oldest to youngest) Tuddal, Vermork, Morgedal, Dalaå, and Gjuve formations (after Menuge and Brewer, 1997; Brewer and Menuge, 1998). The gray shaded box represents the average TDM of the Rjukan Group (Tuddal and Vermork formations) ± one standard deviation (s.d.). Kernel density estimation (KDE) performed using DensityPlotter (Vermeesch, 2012). Mixing percentages between Nd depleted mantle (DM) at 1160 Ma and the average TDM of the Rjukan Group (1636 Ma)

calculated using average Nd content of Gjuve and Morgedal formations (21 ppm) and Rjukan Group (50 ppm) (= 1.4).

4. A) Cathode luminescence (CL) image of zircon CS12-17-30 with outline of typical O (8x15 µm), U-Pb (25 µm), and Hf (35 µm) analytical spots. B) Typical zircon CL images with analytical spots and associated values from each detrital zircon sample in this study.

5. Pb/U concordia diagram of ages (Ma) of zircon grains from each sample. Uncertainties are shown at the 2σ level. Diagram was constructed with the use of Isoplot (Ludwig, 2003).

6. Kernel density estimation (solid line) plots of detrital zircon ages from each sample. Only ages that < 5 % discordant are used. The grey filled-line represents all analyses regardless of discordance. Plot is constructed using densityplotter (Vermeesch, 2012).

7. $\varepsilon Hf_{(t)}$ vs. U-Pb analyses of detrital zircons from the Bandak succession. Gray field represents 95% of zircon Hf data reported from Fennoscandia (data compiled from Bingen et al., 2011 and references therein and Petersson et al., 2014). Uncertainties are displayed as 2σ. DM = depleted mantle (Griffin et al., 2000), CHUR = chondrite uniform reservoir (Bouvier et al., 2008).

8. ∂^{18}O (‰ VSMOW) vs. U-Pb analyses of detrital zircons from the Bandak succession. Uncertainties are displayed as 2σ.

9. Plot of ^{206}Pb/^{238}Pb vs. ^{207}Pb/^{206}Pb ages (Ma) of the youngest, least discordant zircon analyses from each sample to assess the maximum depositional age. Covariance between the ^{206}Pb/^{238}Pb vs. ^{207}Pb/^{206}Pb ages was calculated using the algorithm of McLean et al. (2011).

10. A) Cumulative distribution functions of detrital zircon distributions for samples from this study; B) Metric multi-dimensional scaling plots of the Bandak succession samples using the Cramér-von Mises criterion as a dissimilarity measure and C) using the Kolmogorov-Smirnov test. Solid Lines mark the closest neighbours and dashed line the second closest neighbours (after Vermeesch, 2013). Multi-dimensional scaling plots B and C are construct using metric scaling.

11. A) Stratigraphic column of the Bandak succession after Dons (2004) and Laajoki and Lamminen (2006). The age of the Dalaå and Ljosdalsvatnet formations are constrained by U-Pb ID-TIMS from Laajoki et al. (2002) and the youngest set of zircon analyses that constrain the maximum depositional age of the Eidsborg Formation is reported in this study. B) Combined KDE of samples CS12-18 and -25 within the mid- and upper Eidsborg Formation that exhibit a multimodal U-Pb age spectra. C) Combined KDE of samples CS12-20, -23, and -24 within the Morgedal, Gjuve, and basal Eidsborg formations that exhibit a unimodal U-Pb age spectra. D) Combined KDE of samples CS12-18 and -25 that exhibit a multimodal U-Pb age spectra. Figures B, C, D are constructed using only U-Pb analyses with <5% discordance and densityplotter of

Vermeesch et al. (2012). E) Proposed depositional setting for the Eidsborg Formation of Lamminen (2011). The base of the Eidsborg Formation is dominated by conglomerates of possible alluvial fan origin followed by a braided fluvial system with minor eolian and laucustrine deposits (see Lamminen, 2011); deposition of the Eidsborg was preceded by the eruption of the bimodal Gjuve and Dalaå formations (F) and the basaltic Morgedal Formation (G). The interbedded fluvial sandstones interpreted as having a locally derived provenance. The sandstones of the Røynstaul (H) and the Ofte (I) formations were likely deposited within a braided fluvial system similar to that of the Eidsborg (Lamminen, 2011) albeit with a multimodal U-Pb age spectra centered at ~1.5 Ga. Fluvial flow direction is schematic.

12. Schematic model for the proposed ~1.2-1.1 Ga geodynamic setting in the Telemark block. The mafic magmatism (Morgedal and Gjuve formations) is sourced from a mantle wedge enriched via a previous episode of subduction metasomatism. The mafic underplating associated with this magmatism causes low-crustal anatexis leading to the emplacement of the felsic volcanic Dalaå Formation. The contemporaneous subduction zone and accompanying magmatism west of the intercontinental extension is assumed to have been tectonically eroded during the subsequent orogenic episodes.

Supplementary Material

Text S1: Detailed description of analytical methods.

Figure S1: Pb/U concordia diagram of ages (Ma) of zircon reference materials used to correct unknown U-Pb analyses. See supplementary text for further information.

Figure S2: a) ^{176}Hf/^{177}Hf analyses of zircon reference materials used to correct unknown Hf analyses; b) stable Hf isotope ratios (^{178}Hf/^{177}Hf) of all analyses during two analytical sessions; c) O analyses of zircon reference materials used to correct unknown O analyses.

Table S1: Sample locations and descriptions

Table S2: Whole-rock Geochemistry of the Bandak succession

Table S3: U-Pb data of the Bandak succession

Table S4: Hf data of the Bandak succession

Table S5: O data of the Bandak succession

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We report zircon U-Pb/Hf/O isotopes from the Bandak succession in Telemark, Norway.

These rocks record 3 phases of sedimentation and eruption of bimodal volcanic rocks.

The sedimentation and eruption took place between 1155 and 1118 Ma.

The basalts have compositions akin to melting of an enriched asthenospheric wedge.

The sedimentary rocks record alternating multi- and unimodal zircon age spectra.

Figure 1

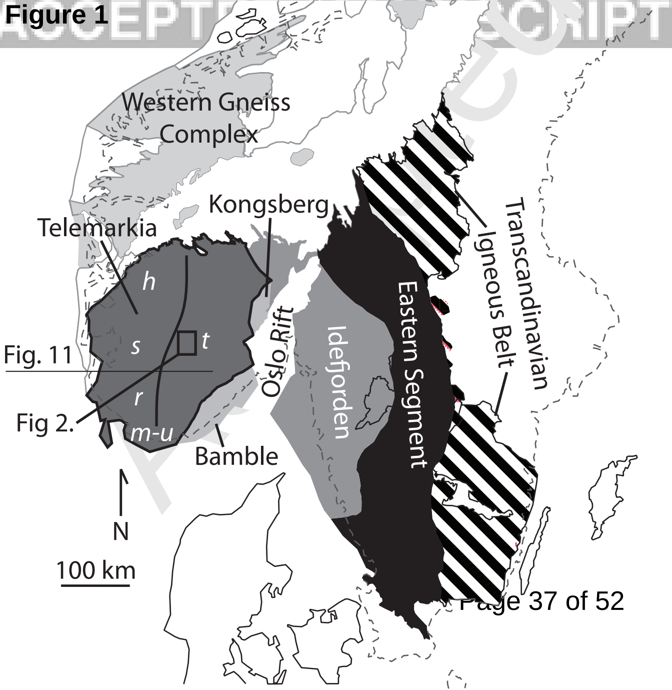
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Fig 2.
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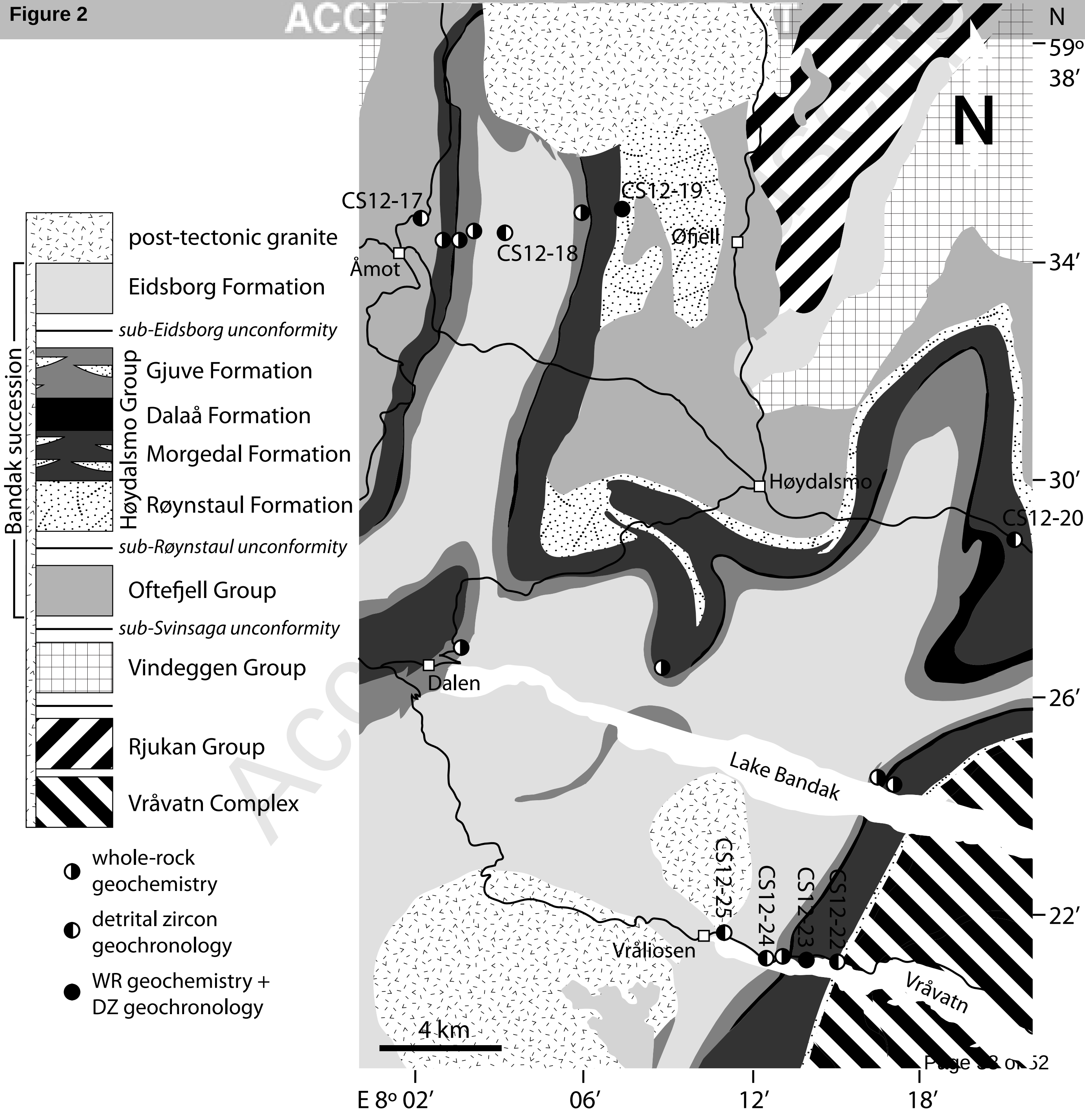
Figure 2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Vråliosen
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12′
18′
post-tectonic granite
Bandak succession
Eidsborg Formation
sub-Eidsborg unconformity
Høydalsmo Group
Gjuve Formation
Dalaå Formation
Morgedal Formation
Røynstaul Formation
sub-Røynstaul unconformity
Oftefjell Group
sub-Svinsaga unconformity
Vindeggen Group
Rjukan Group
Vråvatn Complex
whole-rock geochemistry
detrital zircon geochronology
WR geochemistry + DZ geochronology

Figure 3

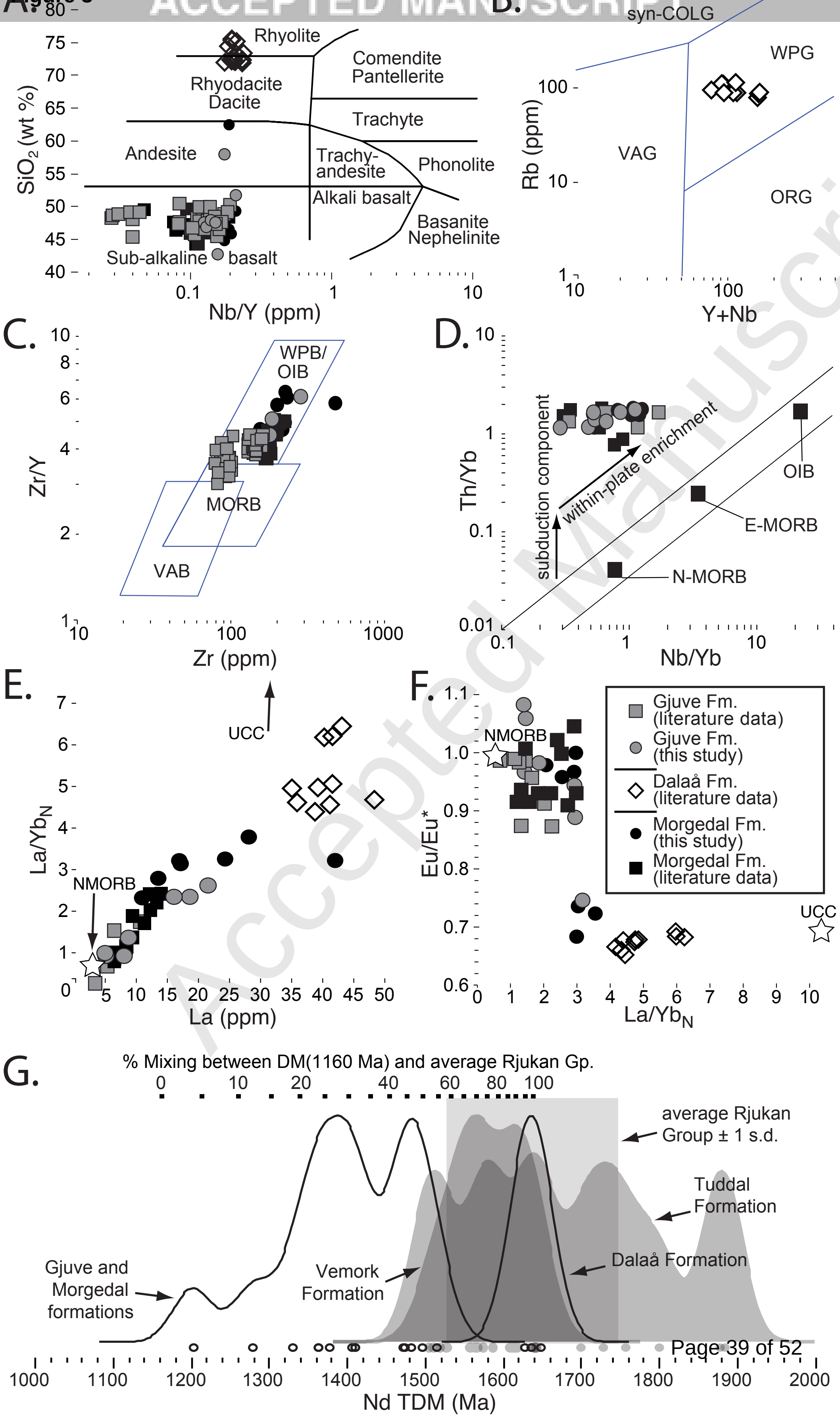

A.
SiO₂ (wt %)
80
75
70
65
60
55
50
45
40
Rhyolite
Rhyodacite
Dacite
Comendite
Pantellerite
Trachyte
Andesite
Trachy-andesite
Phonolite
Alkali basalt
Basanite
Nephelinite
Sub-alkaline basalt
0.1
1
10
Nb/Y (ppm)
B.
1000
syn-COLG
WPG
100
Rb (ppm)
VAG
10
ORG
1
10
100
Y+Nb
C.
10
8
6
4
2
1
Zr/Y
WPB/
OIB
MORB
VAB
10
100
1000
Zr (ppm)
D.
10
1
0.1
0.01
Th/Yb
subduction component
within-plate enrichment
OIB
E-MORB
N-MORB
0.1
1
10
Nb/Yb
E.
7
6
5
4
3
2
1
0
La/Yb_N
UCC
NMORB
5
10
15
20
25
30
35
40
45
50
La (ppm)
F.
1.1
1.0
0.9
0.8
0.7
0.6
Eu/Eu*
NMORB
UCC
0
1
2
3
4
5
6
7
8
9
10
La/Yb_N
Gjuve Fm. (literature data)
Gjuve Fm. (this study)
Dalaå Fm. (literature data)
Morgedal Fm. (this study)
Morgedal Fm. (literature data)
G.
% Mixing between DM(1160 Ma) and average Rjukan Gp.
0
10
20
40
60
80
100
average Rjukan Group ± 1 s.d.
Tuddal Formation
Dalaå Formation
Vemork Formation
Gjuve and Morgedal formations
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Nd TDM (Ma)

Figure 4

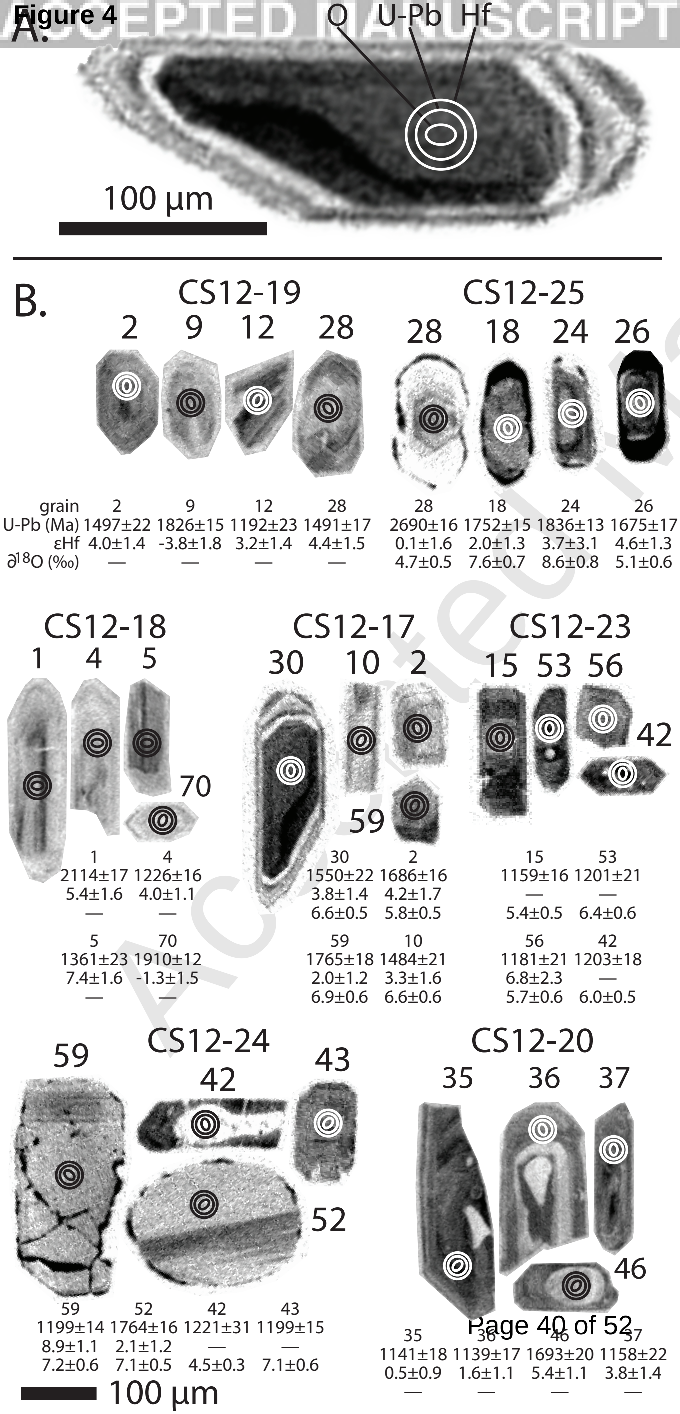

A.
O
U-Pb
Hf
100 µm
B.
CS12-19
2
9
12
28
CS12-25
28
18
24
26
grain 2 9 12 28 28 18 24 26
U-Pb (Ma) 1497±22 1826±15 1192±23 1491±17 2690±16 1752±15 1836±13 1675±17
εHf 4.0±1.4 -3.8±1.8 3.2±1.4 4.4±1.5 0.1±1.6 2.0±1.3 3.7±3.1 4.6±1.3
∂18O (‰) — — — — 4.7±0.5 7.6±0.7 8.6±0.8 5.1±0.6
CS12-18
1
4
5
70
CS12-17
30
10
2
59
CS12-23
15
53
56
42
1 2114±17 5.4±1.6 —
4 1226±16 4.0±1.1 —
5 1361±23 7.4±1.6 —
70 1910±12 -1.3±1.5 —
30 1550±22 3.8±1.4 6.6±0.5
2 1686±16 4.2±1.7 5.8±0.5
59 1765±18 2.0±1.2 6.9±0.6
10 1484±21 3.3±1.6 6.6±0.6
15 1159±16 — 5.4±0.5
53 1201±21 — 6.4±0.6
56 1181±21 6.8±2.3 5.7±0.6
42 1203±18 — 6.0±0.5
59
CS12-24
42
43
52
CS12-20
35
36
37
46
59 1199±14 8.9±1.1 7.2±0.6
52 1764±16 2.1±1.2 7.1±0.5
42 1221±31 — 4.5±0.3
43 1199±15 — 7.1±0.6
35 1141±18 0.5±0.9 —
36 1139±17 1.6±1.1 —
46 1693±20 5.4±1.1 —
37 1158±22 3.8±1.4 —
100 µm

Figure 5

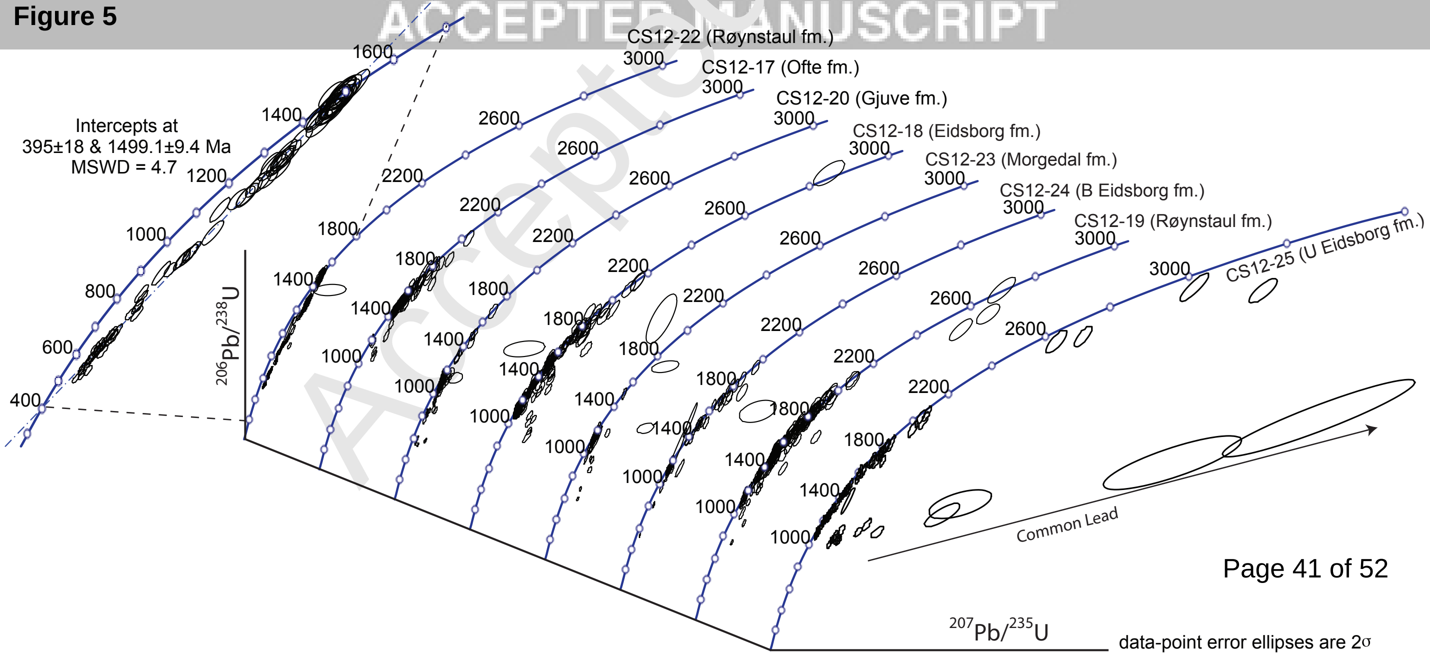

CS12-22 (Røynstaul fm.)
CS12-17 (Ofte fm.)
CS12-20 (Gjuve fm.)
CS12-18 (Eidsborg fm.)
CS12-23 (Morgedal fm.)
CS12-24 (B Eidsborg fm.)
CS12-19 (Røynstaul fm.)
CS12-25 (U Eidsborg fm.)
Intercepts at
395±18 & 1499.1±9.4 Ma
MSWD = 4.7
400
600
800
1000
1200
1400
1600
1800
2200
2600
3000
Common Lead
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
data-point error ellipses are 2σ

Figure 6

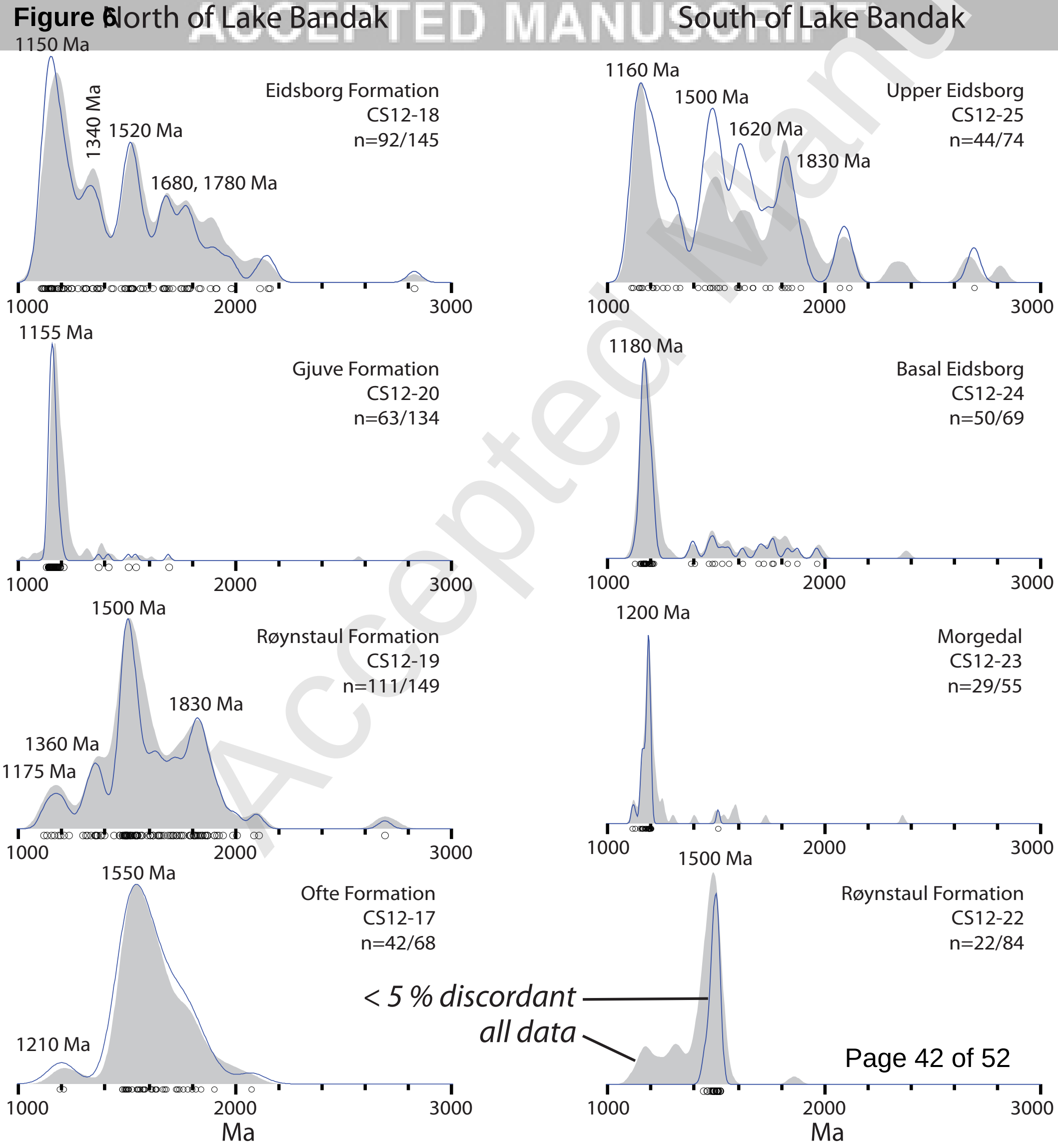

North of Lake Bandak
South of Lake Bandak
1150 Ma
1340 Ma
1520 Ma
1680, 1780 Ma
Eidsborg Formation
CS12-18
n=92/145
1000
2000
3000
1160 Ma
1500 Ma
1620 Ma
1830 Ma
Upper Eidsborg
CS12-25
n=44/74
1000
2000
3000
1155 Ma
Gjuve Formation
CS12-20
n=63/134
1000
2000
3000
1180 Ma
Basal Eidsborg
CS12-24
n=50/69
1000
2000
3000
1500 Ma
1830 Ma
1360 Ma
1175 Ma
Røynstaul Formation
CS12-19
n=111/149
1000
2000
3000
1200 Ma
Morgedal
CS12-23
n=29/55
1000
2000
3000
1550 Ma
1210 Ma
Ofte Formation
CS12-17
n=42/68
1000
2000
3000
Ma
1500 Ma
Røynstaul Formation
CS12-22
n=22/84
< 5 % discordant
all data
1000
2000
3000
Ma

Figure 7 grayscale

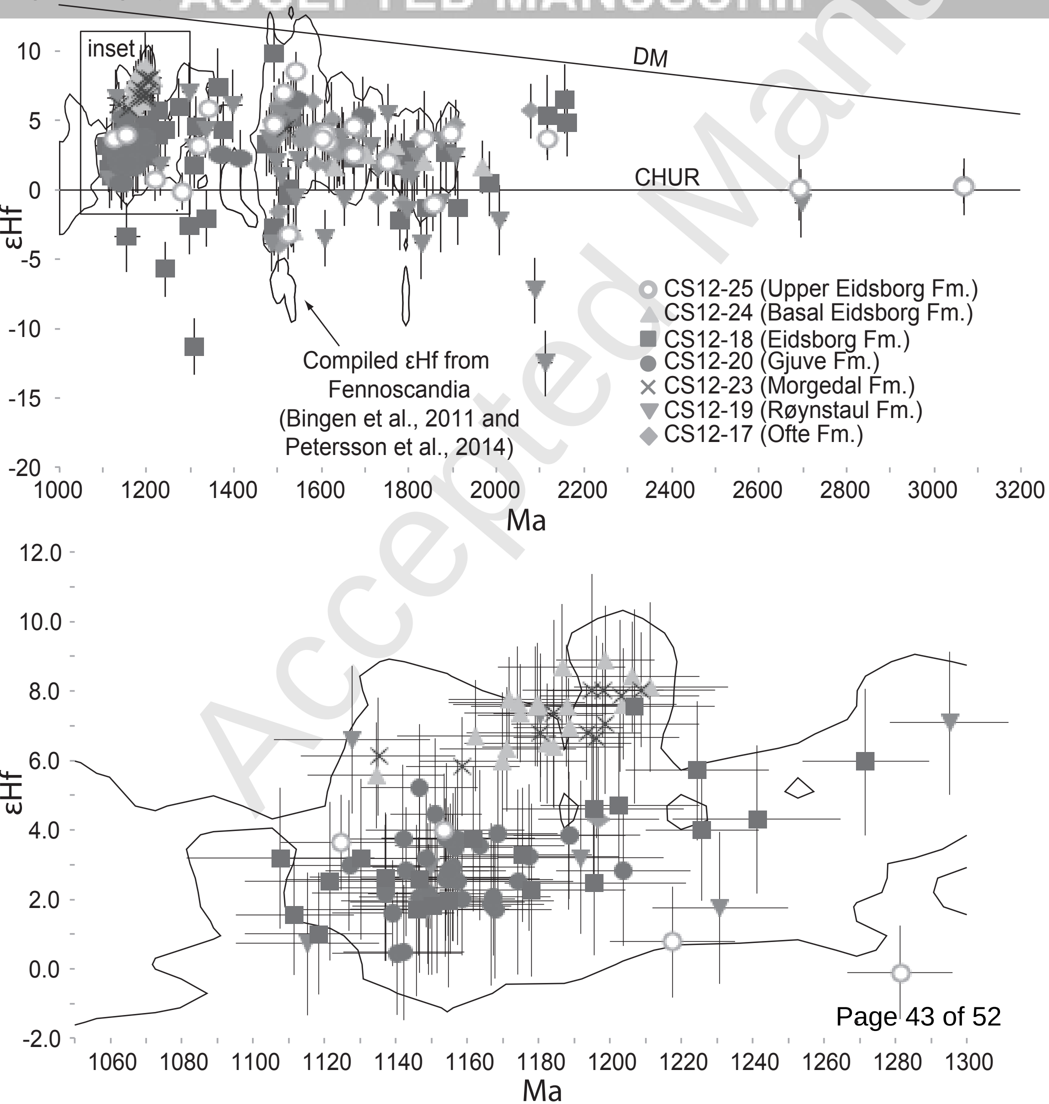


Figure 7 color

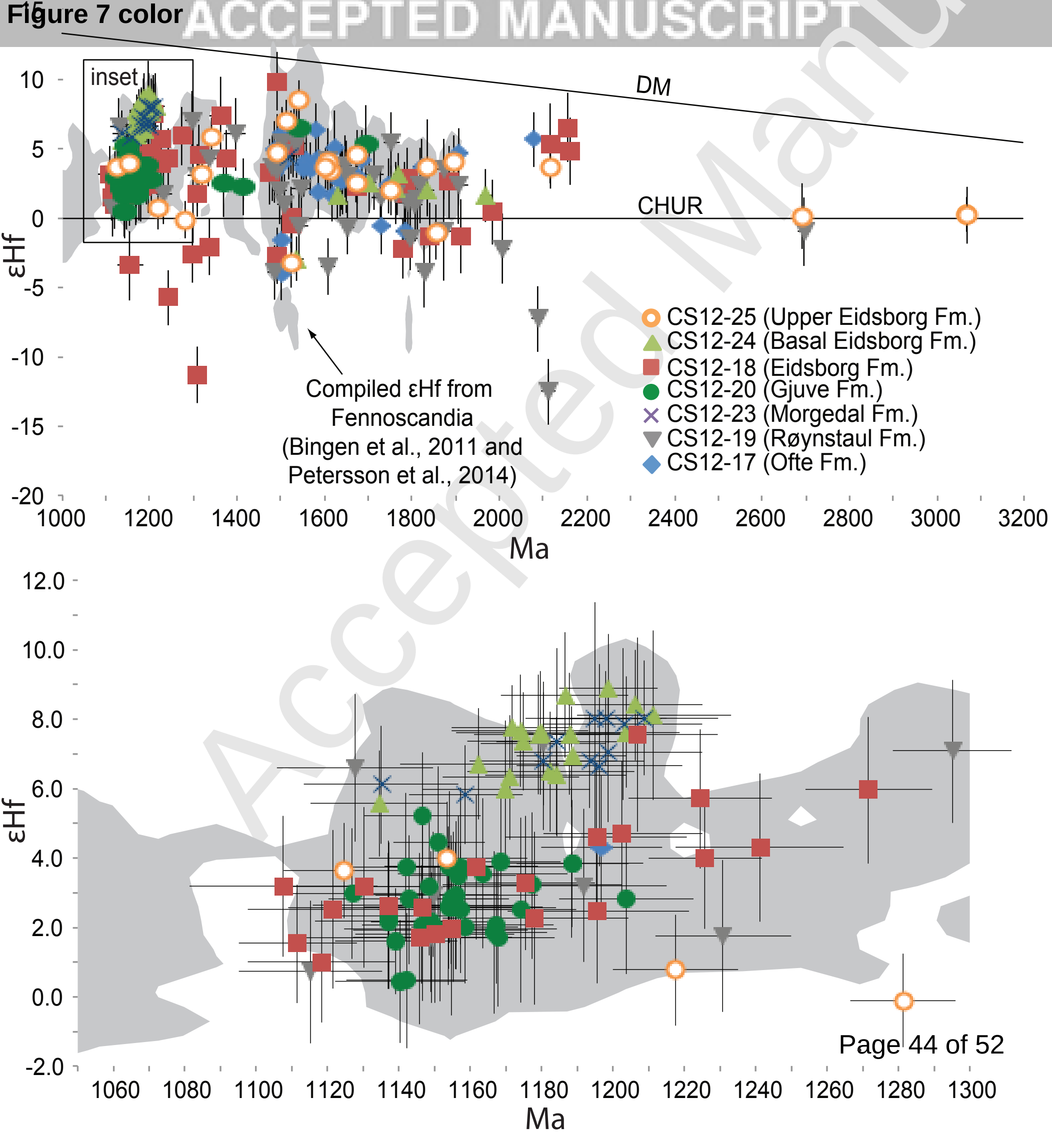


Figure 8 grayscale

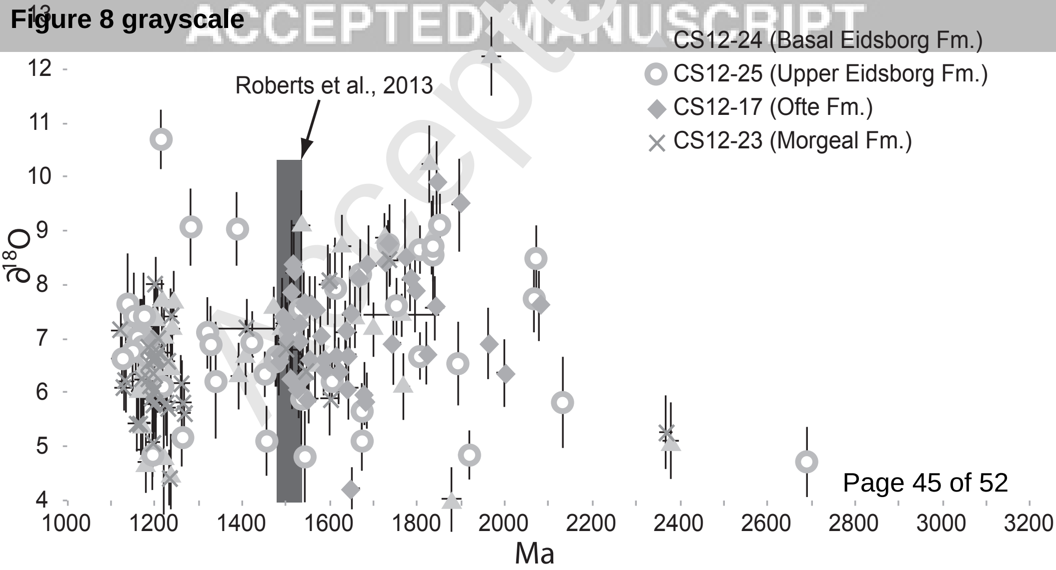


Figure 8 color

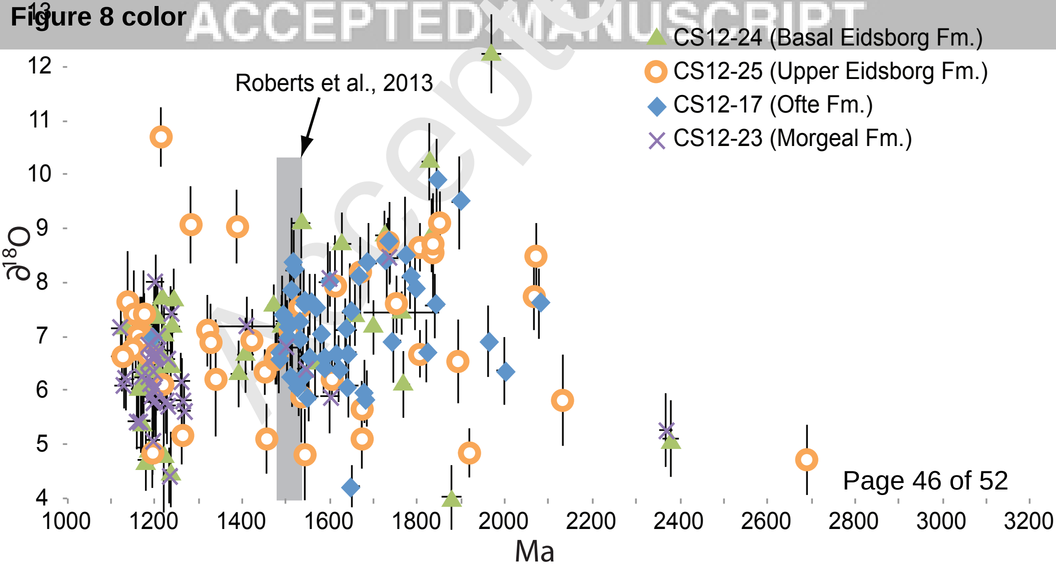


Figure 9 grayscale

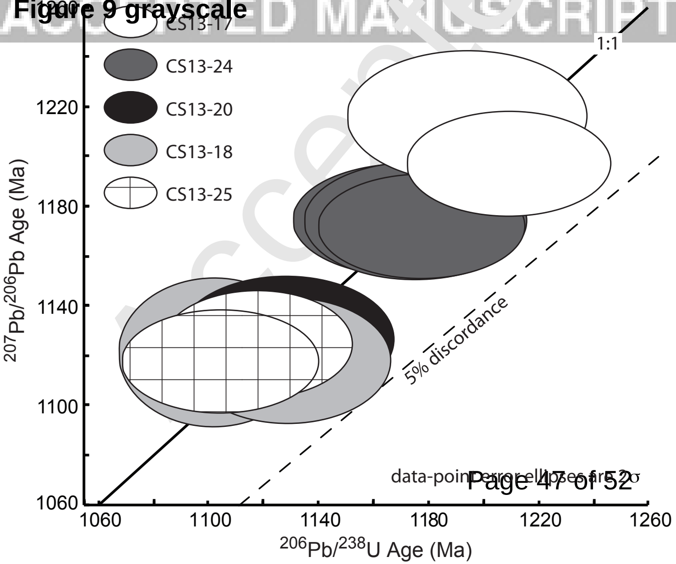


Figure 9 color

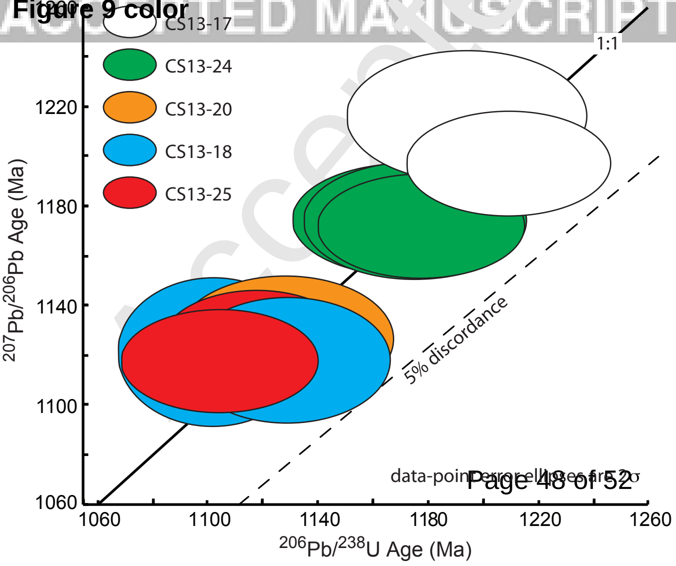


Figure 10

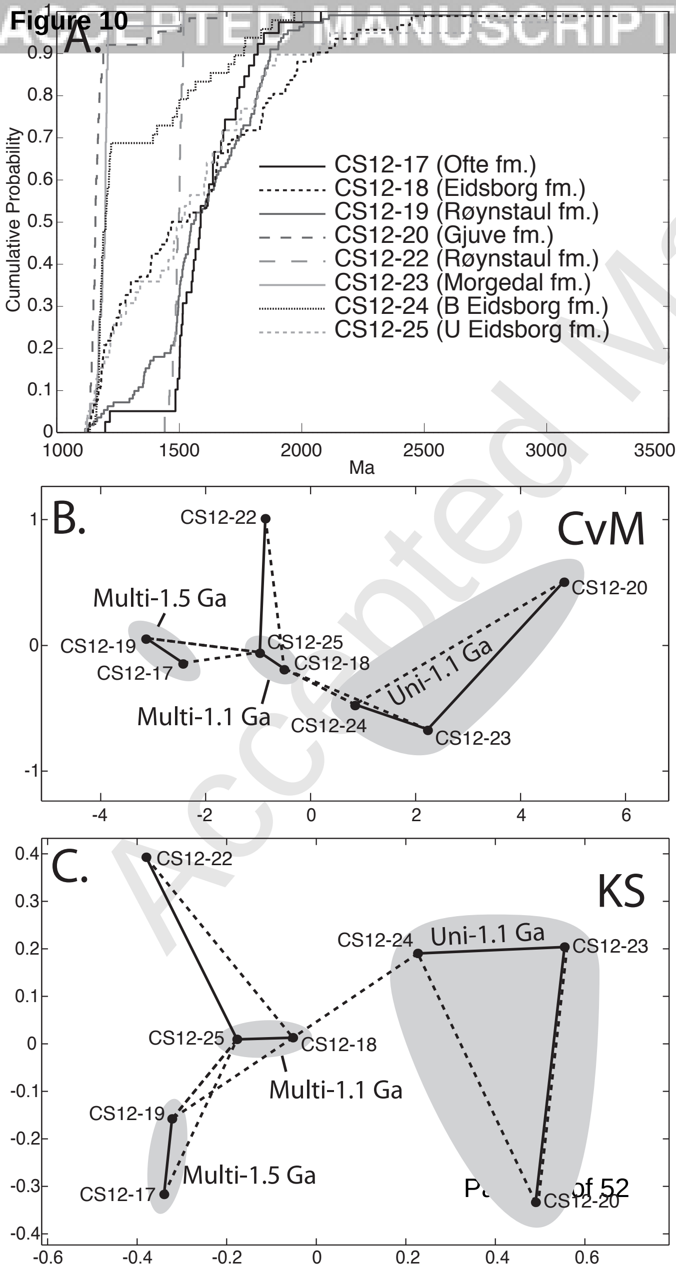

A.
Cumulative Probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1000
1500
2000
2500
3000
3500
Ma
CS12-17 (Ofte fm.)
CS12-18 (Eidsborg fm.)
CS12-19 (Røynstaul fm.)
CS12-20 (Gjuve fm.)
CS12-22 (Røynstaul fm.)
CS12-23 (Morgedal fm.)
CS12-24 (B Eidsborg fm.)
CS12-25 (U Eidsborg fm.)
B.
CvM
CS12-22
Multi-1.5 Ga
CS12-19
CS12-17
CS12-25
CS12-18
Multi-1.1 Ga
CS12-24
CS12-23
Uni-1.1 Ga
CS12-20
1
0
-1
-4
-2
0
2
4
6
C.
KS
CS12-22
CS12-24
Uni-1.1 Ga
CS12-23
CS12-25
CS12-18
Multi-1.1 Ga
CS12-19
CS12-17
Multi-1.5 Ga
CS12-20
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

Figure 11 grayscale

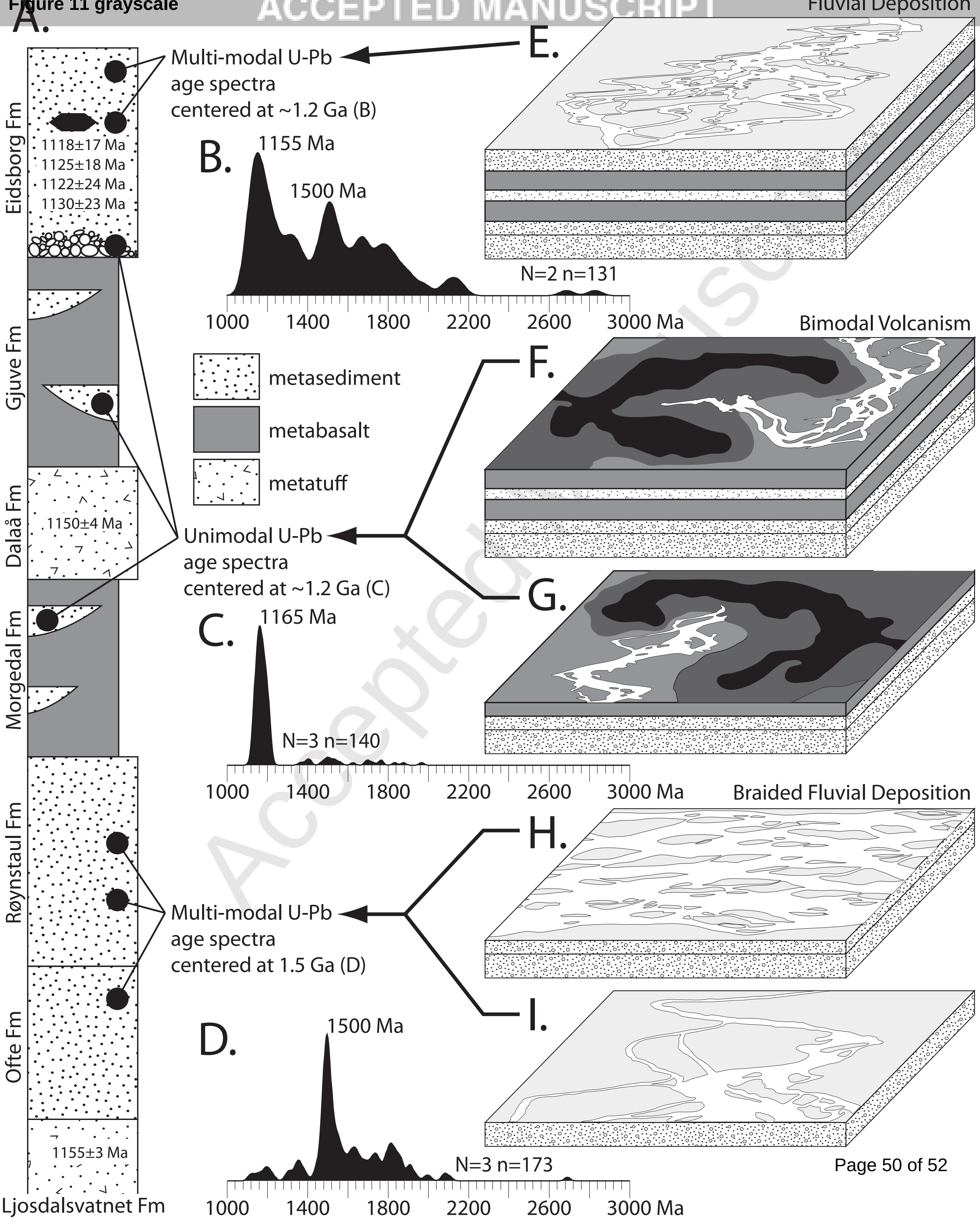


Figure 11 color

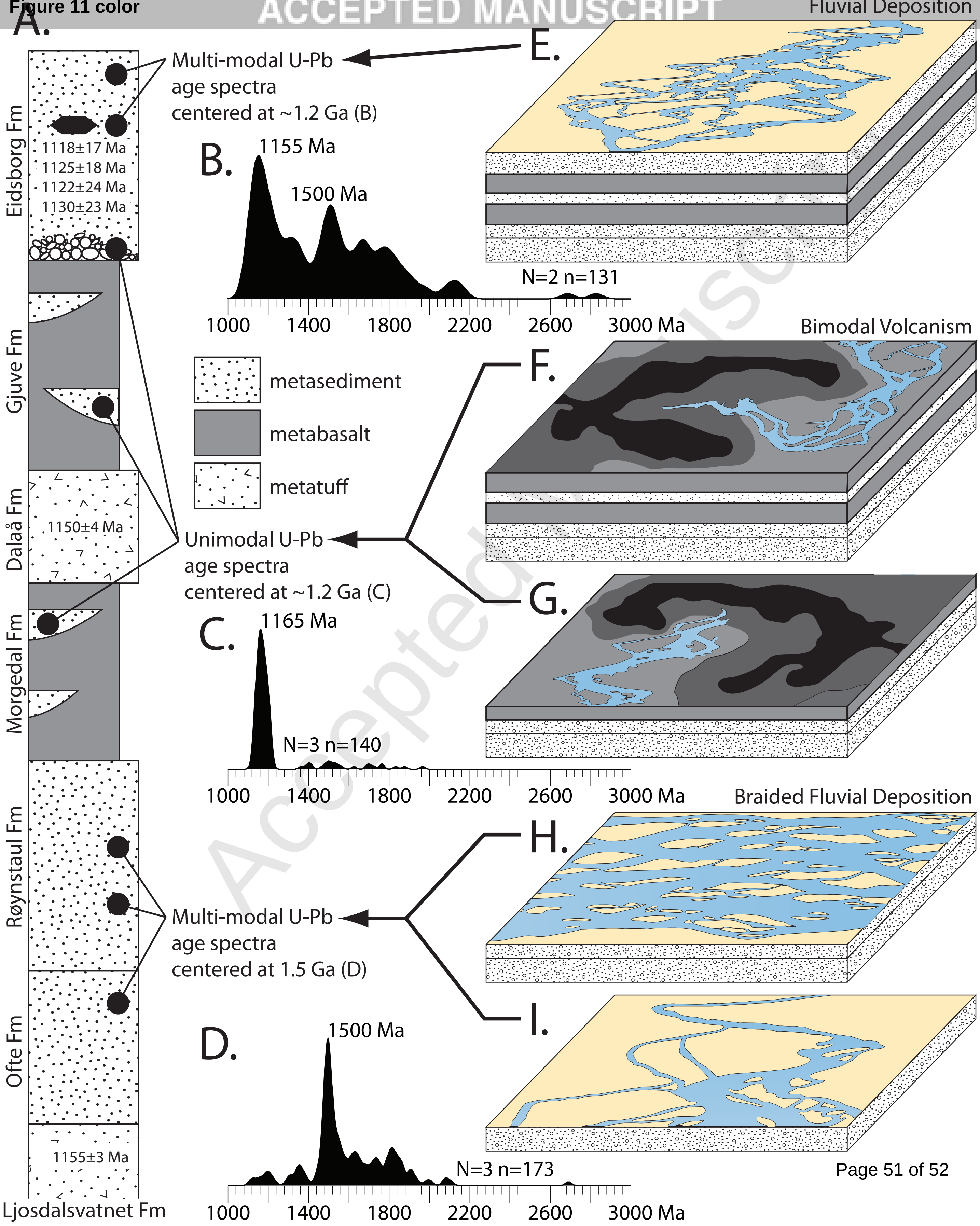
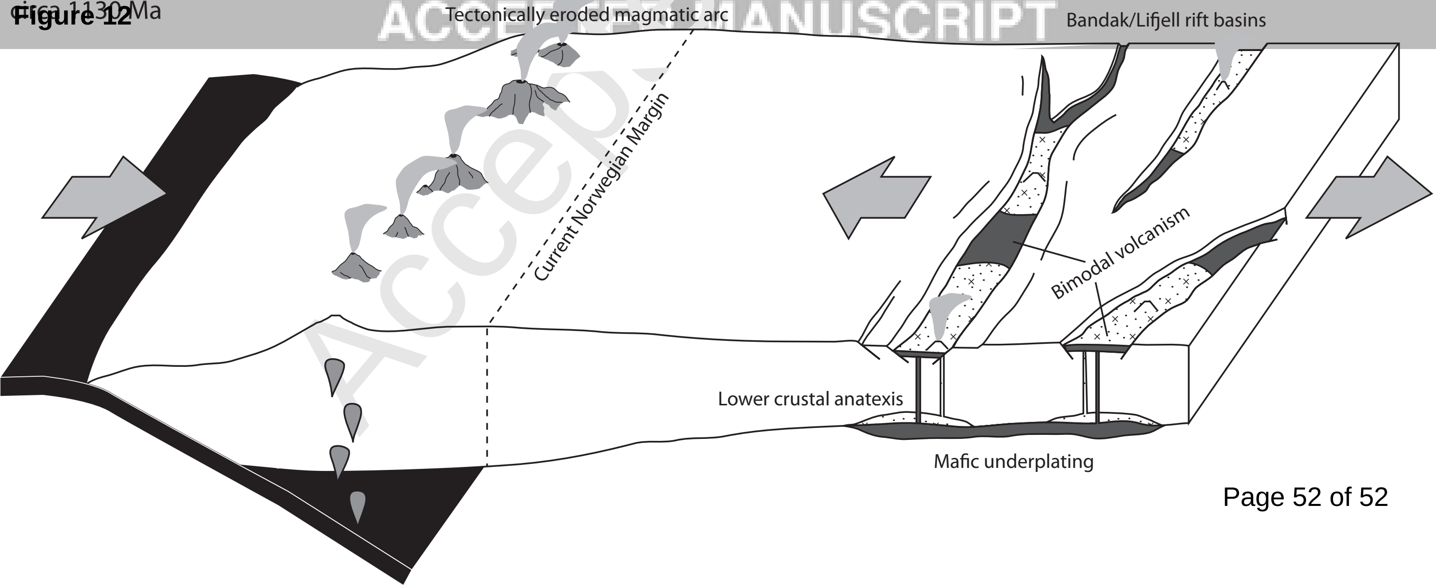


Figure 12


circa 1130 Ma
Tectonically eroded magmatic arc
Bandak/Lifjell rift basins
Current Norwegian Margin
Bimodal volcanism
Lower crustal anatexis
Mafic underplating