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Cover Figure: *Mesoproterozoic Brattefjell Formation in Telemark, southern Norway*

Sedimentology of the Mesoproterozoic Telemark basin-fills, South Norway: implications for sedimentation processes, depositional environments and tectonic evolution

JUHA KÖYKKÄ

Academic dissertation to be presented, with the assent of the Faculty of Science of the University of Oulu for public defense in Auditorium GO101, Linnanmaa, on 25th March 2011, at 12 noon.

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Sedimentology of the Mesoproterozoic Telemark basin-fills, South Norway: implications for sedimentation processes, depositional environments and tectonic evolution

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Abstract

This thesis comprises six original papers that focus on the sedimentology of the Mesoproterozoic (1.6–1.0 Ga) Telemark basin-fills in southern Norway, known as the Telemark supracrustal rocks. It is made up of an approximately 10-km-thick succession of volcanic-sedimentary rocks that are an integral part of the Fennoscandian Shield and record ca. 400 Ma years of sedimentation during evolving tectonics. This study takes a multifaceted approach to the research of volcanic-sedimentary succession, including regional mapping and lithostratigraphy, facies analysis, sequence stratigraphy, clastic petrofacies analysis, geochemistry, and sedimentary basin paleotectonic reconstruction. The combination of these approaches is necessary to understand a sedimentary basin as a dynamic system and to reveal ancient sedimentation processes, depositional environments, and tectonic evolution for building a coherent tectonic-sedimentary model. The main aim of this study is to understand the effects of autogenic (internal) and allogenic (external) processes on the depositional systems and geochemical compositions of the Telemark basin-fills.

The studied formations comprise alluvial fan, braidplain, fluvial, tidal, estuarine-lagoon, and shallow marine depositional environments. This study concludes that the Telemark basin-fills carry a testimony of the tectonic and sedimentary evolution from an extensional continental rift to a strike-slip influenced tectonic setting. These basin tectonic regimes are separated with a first-order unconformity, which represents a ca. 170 Ma hiatus in the stratigraphic record. The provenance studies show that at the early stage of the basin evolution, at around 1.5 Ga, the Telemark sedimentation basin was likely located near the Laurentia supercontinent and moved to its present location along a sinistral strike-slip fault. The sedimentological and geochemical studies in this study indicate that the evolution of the basin rifting, in the Telemark, can be subdivided into (i) syn-rift, (ii) late-syn rift, (iii) early-post rift, and (iv) late-post rift stages, which are characterized by different volcanic-sedimentary patterns. The syn-rift stage comprises deposition of the volcanic-sedimentary Rjukan, Vemork, and Heddersvatnet formations. This was followed by the late syn-rift stage and marine-tidal sedimentation of the Gausta, Bondal, and Lauvhovd formations. The early and late post-rift stages comprise the transition from fluvial to marine-tidal sedimentation, and the deposition of the Skottsfjell, Vindsjå, and Brattefjell formations. The allogenic (external) process caused a fluctuating base level, which created an accommodating space for basin-fills during the pure extensional tectonics. The lack of a deepwater sedimentation prism and oceanic crust, and the non-evolution to passive margin indicate that the rifting failed to complete the continental break-up. At the strike-slip stage, the faulting and volcanism of the basin was likely activated either at a later stage or in certain individual basins. The strike-slip stage comprises deposition of the early Sveconorwegian units in diverse sedimentation environments.

This study shows that although limited outcrops of the Precambrian bedrock can be deformed and metamorphosed, it is possible to build a coherent paleotectonic reconstruction of the ancient sedimentation basin. The main findings of this thesis are: (i) interpretation of sedimentation processes and reconstruction of depositional environments, for the key formations of the Telemark basin-fills; (ii) finding of sediment provenance for the studied rift basin; (iii) discovery of alteration of the bedrock in ancient periglacial climate along one of the prominent first-order unconformity in Telemark; (iv) construction of a comprehensive tectonic-sedimentary model for the Telemark basin-fills; (v) building a plate reconstruction.

Keywords: basin analysis, depositional environment, geochemistry, lithofacies, lithostratigraphy, Mesoproterozoic, Precambrian evolution, provenance, sedimentology, sedimentation processes, South Norway, tectonic setting, Telemark.

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Oulu, February 2011 Juha Köykkä

Abbreviations

2D	two-dimensional
3D	three-dimensional
CH_4	methane
CIA	chemical index of alteration
CO	carbon monoxide
CO_2	carbon dioxide
Ga	billion years
H_2	hydrogen
H_2O	water
Hf	hafnium
HREE	heavy rare earth elements
Ka	thousands years
Ma	million years
LA-ICP-MS	laser ablation with inductively coupled mass spectrometer
Lu	lutetium
N_2	nitrogen
Pb	lead
REE	rare earth elements
U	uranium
yr	years
Yb	ytterbium
XRF	x-ray fluorescence

List of original papers

This thesis is based on the following six papers, referred to as Papers I, II, III, IV, V, and VI.

I Köykkä, J., 2010. Lithostratigraphy of the Mesoproterozoic Telemark supracrustal rocks, South Norway: revision of the sub-Heddersvatnet unconformity and geochemistry of basalts in the Heddersvatnet Formation. *Norwegian Journal of Geology 90, 49–64.*

II Köykkä, J., 2011. Precambrian alluvial fan and braidplain sedimentation patterns: example from the Mesoproterozoic Rjukan Rift Basin, southern Norway. *Sedimentary Geology 234, 89–108.*

III Köykkä, J., Lamminen, J., 2011. Tidally influenced clastic epeiric sea at a Mesoproterozoic continental margin, Rjukan Rift Basin, southern Norway. *Precambrian Research 185, 164–182.*

IV Lamminen, J., Köykkä, J., 2010. The provenance and evolution of the Rjukan Rift Basin, Telemark, south Norway: the shift from a rift basin to an epicontinental sea along a Mesoproterozoic supercontinent. *Precambrian Research 181, 129–149.*

V Köykkä, J., Laajoki, K., 2009. Mesoproterozoic frost action at the base of the Svinsaga Formation, central Telemark, South Norway. *Norwegian Journal of Geology 89, 291–303.*

VI Köykkä, J., in press. The sedimentation and paleohydrology of the Mesoproterozoic stream deposits in a strike-slip basin (Svinsaga Formation), Telemark, southern Norway. *Sedimentary Geology, doi:10.1016/j.sedgeo.2011.01.010.*

Contributions

The following table indicates the major contributions of the authors of the original research articles.

Table 1. Contributions. JK= Juha Köykkä, JL= Jarkko Lamminen, KL= Kauko Laajoki, KS= Kari Strand, JPN= Johan Petter Nystuen, TA= Tom Andersen.

Paper	I	II	III	IV	V	VI
Planning	JK, KL	JK, KL	JK, JL	JL, JK	JK, KL	JK, KL
Data collection	JK, KL	JK, KL	JK, JL, KL	JL, JK, KL	JK, KL	JK, KL
Data analysis	JK	JK	JK, JL	JL, JK	JK, KL	JK
Interpretation of results	JK	JK	JK, JL	JL, JK	JK, KL	JK
Manuscript preparations	JK, KL	JK, KL, KS	JK, JL, KL, KS	JL, JK, KL, KS, JPN, TA	JK, KL	JK, KL, KS

All the data and material used in this thesis was collected by authors. The planning and data collection in the Papers I and II were done by JK and KL. Data analysis and interpretations of the results, in Papers I and II, were done by JK. KL commented Papers I and II and KS commented paper II. Papers I and II were written by JK.

Planning, data analysis, and interpretation of the results in Papers III and IV were done by JK and JL. Data collection, in Papers III and IV, was done by JK, JL, and KL. KL and KS commented Paper III and KL, KS, JPN, and TA commented Paper IV. Both Papers were written by JK and JL.

Planning, data collection, data analysis, interpretation of the results, and writing in Paper V were done by JK and KL. Planning and data collection in Paper VI were done by JK and KL. Data analysis and interpretation of the results in Paper VI were done by JK. KL and KS commented Paper VI and it was written by JK.

Contents

1 Introduction

Precambrian time encompasses approximately 88 % of Earth's geological history between 4600 and 542 Ma. Clastic sedimentary deposits can be traced back to ca. 3.9 Ga, when the Earth was approximately 250 Ma years young (Wilde et al., 2001). These deposits provide fundamental information about the ancient atmospheric and environmental conditions (e.g., Altermann and Corcoran, 2002). Precambrian sedimentation basin is considered to be repository for the accumulation of succession of sedimentary and/or volcanic rocks, whose fill has a somewhat significant preserved surface area and total thickness (Eriksson et al., 2001). Tectonic regimes, which control the formation and evolution of sedimentary basins, were more erratic in terms of origin and rates during the Precambrian (Eriksson et al., 1998, 2004, 2005, 2007). The rates and intensities of processes in Precambrian sedimentary paleoenvironments differ significantly from the Phanerozoic ones, as a result of the lack of vegetation, faster rotation of Earth, faint young Sun, reduced albedo, abundant greenhouse gases, rapid microtectonism, dominant volcanism, and other biological and climatic differences (Eriksson et al., 1998, 2004, 2005, 2007, 2009). By studying and understanding Precambrian geological processes and sedimentary paleoenvironments, is the key to comprehending present-day geological and ecological systems. Thus, the Precambrian past is the key to the present and to the true understanding of the Earth history and fundamental Earth processes (e.g., Altermann and Corcoran, 2002; Bose et al., 2010).

Sedimentology and basin analysis understands sedimentary basins as geodynamical entities. It is a branch of geology that studies the composition, genesis, and depositional processes of sediments and sedimentary rocks deposited within sedimentary basins. Sedimentation basin is a product of isostatic compensation due to tectono-thermal processes operating at the lithosphere scale. However, from a sedimentological perspective, the formation of a sedimentation basin involves interplay between sediment supply and basin floor subsidence. Basin analysis interprets Earth's geological history and reconstructs past sedimentary environments and the tectonic evolution of sedimentary basins by relying on the fundamental principles of uniformitarianism, actualism, and the law of superposition. These fundamental principles and ideas lead to speculations, hypotheses, theories and models of ancient sedimentary basins, including their sedimentary environments and sedimentation processes.

1.1 The aim of the study

The aim of this study is the sedimentology and evolution of the Mesoproterozoic Telemark basin-fills, which are an important part of the Fennoscandian Shield, in southern Norway. An approximately 10-km-thick volcanic-sedimentary succession, called the Telemark basin-fills or traditionally Telemark supracrustal rocks, records ca. 400 Ma years of Earth's geological history during the Mesoproterozoic Era (1.6–1.0 Ga). The topics of this study primarily include (i) the tectonic evolution of the Telemark area, (ii) the tectonic setting of the reconstructed sedimentary basins, (iii) provenance and lithostratigraphic studies, and (iv) interpretations of depositional and sedimentation patterns in different sedimentary environments. The basic idea is to better understand the effects of autogenic (internal) and allogenic (external) processes (e.g., climate, provenance, tectonics, and sediment supply) on the depositional systems and geochemical compositions of the Telemark basin-fills. The sedimentological and basin analysis methods used in this thesis include regional mapping and lithostratigraphy, facies analysis, sequence stratigraphy, clastic petrofacies analysis, geochemistry, and sedimentary basin paleotectonic reconstruction. A multifaceted approach to the studied basin-fills (the Vemork, Heddersvatnet, Gausta, Skottsfjell, Vindsjå, Brattefjell, Svinsaga formations, and the sub-Heddersvatnet and sub-Svinsaga unconformities) was used because such an approach is necessary to understand a sedimentary basin as a dynamic system. Thus it is possible to reveal ancient depositional processes, depositional environments, and tectonic evolution for building a coherent tectonic-sedimentary model. This is the first comprehensive work dealing with the tectonic-sedimentary evolution of the Telemark basin-fills.

The studied basin-fills and the study area is a classical area of Norwegian geology that has been debated for decades. This study area represents the least deformed Mesoproterozoic rocks in southern Norway, and stratigraphy has already been considered to some degree. In addition, the primary sedimentary features are well preserved, allowing tools for coherent tectonic-sedimentological modeling.

1.2 Previous studies in the Telemark area

Most previous studies in the Telemark area have focused on lithostratigraphic correlation, metamorphosis, geochronology, petrogenesis, and structural-crustal evolution modeling (e.g., Wyckoff, 1934; Dons, 1960a, 1960b, 1962, 1963; Brewer and Atkin, 1987, 1989; Atkin and Brewer, 1990; Dahlgren et al., 1990a, 1990b; Dahlgren and Heaman, 1991; Starmer, 1993; Menuge and Brewer, 1996; Sigmond et al., 1997; Brewer and Menuge, 1998; Laajoki, 1998, 2000, 2002, 2003, 2005, 2006a, 2006b, 2006c, 2009; Bingen et al., 2001, 2002, 2005, 2008b; Andersen et al., 2002a, 2002b, 2004a, 2007; Laajoki et al., 2002; Laajoki and Lamminen, 2004; Andersen, 2005; Corfu and Laajoki, 2006, 2008; Laajoki and Corfu, 2007; Lamminen et al., 2009a, 2009b). The first classical lithological and early lithostratigraphic studies of the Telemark supracrustal rocks are made by Werenskiold (1910), Wyckoff (1934), and Dons (1960a, 1960b, 1962). Werenskiold (1910) describes various conglomerate and quartzite units in the Telemark area, whereas Wyckoff describes the geology of the Mount Gausta area and discovered the first angular unconformity. The first published local map from the Telemark area was presented by Bugge (1931), who introduced some new names to the lithostratigraphic classification. The most detailed and comprehensive of the early lithostratigraphic studies is done by Dons (1960a, 1960b, 1962), who established the first lithostratigraphic framework for the Telemark supracrustal rocks. This framework was slightly modified later by Dahlgren (1990b), but recent authors such as Laajoki et al. (2002), Andersen et al. (2004a), Laajoki (2005), and Laajoki and Corfu (2007) have made new adjustments and correlations, mainly based on regional lithostratigraphical mapping and isotope geochronology. The current lithostratigraphical framework and nomenclature of the Telemark supracrustal rocks was presented in the study by Laajoki et al. (2002).

The development of isotope geochemistry also led to the first studies of geological evolution and geochronology in the Telemark area, which are mainly done by Dahlgren et al. (1990a, 1990b), Dahlgren and Heaman (1991), and de Haas et al. (1999). These studies were followed by short notes by Laajoki and Lamminen (2004) and published studies by Andersen et al. (2002a, 2002b, 2007) and Andersen (2005), which focused on the petrogenesis of granites and gneisses and crustal evolution in the Telemark and southwestern Fennoscandian areas. For several years, Bingen et al.

(2001, 2002, 2005, 2008b) have been correlating, modeling and studying the evolution of continental building in the Sveconorwegian orogeny in southern Norway. More recently, new evidence regarding the Telemark tectonic evolution is presented by Corfu and Laajoki (2008), and short notes presented by Lamminen et al. (2009a, 2009b).

The geochemistry of volcanism, metamorphism, and tectonism in the Telemark area have mainly been studied by Brewer and Atkin (1987, 1989), Atkin and Brewer (1990), Brewer and Menuge (1998), and Menuge and Brewer (1996). These studies were based on isotope geochemistry and whole-rock geochemistry. The only structural research from the Telemark area are mostly based on studies of major fault zones, metamorphic events and field evidence by Sigmond (1985), Starmer (1993), and Sigmond et al. (1997).

No comprehensive sedimentological studies of the Telemark area have been made. Some studies briefly describe the occurrence of different sedimentary structures without offering any detailed analyses (e.g., Wyckoff, 1934; Dons, 1959, 1960a, 1960b, 1962, 1963; Singh, 1969; Dahlgren, 1990b; Andersen and Laajoki, 2003). Wyckoff (1934) describes lithology and sedimentary features in the Mount Gausta area. Dons (1960a, 1960b, 1962, 1963) noted the abundance of ripple marks, cross-bedding and shrinkage cracks in Telemark area, but without making any interpretation of their origin. In addition, Dons (1959) describes nodule-rich deposits in the Dalaå sandstone as possible fossils (*Telemarkites Enigmaticus*). Singh (1969) interprets the Telemark depositions as a possible slow subsidence, shallow water basin with tidal influence. Dahlgren (1990b) and Andersen and Laajoki (2003) briefly states and interprets some of the conglomerate deposits as alluvial fan debris flows, but no details were given. The only detailed sedimentological studies from the Telemark area prior to this study are unpublished M.Sc. theses by Lamminen (2005) and Köykkä (2006a) and a few congress abstracts (Lamminen, 2004, 2006; Köykkä, 2006b, 2006c).

2 Precambrian events and sedimentation systems: a brief review

The interactions of plate tectonics and superplume events with related thermal processes are the primary controls on Earth's geological evolution. The Precambrian rock record contains numerous examples of unique events that affected sedimentation systems and patterns during the evolution of the early Earth. Some of these examples are summarized in Figure 1, and they are discussed here briefly.

The formation of the solar system and Earth from a cloud of dust and gas started ca. 4.57 Ga (Nelson, 2004). The first evidence of oceans and submarine magmatism are ca. 3.7 Ga crusts with pillow structures (Meyers, 2001a, 2001b). However, based on zircon oxygen isotope ratios, authors such as Wilde et al. (2001) suggest the occurrence of liquid water on Earth as early as 4.4 Ga. During the Archean, the mantle heat flow was two to three times higher than during the Phanerozoic, indicating a more erratic mantle convection regime and more catastrophic magmatic events. During the Neoarchean, major changes occurred in Earth's magmatic-tectonic evolution: (i) large igneous provinces and their progenitors increased in frequency from 2.8 to 2.6 Ga (e.g., Condie, 2002); (ii) catastrophic mantle overturn events occurred at a global scale at 2.7 Ga (Nelson, 2004); (iii) the transition to a plate-tectonic dominated Earth occurred at 2.7 Ga; and (iv) the first supercontinent (Kenorland) and the first superplume event occurred at ca. 2.7 Ga (Condie, 1998). The magmatic superplume events that occurred at 2.7 Ga and 1.9 Ga were related to a global eustasy rise, peaks in stromatolites, and changes in ocean chemistry (Eriksson et al., 2004). After Kenorland, a second supercontinent, Columbia or Nuna, was formed ca. 1.8 Ga, and this was followed by Laurentia ca. 1.5 Ga. Around 1.1 Ga, Laurentia was part of the fourth major supercontinent Rodinia.

Before 3.0 Ga, the continental crust covered only about 7 % of Earth, which corresponds to approximately 20 % of the present day volume. This early crust formation was accompanied by the formation of layered mantle and the onset of plate-tectonism, which caused large tsunamis and unconformities (Eriksson et al., 2004). Earth's major crustal growth peaked ca. 2.7 Ga, based on the voluminous juvenile crust or thermal over-printing of pre-existing crust on every continent (Arndt, 2004). These early crustal growth processes were closely associated with oceanic terranes followed by passive continental margins and voluminous continental flood basalts. Oceanic terranes such as submarine plateaux or island arcs may have been important building blocks for crustal growth and continents as they collide and accrete to continental margins. Further regional peaks of crustal growth occurred ca. 2.5–1.8 Ga, which indicate possible tectonically active periods. The continental crust formation was related to mantle plume events and plate tectonic subduction processes. Although there have been differing opinions, Nutman et al. (2002) suggested that tectonic processes, which were mostly related to volcanic arc settings, were operating already at ca. 3.8 Ga.

The evolution of the Precambrian paleo-atmospheric and paleo-hydrospheric compositions are mainly based on two different models (Eriksson et al., 2009 and references therein): (i) a model that assumes an early reducing atmosphere, a minor oxygen rise at 3.0–2.8 Ga, and a major oxygen rise at 2.0 Ga; and (ii) a model that assumes a single rise of oxygen in the atmosphere and oxygenic oceans soon after 4.0 Ga. Recent studies by Eriksson et al., (2009) assume that the "great oxidation event" at 2.3 Ga may have been gradational and even diachronous across the Earth's cratons at that time. Oceanic growth was concurrent with atmospheric development, and at ca. 4.0 Ga, 90 % of the current oceanic volume was achieved. Oceanic water depths during that time were probably abyssal, with an absence of biogenic planktonic sedimentation. The formation of ironstones (IF and BIF) during the Paleoproterozoic-Mesoproterozoic (peaks ca. 3.8, 2.5, and 1.8 Ga) was likely related to iron-rich waters as a result of fumarolic origin beneath the pycnocline and oxygen released by photosynthetic cyanobacteria above the pycnocline. The lack of major iron formation during the Mesoproterozoic was likely caused by increased oceanic oxidation due to increasing organism populations and photosynthesis.

During the early evolution of Earth, the atmosphere was mainly composed of CO_2, N_2, CH_4, and possibly small amounts of CO, H_2, H_2O and reduced sulphur gases (e.g., Des Marais, 1994). The elevated green-house gas levels in Earth's early paleo-atmosphere raised weathering rates, and geothermal activity, and acidic waters led to the aggressive breakdown of rocks, which probably affected the deposition of first-cycle quartz arenites (Corcoran and Mueller, 2004). After 2.0 Ga, the red beds became increasingly common in many successions, indicating the presence of free oxygen at that time (Eriksson and Cheney, 1992).

The geochemistry of Precambrian oceans was mainly controlled by reactions with hot magma, sea floor weathering, juvenile water input, and the interactions of fluvial flows (Lambert, 1992; Eriksson et al., 2009). The Paleoproterozoic seawater compositions are thought to be more-or-less similar to the modern seawater composition, which also indicates that the global sea water cycles may not have changed significantly during Earth's history (Lecuyer et al., 1996). Most of the oceanic composition changes occurred between 2.8 and 2.0 Ga and were related to the supercontinent cycles, paleoatmospheric changes, sea surface temperatures, and mantle heat flows (e.g., Condie, 2004).

The first known carbonate platforms (ca. 3.0 and 2.7 Ga) were formed by a variety of abiotic and microbial processes driven by tectonic, eustatic, and climatic components. The Archean and Paleoproterozoic carbonate depositions formed mostly rimmed platforms in which a large proportion of the carbonate was precipitated directly onto the seafloor. During the Mesoproterozoic, the seafloor cement precipitation was greatly diminished except in platforms where contemporaneous evaporates were deposited and stromatolites show greater textural diversity than in older rocks (Grotzinger and James, 2000). Similarities in structural-sedimentary settings and textural-mineralogical characteristics indicate analogous microbiotic and calcification processes for the Precambrian and Phanerozoic carbonate rocks (e.g., Altermann, 2004). The first Precambrian glaciations occurred at 2.4–2.3 Ga. These glaciations were related to supercontinent assembly (and thus low CO_2 drawdown) and low paleolatitudinal locations, leading to increasing albedo (Young, 2004). The younger glaciations were probably related to global sea level lowstand, tectonic and paleoclimatic factors (Frimmel, 2004).

The oldest known zircons date back to 4.4–4.0 Ga. The zircons were probably crystallized during early felsic differentiation (Nelson, 2004), whereas the Earth's rock record begins with the 4.03-Ga-old Acasta Gneiss Complex in Canada (e.g., Williams, 1999). The earliest Archean sedimentary basins (> 3.3 Ga) were controlled by normal faults that linked shallow felsic intrusions with other basin-fills (Nijman and de Vries, 2004). During the Archean, the geodynamics changed from extensional crustal evolution to compressional tectonics, and clastic sedimentation patterns corresponded to more rapid plate motions. The first sedimentation basin patterns at ca. 4.0–3.2 Ga were probably a combination of intra-oceanic island-arcs, oceanic plateaus and plate tectonic collision processes or more stable proto continents (Windley, 1995; Nijman and de Vries, 2004). Although the early basin-fills were dominated by komatites and tholeites, there is are also evidence of passive margin carbonates, banded-iron formations, stromatolites, evaporates, pelites and quartzites as well as synorogenic turbidites, conglomerates and sandstones (Windley, 1995). According to Eriksson et al. (2007), the Mesoarchean sedimentary paleoenvironments were dominated by alluvial fans, braided fluvial styles, shallow marine settings, turbidites, and tidalites associated with erratic tectonism. According to Mueller and Corcoran (2001) and Eriksson et al. (2007), these synorogenic volcanic-sedimentary greenstone successions exhibit subaerial and subaqueous sedimentary rocks interbedded with volcanic material. The earliest evidence of sedimentary recycling was found in South Africa (the Kaapvaal Craton) in a retroarc foreland basin (Catuneanu, 2001). During the Archean, sedimentary patterns were commonly characterized by trangressive-regressive fluctuations in different sedimentary environments, reflecting fining- and coarsening-upward sedimentation patterns in proto-cratonic settings. The orogenic quiescence at 2.6–2.4 Ga is associated with global cratons, large epeiric basins, and passive margins (Windley, 1995). The earliest carbonate-banded-iron formation sequence, at 2.6–2.4 Ga, was probably linked to a eustatic sea level rise. After Archean, tectonic stability led to more common rift and strike-slip basins (Mueller and Corcoran, 1998), with syn-rift volcanic rocks followed by alluvial fans and braided streams. Again, high-energy shallow marine sedimentation was accompanied by intensive weathering.

In Paleoproterozoic to Mesoproterozoic time, the shallow marine nearshore environments were sandstone dominated high-energy settings. In addition, sediment influx and subsidence was probably more finely balanced than in Phanerozoic settings (Eriksson et al., 1998). Overall, littoral barrier-island systems and lagoonal deposits are rare in the Precambrian strata, possibly due to erosional effects by wave scouring during transgression. The lack of stabilizing vegetation combined with rapid erosion, intensive weathering, generally higher basin subsidence rates and steeper topographic slopes during the Precambrian reflect wide and shallow shelves, thick and immature delta sequences and lobes, and braid-dominated fluvial and tidal channels. Fluvial and alluvial fan environments were probably high-energy, with abundant flood-cycles and the presence of coarse-grained materials. Epeiric seas were closely associated with these continental fluvial settings. Eolian ergs became abundant only at 1.8 Ga and re-mained abundant thereafter. This late appearance is possibly due to poor recognition or preservation potential or to paleoclimatic differences. Glacial and periglacial deposits resemble those in the Phanerozoic environments except that the Paleoproterozoic and Neoproterozoic deposits are biased with glaciomarine deposits and loess deposits. The loess deposits, which fringe continental areas, are missing from the ancient strata.

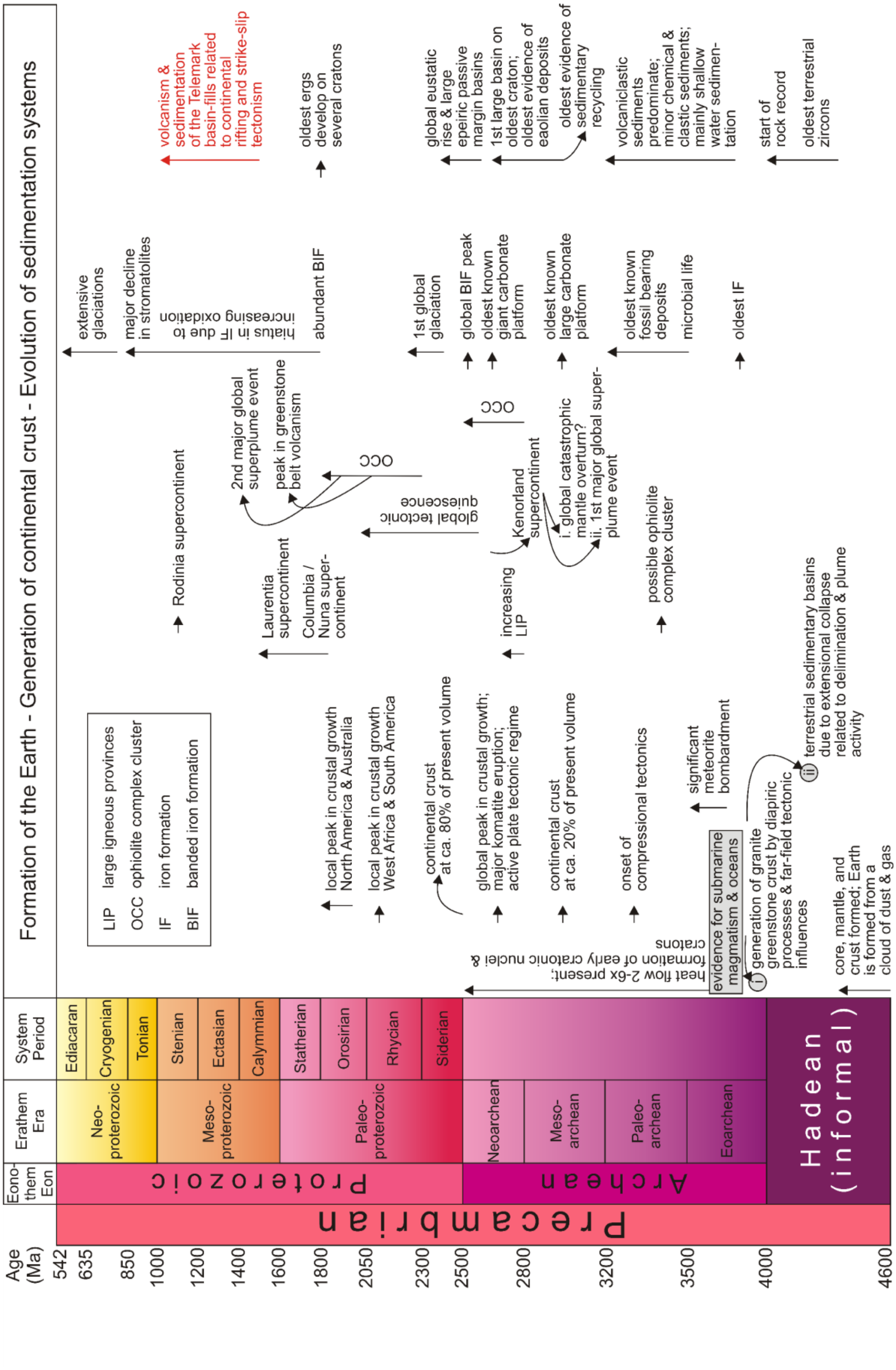

Fig. 1. Summary time-chart illustrating some key events during the Precambrian (modified from Eriksson et al., 2004).

3 Geological setting of the Telemark supracrustal rocks

The Fennoscandian Shield is the northern part of the (proto)Baltica or the East European Craton (review in Gorbatschev and Bogdanova, 1993; Bogdanova et al., 2008). It is composed of an Archean core in the northeast and progressively younger Proterozoic crustal domains towards the southwest. The East European Craton (EEC) was formed between 2.0 and 1.7 Ga by the successive collision of three once autonomous crustal segments or blocks (e.g., Bogdanova et al., 2008). These segments or blocks are Fennoscandia to the northwest, Sarmatia to the south and Vologo-Uralia to the east, which each of them comprises Archean and Proterozoic crust (Fig. 2 insert). The assembly of the EEC began at ca. 2.0 Ga when Sarmatia and Vologo-Uralia joined each other to form the Volgo-Sarmatian protocraton. The Volgo-Sarmatian protocraton existed as a separated until ca. 1.8–1.7 Ga when it docked with Fennoscandia forming a unified craton.

The Archean evolution of Fennoscandia can be traced back to ca. 3.5–3.2 Ga, when a continental core was created in present southeastern part. Between 3.1–2.7 Ga several events of accretion formed the larger Fenno-Karelian protocontinent, while minor continental blocks of that age occur farther northeast (Bogdanova et al., 2008). From 2.5 to 2.0 Ga, the Archean craton was rifted and disturbed, and small ocean were opened, and eventually a wide passive margin was developed along the present southwestern and southern edges of the former craton (e.g., Lahtinen et al., 2005; Bognanova et al., 2008). The formation of continental crust in present southwestern Fennoscandia took place during several episodes of accretion between 1.95 and 1.85 Ga. (Lahtinen et al., 2005). After 1.85 Ga, the Paleoproterozoic growth of crust continued semi-simultaneously with the collision between Fennoscandia and Volgo-Sarmatia (Bogdanova et al., 2008). In southeastern Sweden, three episodes of accretion occurred toward the present south-southwest at between 1.83–1.75 Ga, which led to the formation of E-W to NW-SE trending belts of juvenile crust and continental magmatic arcs (e.g., Andersson et al., 2004). After 1.75 Ga, accretionary growth of new crust in the southwestern part of the EEC was resumed and directed toward present west and roughly NS-trending crustal belts were formed. From east to west, the belts are (Fig. 2A): (i) Eastern Segment; (ii) Idefjorden block; (iii) Begna sector; (iv) Bamble and Kongsberg blocks; (v) Telemark block; (vi) Hardangervidda-Rogaland block. During the late Paleoprotorezoic and early Mesoproterozoic, Fennoscandia was part of the Columbia/Nuna supercontinent, and later part of the Laurentia (Fig. 1).

Gothian Orogeny can be described as a ca. 200–250 Ma period of subduction of oceanic crust along the southwestern margin of the Fennoscandia during the 1.66–1.5 Ga (e.g., Brewer et al., 1998; Andersen, 2005; Åhäll and Connelly, 2008). The orogeny evolution was charachaterized by near-continuous oceanward-stepping crustal growth, relative to the active trench, and an average continental growth for major stages of continental magmatism is estimated at ca. 1.6 km/Ma (Åhäll and Connelly, 2008). It is assumed that southwestern part of the Fennoscandia may have formed during the Gothian Orogeny, when fragments of magmatics arcs with limited geochemical character have been accreted onto Fennoscandia in distinct event in the period between ca. 1.66 to 1.5 Ga. (e.g., Brewer et al., 1998; Åhäll et al., 2000). This period of accretionary orogeny was terminated by merging of a continental fragment, making up present-day southern Norway. The subduction event was followed by a period of anorogenic crustal extension magmatism and sedimentation starting at the 1.51–1.50 Ga (Bingen et al., 2005).

The western margin of the EEC was affected by the Sveconorwegian Orogeny at the end of the Mesoproterozoic (ca. 1.14–0.90 Ga), which suggest that Baltica collide with another major plate. Bingen (2005) subdivided the Sveconorwegian Orogeny to four major phases: (i) 1.14–1.05 Ga accretion and local early collision; (ii) 1.05–0.98 Ga continent-continent (Baltica-Amazonia collision); (iii) 0.98–0.96 Ga final convergence; (iv) 0.96–0.90 Ga post-collisional relaxation. Models involving oblique continent-continent collision with significant strike-slip motion between a coherent Baltica-Laurentia margin and possible Amazonia (e.g., Bingen, 2005, 2008a, 2008b). Prior to the major collisional stage, the Sveconorwegian Orogeny shortly followed upon an event of continental magmatism and basin formation in the Telemark, Kongsberg, and Bamble blocks, suggesting extensional or transtensional tectonic regime at the onset of the Sveconorwegian Orogeny.

Collision between then Laurentia and possible Amazonia resulted that the Rodinia supercontinent was formed by the agglunation of the existing cratonic fragments. Rodinia supercontinent -related collisional tectonic affected the southwestern EEC. Passive continental margins heralding incipient break-up began to form along it northeastern, eastern and southeastern peripheries. From the Cryogenian onwards (ca. 0.85–0.60 Ga), rifting of the EEC continued in conjunction with the general dispersal of Rodinia (Pease et al., 2008). The available paleomagnetic data suggest that Laurentia and Amazonia remained attached until at least 600 Ma, since all other cratonic units surrounding Laurentia have already drifted away by that time. The separation between Amazonia and Laurentia remarks the final break-up of Rodinia with opening of the Iapetus Ocean ca. 700 Ma and resulted several rift basins on the Fennoscandia. It is assumed that, for the time between 1.1 and 0.9 Ga, a clock-wise approximately 60^{o} rotation of Baltica in relation to Laurentia is required to satisfy the apparent polar wandering paths for supercontinents (e.g., Bogdavona et al., 2008).

3.1 The Southwest Scandinavian Domain

The area of southwest Sweden and southwest Norway is the youngest crustal component of the Fennoscandian Shield and it has been called the Southwest Scandinavian Domain (SSD, Gaal and Gorbatschev 1987), the Sveconorwegian Belt (Bingen et al., 2008b) and the Sveconorwegian Orogen (e.g., Corfu and Laajoki, 2008). Because this area includes rocks of multiple orogens and ages, ranging from the late Paleoproterozoic to late Mesoproterozoic, it is more appropriate to call it the SSD. The SSD is structurally complex and includes several Precambrian fault zones and shear zones that generally run north to south and subdivide the area into several structural parts. The Precambrian bedrock areas bordered by these fault and shear zones have been called sectors, terranes and blocks. The tectonostratigraphic status of these crustal entities is somewhat unclear, so the non-genetic “block” terminology introduced by Andersen (2005) is preferred, and a modified version of it is used here (Figs. 2A and B).

The SSD is bordered in the east by the approximately 1400-km-long Transscandinavian Igneous Belt (TIB). The TIB ranges from 1.86 to 1.66 Ga and consists mainly of alkali-calcic granitoids and their volcanic equivalents, and minor mafic rocks (e.g., Gorbatschev, 2004 and Fig. 2A). The TIB is considered a continental magmatic arc that developed along the central axis (running NNW-SSE) of the present-day Fennoscandian Shield. The magma of the TIB rocks was likely formed by the remelting of older Svecofennian rocks with minor mafic additions (Högdahl et al., 2004).

The Eastern Segment, to the west of the TIB, is a parautochthonous crustal domain with a fault contact and it consists of reworked TIB rocks. It is bounded in the east by orogeny-parallel lineament, the Protogine Zone or the Sveconorwegian Frontal Deformation Zone (Figs. 2A and B). The Protogine Zone is made up of generally extensional shear zones defining the eastern limit of penetrative Sveconorwegian reworking. The Eastern Segment is interpreted as a part of the TIB that was underthrust, reworked, and exhumed during the Sveconorwegian Orogeny (Söderlund et al., 2002). It is mainly made up of 1.8–1.64 Ga gneissic granitoids, compositionally similar to rocks of the TIB (e.g., Söderlund et al., 2002) and is characterized by distinctive late-Sveconorwegian high-pressure metamorphic overprint dated at 0.97 Ga (Bingen et al., 2005).

Other crustal blocks, west of the Eastern Segment, are classified as Sveconorwegian allochthons (Stephens et al., 1996). The first allochthon is the Idefjorden block (Fig. 2A), which is made up of 1.66–1.52 Ga calc-alkaline and tholeiitic plutonic and volcanic rocks, associated with sedimentary rocks (e.g., Åhäll and Connelly, 2008). The Idefjorden block contains several amphibolites-facies orogeny-parallel shear zones (Bingen et al., 2008b). It is bounded by the Mylonite Zone to the east and by the Östfold-Marestrand and Åmot-Vardefjell Shear Zones to the west. Idefjorden block is interpreted as a composite and increasingly mature arc formed between 1.66–1.52 Ga at margin of Fennoscandia (Andersen et al, 2004), or alternatively as an exotic block assembled on Fennoscandia during the Sveconorwegian Orogeny (see Bingen et al., 2005 and references therein). Bingen et al. (2001) suggested that magmatic rocks with a juvenile, low-K tholeiitic geochemical signature indicate that at least part of the Idefjorden block formed in a volcanic arc outboard of the Paleoproterozoic continent, possibly in a front of back-arc basin.

The Permian Oslo Rift and Begna sector lies to the northwest of the Eastern Segment (Fig. 2A). Permian Oslo Rift form an exotic microcontinent, accreted on to Fennoscandia in a collision event between 1.58–1.50 Ga along a suture zone now masked by the Paleozoic rocks of the Oslo Rift (Andersen et al 2002). Begna sector comprises NW-SE trending amphipholite-facies rocks, and banded gneiss complex, which grades to the northeast into a complex of sedimentary origin rocks.

Further to the west, the Bamble and Kongsberg blocks are separated by the Permian Oslo Rift (Starmer, 1996 and Fig. 2A). They are made up of 1.57–1.46 Ga, mainly calc-alkaline, plutonic suites associated with quartzite-dominated metasediment complexes (e.g., Andersen et al, 2004). Based on petrophysical and seismic studies, it is considered that these two blocks lie over other blocks in the SSD (Ebbing et al., 2005). It is thought that these two blocks were originally connected (Starmer, 1996) and collision between Telemark and Idefjorden blocks generated Bamble and Kongsberg orogenic wedges at ca. 1.14–1.08 Ga. (Bingen et al., 2005). The Kristiansand-Porsgrun Shear Zone forms the boundary between the Bamble and Telemark blocks. Metamorphism to the upper amphibolites to granulite facies has been dated to 0.99–1.13 Ga (e.g., Bingen et al., 2008b).

The remaining part of the SSD, which is further to the west in southwestern Norway, comprises Telemark and Hardangervidda-Rogaland blocks (Fig. 2A). The Mandal-Ustaoset shear zone (Sigmond, 1985) separates these two blocks, but they are generally considered to be genetically similar. Bingen et al. (2005) coined the term “Telemarkia” for this part of the SSD. The Telemark block consists of a well-preserved volcanic-sedimentary succession in the north (Telemark supracrustal rocks or Telemark basin-fills) and gneisses in the south (the Vradal gneiss complex). Telemark block occurs to west of the Åmot-Vardefjell and Saggrenda-Sokna shear zones, and to the northwest of the Porsgrunn-Kristiansand shear zone surrounded by amphobolite facies gneiss complexes (Fig. 2B). Two possible models are considered for the Telemark block (Bingen et al., 2005). Either (i) Telamark was situated in the vicinity or at the margin of an evolved craton, or (ii) Telemark was possible exotic to Fennoscandia, and accreted during the Sveconorwegian Orogeny, by close of an oceanic basin. The possible suture zone, if any, lies between Telemark and Idefjorden blocks. In the Telemark block, 1.05 Ga syn-collision crustal melting was followed by regional metamorphism between 1.03 and 0.97 Ga. At the 0.98 Ga, the orogeny prograted further towards the east to include the Eastern Segment and After 0.97 Ga the Sveconorwegian belt progressively collapsed probably in a dominantly extension regime (Bingen et al., 2008b). The Hardangervidda-Rogaland block consists mostly of orthogneisses and granites, with some supracrustal rocks. These supracrustal rocks are Mesoproterozoic, and they include the sedimentary Hettefjorden and Festningsnutan groups and the volcanic-sedimentary Valldal-

Sasvatn groups (Bingen et al., 2002). They are potentially correlated with the Telemark supracrustal rocks (Torske, 1985; Bingen et al., 2002).

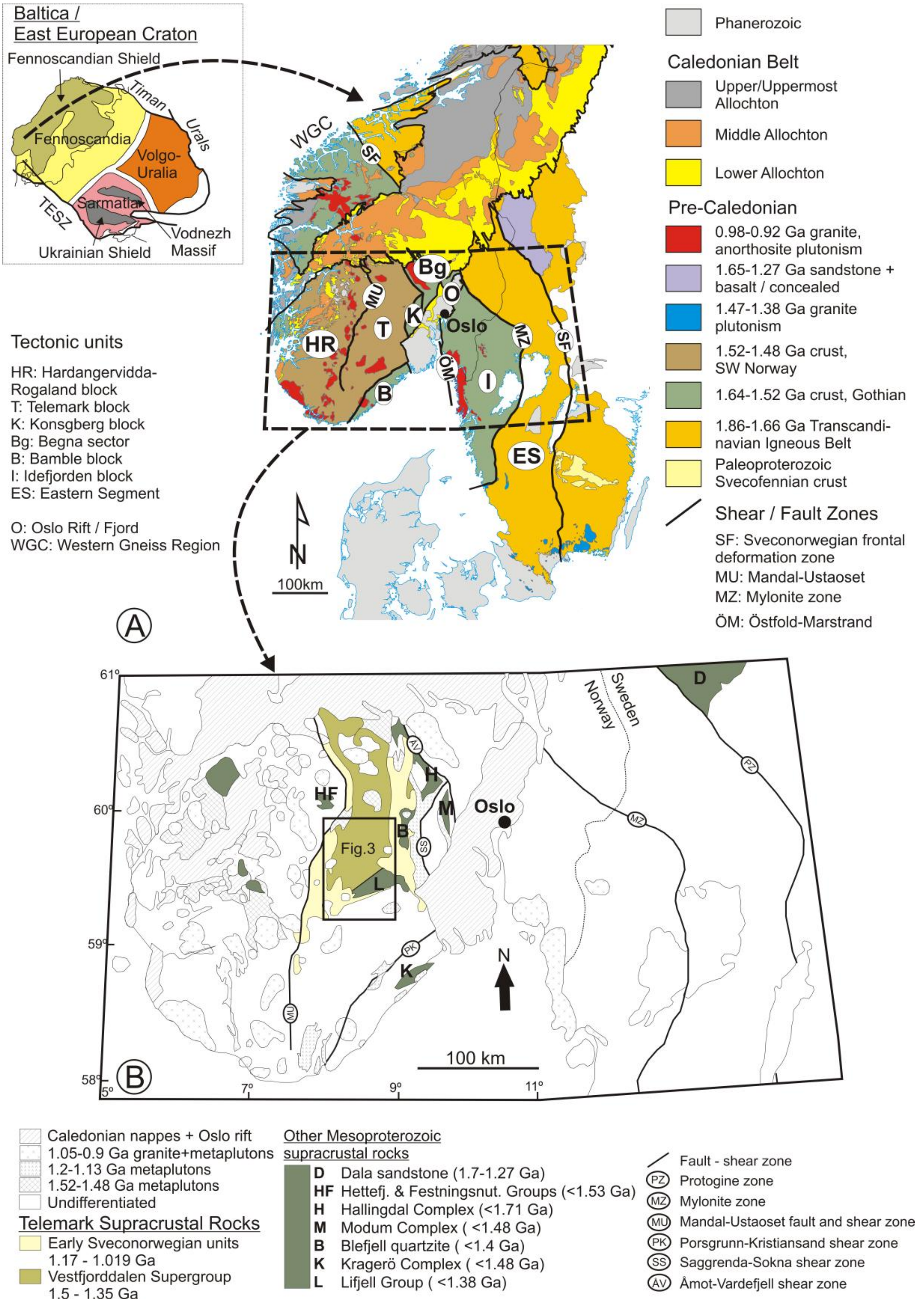

Fig. 2. Simplified geological maps of southwest Fennoscandia. (A) A geological sketch map of southwest Fennoscandia showing the principal tectonic units (modified from Bingen et al., 2008a).

Major shear and fault zones in divide it into blocks (thick black lines). Insert (Baltica/East European Craton): TESZ: Trans-European Suture Zone. (B) Close-up view of southwest Fennoscandia showing the Telemark block and the Telemark supracrustal rocks (modified from Bingen et al., 2003). Other possible correlative supracrustal formations are shown in dark green.

3.2 Regional correlation of sedimentary-dominated successions

Smaller occurrences of sedimentary-dominated successions are found outside of the Telemark block (Fig. 2B) in the Rogaland-Hardangervidda block (west of the Telemark block), the Bamble block (south of the Telemark block) and the Kongsberg block (east of the Telemark block) (Bugge, 1943; Dons 1960a, 1960b). In these areas, the rocks are commonly intensively deformed, and sedimentary structures are obliterated, but some of these can potentially correlated with the Telemark supracrustal rocks. Torske (1985) correlated the Dala sandstone in western Sweden and easternmost south Norway with the Vindeggen Group (part of the Telemark supracrustal rocks). Both units are dominated by sandstone and are heavily intruded by diabase dykes. A study by Bingen et al. (2001) compared detrital zircon U-Pb data from several quartzites in Norway (with the exception of the Dala sandstone). These sediments contain abundant Paleoproterozoic zircon age modes peaking at ca. 1.9–1.8 Ga with a significant Archean mode. The youngest grain was not younger than ca. 1.4 Ga. Although their datasets did not contain a statistically robust number of observations, their results suggested a common Archean-Paleoproterozoic source for the detritus and a surprisingly low (ca. 1.5 Ga) signature, given that rocks of this age are widely abundant at present-day erosional levels. The age distribution of detrital zircons in the Vindeggen Group display similar age distribution than quartzite samples from the Kragero and Modum complexes (de Haas et al., 1999, Bingen et al., 2001), and possible indicate that they are correlative and deposited along the same continent. Andersen et al., (2004) suggested that Blefjell quartzite unit (east from the Telemark) possible correlate with the Lifjell Group in the Telemark (Fig. 2B). The Blefjell quartzite unit consist laminated and cross-bedded sandstones deposited between ca. 1155 and 1145 Ma (Andersen et al., 2004). The stratigraphic position of the Dala sandstone indicates that they are younger than 1.67 Ga. The occurrence of 1.71 Ga zircons in the quartzite of the Hallingdal complex, corresponding to the Dala granitoids and porphyries, is compatible with a Fennoscandia origin of the Hallingdal complex and is suggestive of correlation between them (Bingen et al., 2001).

3.3 Lithostratigraphy

The present study area belongs to the well-preserved Mesoproterozoic volcanic and sedimentary rocks, referred to as the Telemark supracrustal rocks as a traditional sense or Telemark basin-fills as a sedimentological sense, which form a prominent feature of the Telemark block (Dons, 1960a, 1960b; Sigmond et al., 1997; Laajoki 2000, 2003; Laajoki et al., 2002; Bingen et al., 2001, 2005, Fig. 3). The succession is approximately 10-km-thick and is metamorphosed under low-grade greenschist-amphibolite facies (Brewer and Atkin, 1987, Atkin and Brewer, 1990). In the work by Dons (1960a), the Telemark supracrustal rocks were divided into three groups separated by major unconformities: Rjukan (oldest), Seljord (middle) and Bandak (youngest). This subdivision was later abandoned (except for the Rjukan Group) after new radiometric datings were obtained (Laajoki et al., 2002), and several new unconformities were discovered. Presently, the Telemark supracrustal rocks have been shown to consist of two main successions: a lower succession deposited between ca. 1.51 and 1.347 Ga, referred to as the “Vestfjorddalen Supergroup”; and one overlying succession deposited between ca. 1.17 and 1.019 Ga, referred as the “early Sveconorwegian units”, which are separated by a major first-order unconformity (the sub-Svinsaga unconformity, Laajoki, 2000, 2003, 2009, Figs. 3, 4). The stratigraphic position of the Vemork Formation has been a matter of debate. In this study, the Vemork Formation is regarded traditionally as part of the Rjukan Group. The Rjukan Group is unconformably overlain by the approximately 8-km-thick sedimentary-dominated Vindeggen Group (Figs. 3, 4). The Vindeggen Group consists of several sandstone and mudstone formations deposited in various environments.

The pre-rifting basement of the Telemark supracrustal rocks has not been identified with certainty. In the original description, it was suggested that “granitization” had obliterated contact with the basement, which was generally thought to be the gneisses in the south (Dons, 1960b, 1962). However, the southern contact is highly sheared, and some age determinations have provided ages that are too young for it to be a viable basement for the Rjukan Group (Andersen et al., 2007). Sigmond et al. (1997) suggested the amphibolite facies Goyst metasupracrustal complex in northern Telemark as a possible basement. However, this proposal was questioned by Bingen et al. (2005), who demonstrated that the analyzed detrital zircon sample from the Goyst metasupracrustal complex (main mode, 1508 ±10 Ma) is coeval or younger than the 1.51 Ga

Rjukan Group and, consequently, is either a part of the Rjukan Group or is possibly correlated with the lower part of the overlying Vindeggen Group. In addition, Bingen et al. (2001, 2005) analyzed a detrital zircon sample from the Hallingdal gneiss and quartzite complex near the Åmot-Vardefjell shear zone. This zircon data indicated that the complex was deposited after 1.71 Ga and that it represents a possible depositional basement for the Rjukan Group. The analyzed sample from the Hallingdal gneiss and quartzite complex contains detrital zircons ranging from 3.13 to 1.71 Ga, although a depositional age younger than 1.51 Ga is still possible (Bingen et al., 2001, 2005).

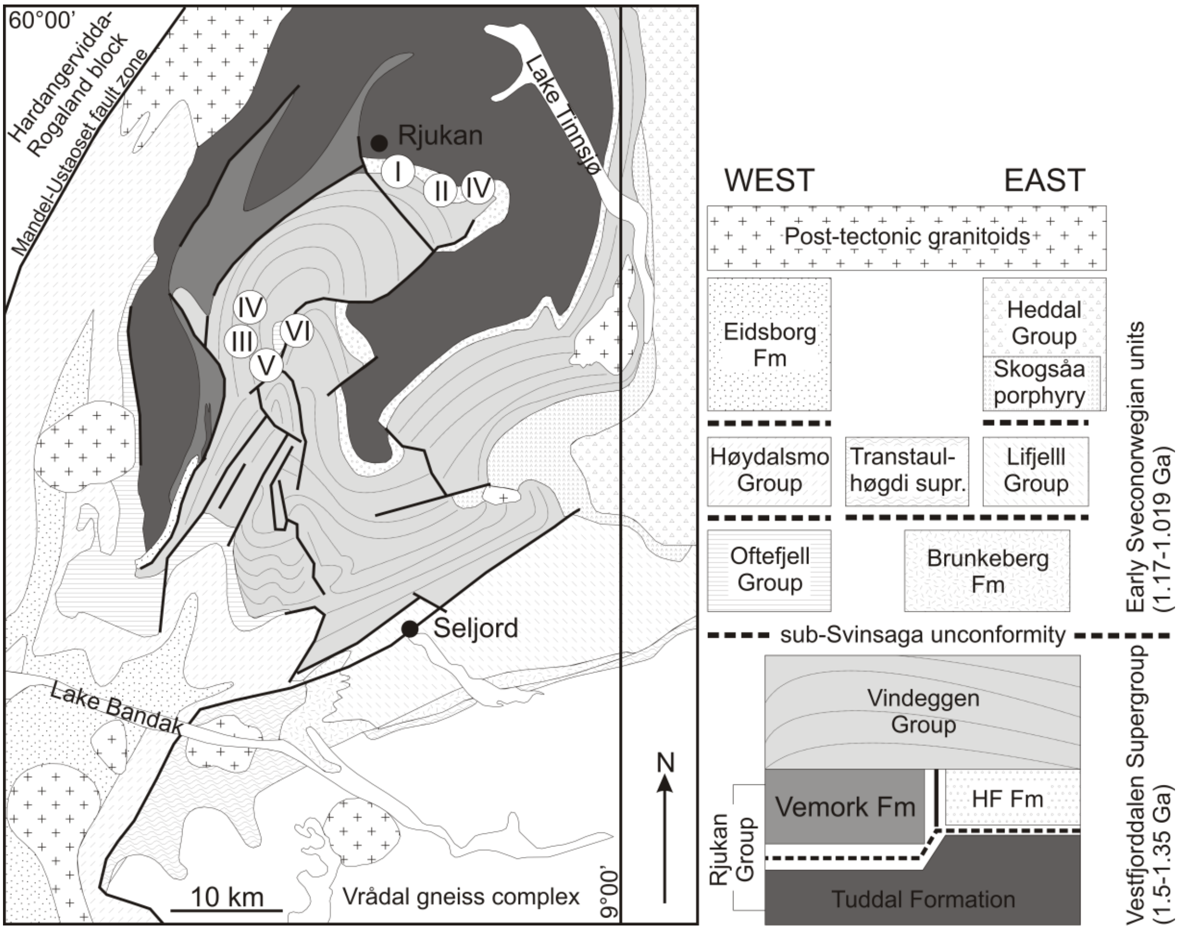

Fig. 3. A simplified geological map of the study area. The Telemark block is dominated by the felsic Tuddal Formation, volcanic-sedimentary Vemork and Heddersvatnet Formations, and sedimentary Vindeggen Group. The early Sveconorwegian units are located west and east side from the town of Rjukan. Thick black lines indicate major fault and shear zones. HF: Heddersvatnet Formation. Circles with Roman numbers indicate study locations reflecting Paper number.

3.3.1 Vestfjorddalen Supergroup

The Vestfjorddalen Supergroup (i.e., the Rjukan Rift Basin) starts with the Rjukan Group, which comprises the Tuddal and Vemork Formations (Figs. 3, 4). The Tuddal Formation is made up of ca. 1.51 Ga continental felsic volcanic rocks (Dahlgren et al., 1990a; Nordgulen, 1999; Bingen et al., 2005). The exact thickness of the Tuddal Formation is difficult to estimate due to deformation and a lack of clearly visible bedding in many areas. Laajoki and Corfu (2007) structurally subdivided the Tuddal Formation into different domes representing primary volcanic complexes folded during the Sveconorwegian Orogeny. The formation mainly consists of rhyolitic flow-banded lavas, lithophysa lavas, porphyric lavas, lapilli tuffs and minor volcaniclastic conglomerates (Wyckoff, 1934; Laajoki, 2005; Laajoki and Corfu, 2007). The contacts between the individual lava beds are difficult to determine due to the lack of sufficient outcrops and due to the strong deformation, which has also distorted the flow banding. The Tuddal formation is overlain by an approximately 2-km-thick succession of the volcanic-sedimentary Vemork Formation (ca. ≤1495 ±2 Ma, Laajoki and Corfu, 2007), which is characterized mainly by mafic volcanics (Figs. 3, 4). The stratigraphic position of the Vemork Formation has been debated for decades (cf. Dahlgren et al., 1990a; Dahlgren and Heaman, 1991; Laajoki and Corfu, 2007) and is discussed more closely in Paper I. The basal part of the approximately 2.2-km-thick Vemork Formation consists of a mass flow conglomerate unit that is about 100-m-thick (Dons et al., 2004; Laajoki and Corfu, 2007) and has minor sandstone interbeds. The conglomerate unit passes upward into a 20- to 50-m-thick unit of rhyolitic autoclastic and hyaloclastic breccias, which were extruded under subaerial conditions and flowed into water (Laajoki and Corfu, 2007). These units are overlain by basaltic lavas and fluvial trough cross-bedded sandstone interbeds with mudstone rip-ups that make up the majority of the Vemork Formation. The geochemical signatures of the Vemork Formation basaltic lavas suggest a partial melting of the depleted mantle and within-plate paleotectonic setting (Brewer and Atkin, 1989; Menuge and Brewer, 1996). Paper I suggests that the volcanic-sedimentary Vemork Formation represents the axial part of the Rjukan Rift Basin, where the extrusion of abundant mafic lavas reflects a change in the magmatic regime in the rift basin, possibly coeval with a syn-rift tectonic phase.

The Skardfoss rhyolite, in the lower part of the Vemork Formation, is dated at ca. 1.495 Ga (Laajoki and Corfu, 2007) and Sandvik diabase, which is cutting the upper part of the Brattefjell Formation, at 1.347 Ga (Corfu and Laajoki, 2008). This gives the sedimentation age for the Vindeggen Group. This group contains the Heddersvatnet, Gausta, Bondal, Lauvhovd, Skottsfjell, Vindsjå and Brattefjell formations (Figs. 3, 4). The group begins with a ca. 400-m-thick alluvial fan and associated braidplain Heddersvatnet Formation, which is deposited directly above an unconformity (sub-Heddersvatnet unconformity in Fig. 4). The Heddersvatnet Formation consists mainly of massive debris flow conglomerates and trough cross-bedded arkosic sandstone with mudstone and basaltic lava interbeds. The sedimentation patterns, tectonic setting, and geochemistry of the Heddersvatnet Formation sandstones, mudstones and basaltic lavas are studied in Papers I and II.

The Heddersvatnet Formation grades into the ca. 750-m-thick Gausta Formation. Sedimentary facies and structures indicate that the transition corresponds to an evolution from alluvial to marine depositional environment (Fig. 4). The lower part of the Gausta Formation is comprised of mostly tabular low-angle cross-bedded quartz sandstone free of epiclastic volcanic detritus and of locally conglomeratic units with pebble-sized clasts. The clasts are composed of felsic volcanics and quartzites. The sandstone units are overlain by wave ripple-marked and tabular cross-bedded sandstone beds. The termination of volcanism and the deposition of conglomerates with extrabasinal clasts in the lower part of the Gausta Formation indicate a major change in the rift basin evolution. The Gausta Formation is overlain by mudstones of the Bondal and Lauvhovd formations (Fig. 4). The contacts are unexposed. The ca. 250-m-thick Bondal Formation contains mostly heterolithic mudstone-sandstone successions. The mudstones of the ca. 350-m-thick Lauvhovd Formation are calcite-bearing. Both formations are mainly characterized by heterolithic, thinly bedded sandstones and siltstones with wave ripplemarks and cross-bedding with mud-drapes. These sedimentary structures and facies assemblages suggest a tidal depositional environment. The Lauvhovd Formation is overlain by the ca. 1-km-thick Skottsfjell Formation (Fig. 4). The Skottsfjell Formation is composed of fluvial conglomerates in its lower part that are overlain by thick trough cross-bedded arkosic sandstone beds with interbeds of mudstone. The conglomerates are mainly quartzites and siltstones. Based on sedimentary structures and facies associations, the Skottsfjell Formation is understood to represent a braided-type fluvial depositional environment. The Skottsfjell Formation passes into the ca. 500-m-thick Vindsjå Formation. The contact is again unexposed. The Vindsjå Formation is characterized by heterolithic and thinly bedded sandstone, siltstone and mudstone beds with mud cappings and mud-drapes. The lower part of the formation is composed of sandstone units with small-scale trough cross-bedding followed by low-angle tabular cross-bedding and wave ripple marks. The Vindsjå Formation most likely represents a transition from a fluvial to tidal-dominated environment.

The Vindsjå Formation is overlain by the ca. 2.5-km-thick Brattefjell Formation, which is the topmost unit of the Vindeggen Group (Fig. 4). The boundary between the two formations is unexposed. The Brattefjell Formation is subdivided into lower, middle and upper members (Fig. 4) based on their distinctive facies assemblages and sharp, conformable boundaries. The lower member contains mainly wave ripple-marked and bipolar cross-bedded arkosic sandstone beds with abundant mud-drapes. It is overlain by the ca. 500-m-thick middle Brattefjell member, which is a heterolithic unit of arkosic wave-rippled sandstone and thin mudstone beds. The ca. 1-km-thick upper Brattefjell member begins with a pebble-sized transgressive lag conglomerate overlain by low-angle tabular cross-bedded and wave ripple-marked sandstone beds. The pebble conglomerate consists of quartzite clasts. Sedimentary structures and facies associations indicate that the Brattefjell Formation was deposited in a subtidal and nearshore shallow marine environment. The sedimentation processes and cyclic features of the Brattefjell Formation are studied in Paper III. A distinct feature of the Brattefjell Formation is the rather thick, monotonous lithological nature of its members. The lack of variability in its facies reflects an aggradational stacking pattern that was controlled by a balance between sediment supply and the creation of accommodation space over a significant amount of time. The evolution and provenance of the whole Rjukan Rift Basin (i.e., the Vestfjorddalen Supergroup) is dealt with in Paper IV. The Brattefjell Formation is overlain by early Sveconorwegian units, starting with the Oftefjell Group. This group is separated by the sub-Svinsaga angular unconformity. The unconformity is marked by fractures in underlying rocks of the Vindeggen Group and by a breccia boulder zone that accumulated in periglacial climate. These periglacial cold-climate processes are studied in Paper V. The original thickness of the Vindeggen Group is unknown. Recent detrital zircon ages from sandstone located directly above the unconformity show that a hiatus of at least 170 Ma is associated with this unconformity (Lamminen et al., 2009b).

3.3.2 Early Sveconorwegian units

The sedimentation of the early Sveconorwegian units is bracketed between ca. 1170 and 1019 Ma (Lamminen et al., 2009b and Fig. 4). These units are more complex due to deformation and faulting, and the lithostratigraphical correlation of different units is problematic. The early Sveconorwegian units comprise the Oftefjell, Høydalsmo, Lifjell, and Heddals Groups; the Brunkeberg and Eidsborg formations; the Transtaulhøgdi supracrustals, which are separated by the sub-Lifjell, sub-Røynstaul, and sub-Heddal unconformities; and a possible sub-Eidsborg unconformity (Figs. 3, 4). The whole succession consists mainly of coarse-grained sedimentary rocks interbedded with bimodal magmatic rocks. On a regional scale, the formations are laterally restricted and lithologically variable, and their true thickness is unknown. Although the sedimentary features, depositional environments, and lateral correlations of the different units are not well known, some of the general lithostratigraphical features are summarized here.

The sub-Svinsaga angular unconformity is overlain by the ca. 1-km-thick Oftefjell Group. The Oftefjell Group starts with the ca. 250-m-thick Svinsaga Formation, which consists of basal sedimentary breccias, conglomerates, sandstones and mudstones deposited in the fluvial-lacustrine environment. The sedimentation patterns and paleohydrology of the Svinsaga Formation are treated in Paper VI. The Svinsga Formation is overlain by the felsic porphyres, minor volcanic conglomerates and sandstones interbeds of the Robekk and Ljosdalsvatnet Formations. The age determinations from the Ljodalsvatnet felsic porphyre (ca. 1155 ± 3 Ma) indicate that it can probably be correlated with the Brunkeberg Formation (ca. 1155 ± 2 Ma) in the east (see Laajoki et al., 2002).

The Oftefjell Group is overlain by the ca. 1-1.5-km thick Høydalsmo Group, separated by the sub-Røynstaul unconformity (Fig. 4). The volcanic-sedimentary Høydalsmo Group starts with the conglomerate-dominated Røynstaul Formation followed by the mafic lava-dominated Morgedal Formation. The Morgedal Formation is overlain by the porphyre of the Dalaå Formation (ca. 1150 ± 4 Ma, Laajoki et al., 2002) and, again, the mafic lavas of the Gjuve Formation with minor sedimentary interbeds (Fig. 4). In the west, the Brunkeberg Formation is overlain by the Transtaulhøgdi supracrustals and the Lifjell Group, and the two are separated by the sub-Lifjell unconformity (Fig. 4). The Lifjell Group comprises the Heksfjellet conglomerates followed by the sedimentary-dominated Vallar Bru

Formation. The lateral stratigraphic correlation of these units is uncertain. It is possible that the Transtaulhøgdi supracrustals and the Lifjell Group correlate with the Høydalsmo Group. However, recent studies and isotope geochemistry suggest that the Lifjell Group may be tectonically displaced and may even correlate with the Vindeggen Group (Lamminen, pers. comm.)

The Høydalsmo Group is overlain by the ca. 1.0-km-thick Eidsborg Formation, which is the topmost unit of the Telemark supracrustal rocks. The contact between these units is uncertain, but it is likely that they are separated by the unconformity. The Eidsborg Formation consists mainly of conglomerates and sandstones, possibly deposited in the alluvial fan-fluvial environment. In the east, the Lifjell Group is overlain by the ca. 1.0-km-thick Heddal Group, and these are separated by the sub-Heddal unconformity (Fig. 4). The Heddal Group comprises the Skogsåa Formation porphyres (ca. 1145 ± 4 Ma) and overlying successions of undifferentiated sediments. It is possible that the Heddal Group can be correlated with the Høydalsmo Group or the Eidsborg Formation. The northwestern margin of the Telemark supracrustal rocks comprises a ca. 5-km-wide N-S trending belt of sandstones, conglomerates, and quartz-bearing schists, called as the Kalhovd Formation. The youngest analyzed detrital zircon from the Kalhovd Formation sandstone has an age of ca. 1054 ± 22 Ma (Bingen et al., 2003), which post-dates the age of the Skogsåa porphyre. Laajoki et al., (2002) suggested that the Kalhovd Formation could be coeval with the bulk sedimentary part of the Heddal Group. However, it is not possible to establish whether the Kalhovd Formation is younger than the Heddal Group and Eidsborg Formation or correlate with them (see Bingen et al., 2003). Thus, the lithostratigraphic position of the Kalhovd Formation is uncertain.

The ca. 1019 Ma Re-Os molybdenite age from a crosscutting quartz vein gives the upper limit for the Telemark supracrustal rocks (Bingen et al., 2006). This supracrustal event was followed by the emplacement of post-tectonic granitoids that are ca. 970–930 Ma in age.

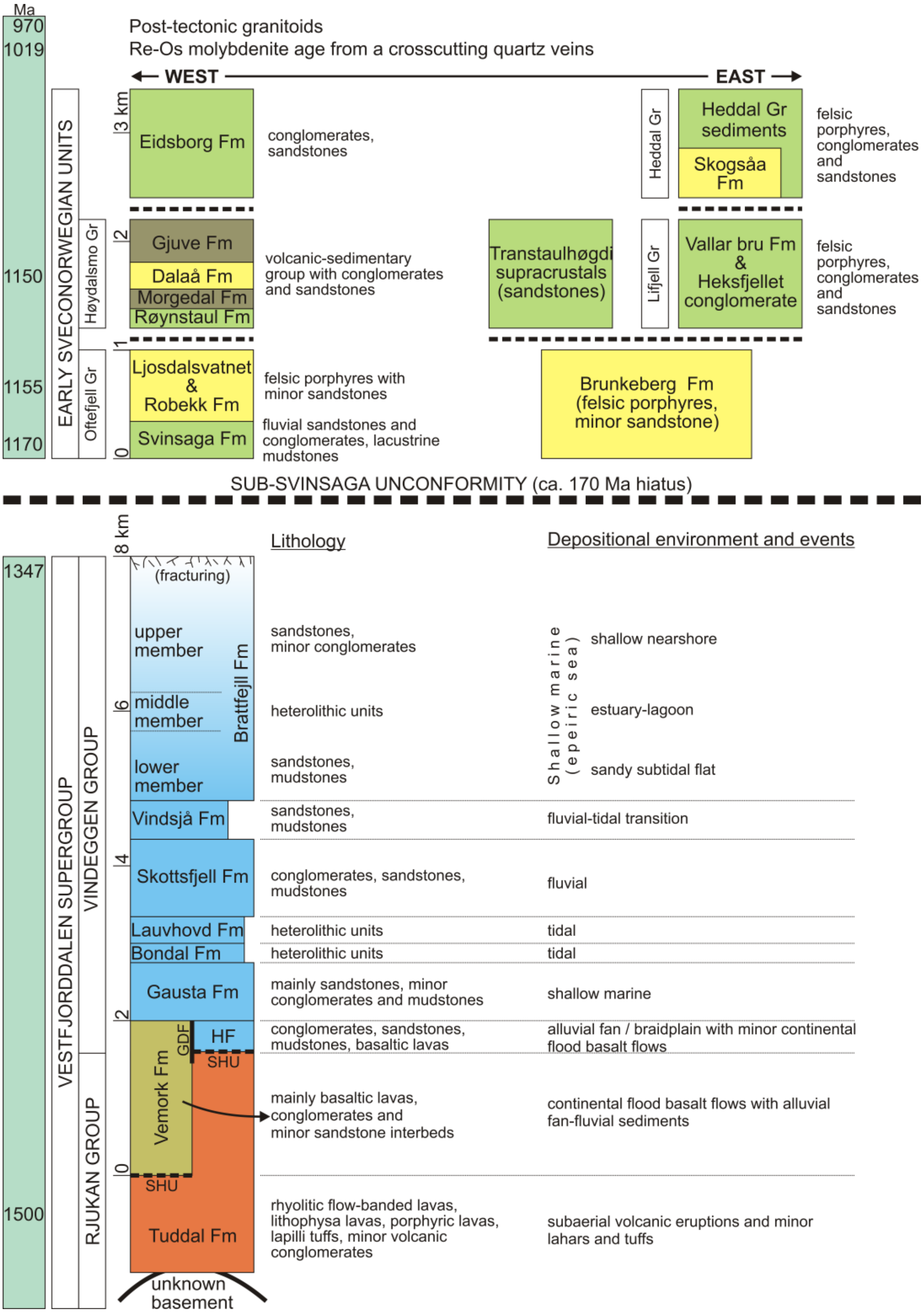

Fig. 4. Lithostratigraphy of the Telemark supracrustal rocks. The succession is subdivided into the Vestfjorddalen Supergroup (ca. 1.5–1.35 Ga) and overlying early Sveconorwegian units (ca. 1.17–1.019 Ga) separated by the sub-Svinsaga unconformity. Studied formations in this thesis included the Vemork, Heddersvatnet, Gausta, Skottsfjell, Vindsjå, Brattefjell, and Svinsaga formations. Also, sub-Heddersvatnet and sub-Svinsaga unconformities were considered. Age limits are taken from Laajoki et al. (2002), Bingen et al. (2003, 2006), and Lamminen et al. (2009b). SHU: sub-Heddersvatnet unconformity, HF: Heddersvatnet Formation, GDF: Gausdalen fault zone.

4 Methods

From the viewpoint of research and methods, sedimentology is a broad concept that involves elements of stratigraphy, sequence stratigraphy, sedimentary petrology and geochemistry. The data collection and analytical procedures of the study of sedimentary basins are mostly determined by the nature and purposes of the research project.

A successful basin analysis with sedimentological constructions and interpretations requires the understanding and integration of several methods, as well as sufficient data and robust analyses to build a coherent basin model and synthesis of geological evolution. This is particularly true when dealing with Precambrian strata, which are usually at least partially metamorphosed and tectonically deformed. The main methods and analytical tools used in this thesis include (1) regional mapping and lithostratigraphy, (2) facies analysis, (3) sequence stratigraphy, (4) clastic petrofacies analysis, (5) geochemistry, and, finally, (6) sedimentary basin paleotectonic reconstruction. The basin analysis flow chart used in this thesis is presented in Figure 5. This chapter summarizes the principles and fundamental ideas of each method and the tools used in this thesis.

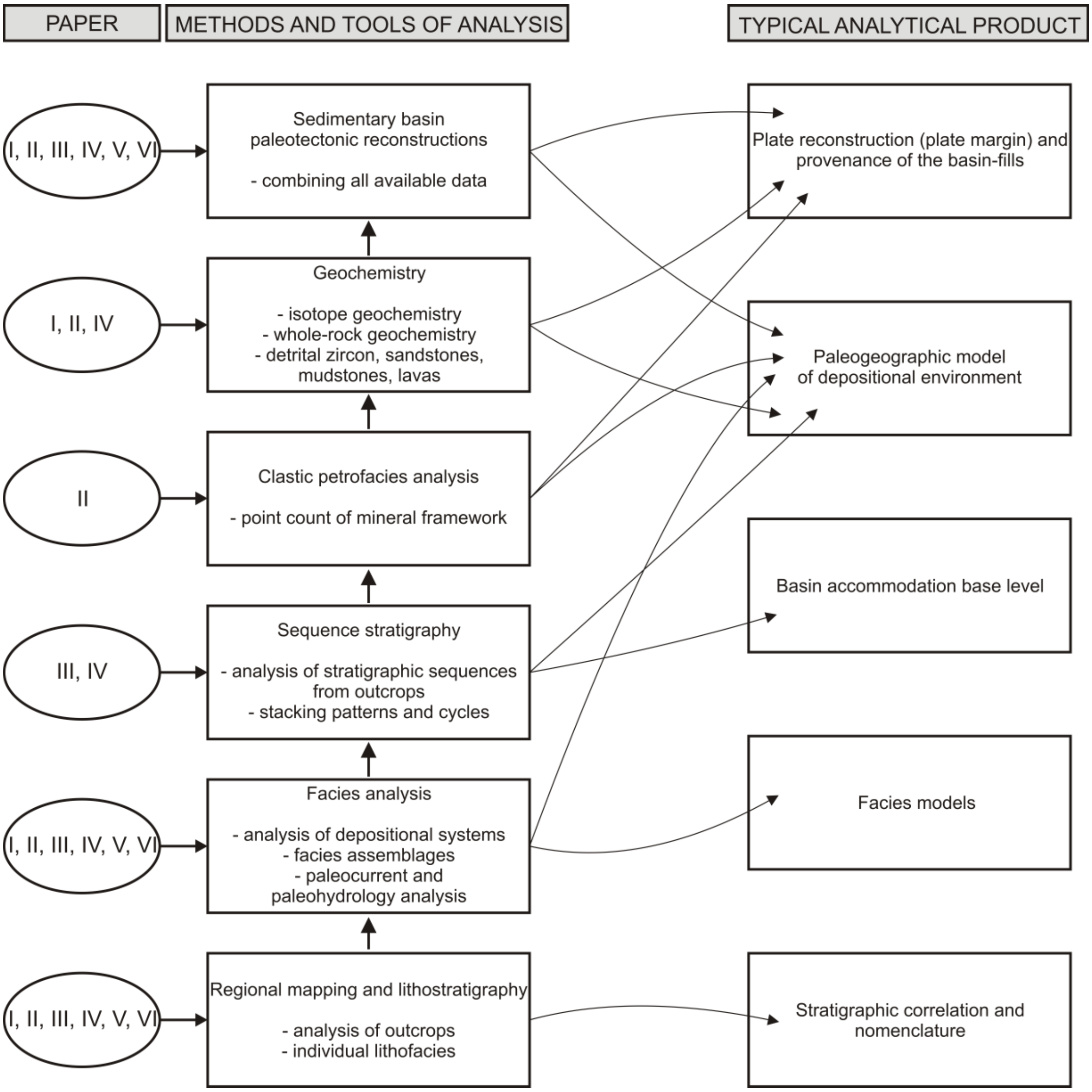

Fig. 5. Basin analysis flow chart used in this thesis (modified from Miall, 1978, 2000). Regional mapping and lithostratigraphy, lithofacies analysis, and finally paleotectonic reconstruction form a fundamental core of the analysis. The usage of sequence stratigraphy, clastic petrofacies analysis, and geochemistry depends on study purpose, and thus some methods and tools are not always needed to reach the aims of the research.

4.1 Regional mapping and lithostratigraphy

The basin analyses are based on the compilation and correlation of vertical and lateral lithostratigraphic sections, which entails studies of the physical and temporal relationships of strata. The study of ancient sedimentary environments usually begins with regional mapping (see Fig. 5), and it includes lithostratigraphic field measurements and correlations to define the rock types, geometry, and distinct internal sedimentary structures. Lithostratigraphic mapping and measurements of rock sequences also provides information about the changes in sedimentation processes trough time and thus provides clues to the nature of sedimentation environments and their evolution trough time. Regional mapping and lithostratigraphy analysis also integrate elements detected by facies analysis.

The objective of regional mapping and lithostratigraphy is to subdivide the observed rocks into descriptive units by observing changes in lithology, grain size, bedding, color, sedimentary structures (primary *vs.* post-depositional), contacts, and cyclic sequences. The lithology of the sedimentary unit is mainly controlled by depositional environment, sediment supply, climate, and basin subsidence. The establishment of lithostratigraphic units in basin analysis usually starts with (i) identification of the lithostratigraphical units and the possible stratigraphic events to be correlated at the local and regional scale (or even global). This step is followed by (ii) the identification of unconformities and their chronostratigraphic significance. The resolution of the lithostratigraphic correlation can be improved by (iii) assigning absolute ages by radiometric dating. The final stage, if necessary, includes (iv) establishing the formations and possible groups, members and supergroups associated with the results after the lithofacies analysis.

Most of the regional lithostratigraphic framework of the study area was established in earlier works described in Chapter 1.2. In this thesis, the lithostratigraphic mapping was mainly additional data to the previous studies in the local scale. This data were used in each of the six papers. Most of the rock samples were also collected during this phase.

4.2 Facies analysis

Lithofacies is defined as a body of rock or unlithified sediment that is characterized by a particular combination of lithological and physical sedimentary structures formed in sedimentary processe(s) that are distinguishable from the lithology above, below and laterally adjacent to it. Sedimentary structures play a major role in the interpretation of sedimentary environment depositional processes, hydrodynamics and, thus, facies analysis. A group of genetically related lithofacies that have some environmental significance can be combined to lithofacies associations. Lithofacies associations are a collection of commonly associated sedimentary attributes within lithological units. Thus, lithofacies associations represent the basic building blocks of facies models that summarize a particular depositional system within the sedimentary environment and basin. According to Walker (1992), the four fundamental purposes and functions of a facies model are that it must (i) act as a norm for comparison, (ii) act as a framework and guide for future observations, (iii) act as a predictor in new geological situations, and (iv) act as an integrated basis for the interpretation of the system it represents. The lithofacies associations can be later grouped to form even bigger lithofacies successions in which a series of lithofacies pass gradually from one to another.

To extent the lithofacies analysis to the entire basin, it is necessary to follow the basin analysis workflow, starting with the lithostratigraphic mapping and correlations. The lithofacies analysis usually starts by establishing a facies scheme that encompasses all the lithological units in the studied area. The lithofacies in these schemes include detailed measurements of different structures, lithofacies logs, outcrop sketches and photographs, additional sample collection, paleocurrents, paleohydrology and ripple-index measurements. The lithofacies classification used in this thesis was designed to be as simple as possible to cover all the necessary information from each lithological unit and to form a fundamental core that was used in every paper.

4.3 Sequence stratigraphy

Sequence stratigraphy studies the change in depositional trends and cycles in response to the interplay of accommodation and sediment supply, from the scale of individual depositional systems to entire basin-fills (Catuneanu et al., 2005, 2009; Catuneanu, 2006). Sequence stratigraphy reveals the history of sedimentation in a basin in response to base level cycles, which is the highest level to which sediment successions can be built (i.e., more-or-less sea level). Therefore, sequence stratigraphy assumes a subdivision of the sedimentary pile into sequences, which are stratigraphic units related to cyclic change in the sedimentation through time. A sequence stratigraphic framework includes genetic units that result from the interplay of accommodation and sedimentation, which are bounded by stratigraphic surfaces. Each genetic unit is defined by special strata stacking patterns and bounding surfaces, and consists of a tract of correlatable depositional systems (i.e., system tracts). The mappability of system tracts and sequence stratigraphic surfaces depends on depositional setting and types of data available for analysis.

However, the essence of sequence stratigraphy is the mapping of strata based on an identification of stratigraphic surfaces (e.g., subaerial unconformity, maximum flooding surface), which refer to linkages of correlative depositional systems commonly associated with significant lateral changes of facies (Fig. 6). These stratigraphic surfaces mark shifts through time in a depositional regime, and they are created by the interplay between base level changes and sedimentation. Thus, surfaces are also tied to depositional models, and they form the fundamental framework for the genetic interpretation of sedimentary succession. However, in Precambrian sequence stratigraphy, time is largely irrelevant as a parameter in the classification of stratigraphic surfaces (independent of base-level cycle duration). Instead of time, it is rather the record of changes in the tectonic setting that provides the key criteria for the basic subdivision of the stratigraphic record into basin-fill succession separated by first-order sequence boundaries (e.g., Eriksson et al., 2005). Boundaries not expected to correlate to other sequences of other basins, which are likely characterized by different timing and duration.

System tract is a linkage of contemporaneous depositional systems, forming subdivision of a sequence. Due to different “schools” in sequence stratigraphy concept, the model-independent approach for the sequence models is the most flexible and suitable for the ancient rock record. Therefore, system tracts can be classified as follows: (i) regressive system tract, including (a) forced regression (regression of the shoreline driven by base-level fall; progradational and downstepping stacking patterns), and (b) normal regression (regression of the shoreline driven sediment supply, during a time of base-level rise at the shoreline or at a time of base-level stillstand; normal regression occurs when sedimentation rates outpace the rates of new accommodation added due to base-level rise at the shoreline; combination of progradational and aggradational depositional trends); (ii) lowstand system tract (accumulates at the stage of early-rise of normal regression; rate of rise outpaced by the sedimentation rate; (iii) transgressive system tract (landward shift of marine or lacustrine system, triggered by a rise in base-level at rates higher than the sedimentation rates; retrogradational stacking patterns; (iv) high-stand system tract (forms during the late stage of base level rise, when the rates of rise drop below sedimentation rates; aggradational and progradational stacking patterns). These system tracts controlled by a combination of autogenic and allogenic processes, and which are interpreted based on strata stacking patterns, position within the sequence, and types of bounding surfaces. These processes determine the distribution of depositional elements within systems as well as large-scale stacking patterns of depositional systems within each system track. Not all the system tracts need be present in each sequence either because the shape of the base level curve did not allow one or more system tracts to form, or because subsequent erosion.

During the full base-level cycle, four main events can be recognized which control the timing of formation of all sequence stratigraphic surfaces and systems tracts (Fig. 6): (i) onset of forced regression (onset of base-level fall at the shoreline); (ii) end of forced regression (end of base-level fall at the shoreline); (iii) end of regression (during base level rise at the shoreline); and (iv) end of transgression (during base-level rise at the shoreline). The expression in the rock record of each one of the four events of the base-level cycle may vary from mappable to cryptic, depending on depositional setting, tectonic setting, and the type(s) of data available for analysis. In addition, seven sequence stratigraphic surfaces are defined relative to the four main events of the base-level cycle, and the recognition of these surfaces in the rock record is data dependent.

In this thesis, the workflow of the sequence stratigraphy analysis was to first identify the genetic units and bounding surfaces that compose the lithostratigraphic section in the outcrop. In Precambrian sequence stratigraphy, these surfaces can be recognized by the nature of their contacts, lithofacies, and depositional trends. Sequence stratigraphy was used in Paper III study the depositional cyclicities in epeiric sea paleoenvironment and in Paper IV to recognize major base level cycles within the entire basin.

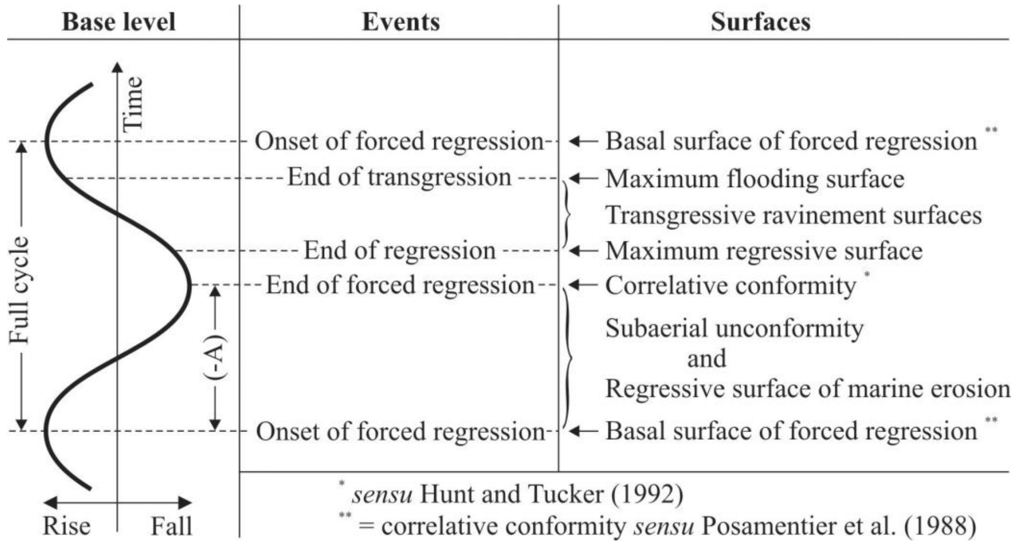

Fig. 6. Full base level cycle relative to the sequence stratigraphic surfaces (from Catuneanu, 2006). The base level cycle reflects fluctuations in coastline and thus in accommodation space. The trend of the base level curve depends on complex interplay of allogenic controls that affect to the sedimentary basin. Time is irrelevant in Precambrian sequence stratigraphy. (-A) = negative accommodation.

4.4 Clastic petrofacies analysis

Clastic petrofacies analysis can be used to identify the tectonic setting of the provenance area. The detrital composition of siliciclastic sedimentary rocks is a complex function of the following: (i) composition of the source rock (i.e., the provenance); (ii) transportation; (iii) chemical and mechanical abrasion/weathering during the transportation and deposition; (iv) climate and relief; and (v) diagenetic alteration during the burial and post-depositional metamorphic processes (e.g., McLennan et al., 1993; Osae et al., 2006). Despite the interplay between different functions, the tectonic environment of the source area region can be identified from the detrital framework composition of the silisiclastic rocks. Recognition of the source area tectonic environment is important for basin analysis and for determining ancient detrital sequences because it provides information about the transport directions, drainage areas, and the provenance area tectonic evolution (uplift *vs.* subsidence).

The principle of the petrofacies analysis is a selected thin section from a collected sedimentary rock and a slide advance mechanism that will randomly select points on the slide with a petrographic microscope. This can be determined by using the Dickson-Gazzi point-count method, described and recommend by Ingersoll et al. (1984), for minimizing the grain-size effect. The advantage of the Dickinson-Gazzi technique is that sandstone maturity effects are minimized, and sandstones of different grain sizes can be compared. From a modal point-count analysis, the percentages of various combinations of grains are plotted on ternary diagrams, which are based on quartz-feldspar-lithic fragment proportions that reflect different provenance terranes (Dickinson and Suzek, 1978; Dickinson et al., 1985). These terranes are subdivided as follows: (i) stable craton, (ii) basement uplift, (iii) magmatic arc, and (iv) recycled orogeny.

Clastic petrofacies analysis was used in Paper II as supplementary data to identify the tectonic setting of the provenance area. A total of 500 grains were counted from each thin section by the method described above.

4.5 Geochemistry

Geochemistry and geochemical data were used to identifying the geochemical signatures of the (i) geological process, (ii) depositional basin tectonic evolution, and (iii) provenance of the sampled rocks. The main geochemical tools used in this thesis (Papers II and IV) included an X-ray fluorescence spectrometer (XRF) and laser ablation with an inductively coupled plasma mass spectrometer (LA-ICP-MS).

4.5.1 XRF analysis

XRF analysis can be used as an analytical tool to determine the major and trace element geochemistry of rock samples. XRF analysis is based on the theory that a primary X-ray beam excites secondary X-rays, which have wavelength characteristics of the elements present in the analyzed rock samples. The intensity of the secondary X-rays is used to determine the concentrations of the elements present by reference to calibration standards, with appropriate corrections being made for instrumental errors and the effects the rock samples have on the X-ray emission intensities (matrix effects).

The rock samples used in this thesis were crushed, milled and analyzed at the University of Oulu, Institute of Electron Optics, using the Siemens SRS 303AS X-ray fluorescence spectrometer with a cobalt tube and pressed powders. The loss of ignition was determined from the total weight of loss after ignition at 950^{o}C for 2 hours. The accuracy of the measurements was within <5 % relative for all major elements, and the trace element analyses were accurate to <15 % relative. The precision accuracy was controlled by repetitive measurements of standards. XRF analysis was used to determine the geochemical compositions and interpret the tectonic settings and paleoweathering of the Heddersvatnet and Gausta formations sedimentary rocks (sandstones and mudstones) and basaltic lavas (Papers I and II).

4.5.2 LA-ICP-MS analysis

Isotope geochemistry and radiometric dating can be a fundamental part of basin analysis, and some of their main principles are summarized here. The use of radiometric dating in geology is based on two fundamental principles: (i) uniformitarianism, which assumes that the decay constant of the present radionuclide has not changed throughout Earth history; and (ii) we can determine how much of the daughter isotope there was to begin with. The isotope geochemistry of the ancient rock record can be mainly subdivided into geochronology and tracer studies. Geochronology makes use of the constancy of the rate of radioactive decay. Because a radioactive nuclide decays to its daughter at a rate that is independent of everything, it is possible to determine a time simply by determining how much of the parent isotope is remaining and how much of the daughter isotope has been generated. Tracer studies make use of the differences in the ratio of the radiogenic daughter isotope to other isotopes of the element, which can be used to investigate fundamental Earth processes.

In this thesis, sampled sedimentary rocks from known lithofacies were evaluated from *in situ* detrital U-Pb and Lu-Hf zircon analyses. U-Pb data provide the age of crystallization of zircon, while the Lu-Hf data are useful as an isotope tracer delivering petrogenetic information on the host rock in which the zircon was crystallized, at the time of crystallization. U-Pb geochronology combined with the Lu-Hf isotope signatures of detrital zircons within the sedimentary basin was used in Paper IV to build the paleotectonic reconstruction, the plate reconstruction and the provenance studies. The U-Pb ages and Lu-Hf isotope ratios were determined independently from the same grain. Zircon ($ZrSiO_4$) is particularly important for Precambrian basin analysis because it usually survives multiple erosion-transport processes and metamorphic events, and it incorporates U in its structure, replacing zirconium, but it accepts little or no Pb at the time of crystallization. The zircon grains were separated using standard methods (sawing, crushing, heavy-liquid separation, hand-picking, and the Wilfley concentration table), and they were photographed using an electron-microscope to identify suitable microanalytical locations. The U-Pb dating and isotope analyses were performed using a Nu Plasma HR multicollector ICPMS and a New Wave / Merchantek LUV-213 laser microprobe at the University of Oslo, Department of Geosciences. LA-ICP-MS involves the ejection of matter from a solid by a laser beam, ionization of the ablated material by argon plasma and the measurement of isotopic ratios by a mass spectrometer. The main components of the system include the following: (i) a vacuum system; (ii) a source (ICP) from which ions created by the sample are focused and accelerated; (iii) an analyzer in which ions are separated by their mass to charge ratios; and (iv) a detector, which converts the ion beam to a number.

U-Pb geochronology is based on the natural decay of ^{238}U and ^{235}U to stable ^{206}Pb and ^{207}Pb with half-lives of 4.468 Ga and 0.704 Ga. In this thesis, masses 204, 206, 207, and 238 were measured, and ^{235}U was calculated from ^{238}U by using a natural ^{238}U to ^{235}U ratio of 137.88. Mass 204 was used as a monitor for common ^{204}Pb. The raw data were reduced to U and ^{206}Pb concentrations and U-Pb isotope ratios by a sample-standard bracketing routine similar to that used by Jackson et al. (2004). The zircon used for calibration included zircon standards GJ-01 (609 ± 1Ma; Jackson et al., 2004) and 91500 (1065 ±1 Ma; Wiedenbeck et al., 1995) and an in-house Paleoproterozoic standard A382 (1876 ±2 Ma; Patchett and Kouvo, 1986). The program Isoplot Ex 3.0 (Ludwig, 2003) was used to plot the concordia and probability density diagrams. Zircon standard 91500 was also run as an unknown to verify the accuracy of the method. The concordia age calculated from all of the standards run as unknowns was 1054 ±3 Ma, which is slightly younger than the reported TIMS age. The laser settings were ca. 32 % power, 40-μm spotsize and 10-Hz repetition rate. The data are presented in the $^{207}Pb/^{235}U$ *vs.* $^{206}Pb/^{238}U$ diagram, called the concordia diagram, in which the ensemble of the points having the same age with the two isotope systems (^{238}U-^{206}Pb and ^{235}U-^{207}Pb) defines the concordia line. The $^{207}Pb/^{206}Pb$ age can be visualized as the projection of the analytical point on the concordia line from the origin of the diagram (0, 0). An example of the concordia diagram is given in Figure 7.

^{176}Lu decays to ^{176}Hf with a half-life of ca. 3.73 ±0.05 to 3.69 ± 0.02 × 10^{10} yr. In this thesis, masses 172-179 were measured for the Lu-Hf isotope analysis of zircon.

The isobaric interferences on ^{176}Hf by ^{176}Lu and ^{176}Yb were corrected using an empirical procedure (cf. Griffin et al. 2000). A decay constant value for ^{176}Lu of 1.867×10^{-1} yr^{-1} was used for all calculations (Söderlund et al., 2004; Scherer et al., 2001, 2007). The reference zircon standards were MudTank (Black and Gulson, 1978; Woodhead and Hergt, 2005) and Temora-22 (Black et al., 2004). The long-term precision of the method was approximately 2.5 units. The laser settings were ca. 50 % power, 55-µm spotsize and 5-Hz repetition rate.

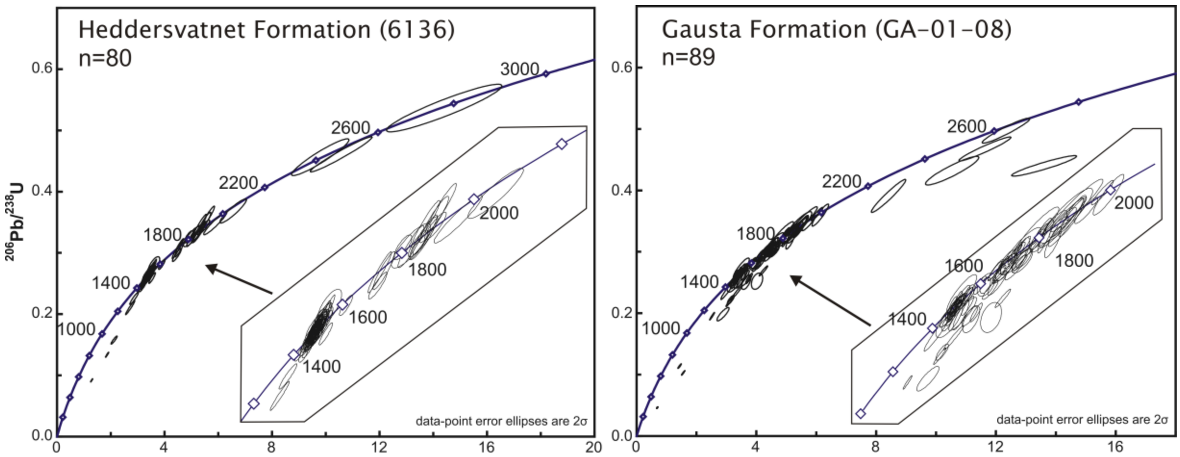

Fig. 7. Concordia diagrams from detrital zircons of the Heddersvatnet and Gausta formations sandstone samples (from the Paper IV).

4.6 Sedimentary basin paleotectonic reconstruction

The purpose of the final stage in the basin analysis flow chart (Fig. 5) is to build paleotectonic reconstructions for sedimentary basins, which can be achieved by combining all of the available data collected in the basin analysis flow chart. It is crucial to understand a basin as a large-scale dynamic system, the processes of which control the sedimentation and stratigraphic evolution within the basin.

Sedimentary basins, which exist in a background environment of plate motions, are regions of prolonged subsidence of Earth's surface. According to Ingersoll and Busby (1995), subsidence mechanisms can be the following: (i) crustal thinning as a result of extensional plate movements; (ii) supracrustal loading by magmatism, stacking of nappe and thrust sheets; (iii) mantle-lithosphere thickening during cooling of under thrusting; (iv) asthonospheric flows; and (v) sedimentary and volcanic loading. To build a sedimentary basin paleotectonic reconstruction, it is important to understand the driving mechanisms and stress environments in which the sedimentary basin was created. From a genetic point of view, the sedimentary basin classification can be simply subdivided into the following: (i) extensional basins controlled by heating of the lithosphere from below and stretching and thinning of the crust, leading to rifting and thick sedimentation prisms (e.g., rifts and passive margins); (ii) pull-apart basins controlled by same mechanisms and formed in shear settings; and (iii) compressional basins, where contraction process caused crustal thickening, leading to local loads and isostatic subsidence (e.g., forelands, back-arcs, and ocean trenches).

Sedimentation in a basin is generally controlled by a combination of autogenic (internal) and allogenic (external) processes. The relative importance of each mechanism depends mostly on basin configuration and proximal *vs.* distal settings. Autogenic processes can be studied by lithofacies analysis, but allogenic processes also require an understanding of sequence stratigraphy, geochemistry, and possible clastic petrofacies. These processes determine the distribution of depositional elements within a depositional system in a sedimentary basin (e.g., Ingersoll and Busby, 1985; Allen and Allen, 1990; Einsele, 2000; Miall, 2000). Allogenic controls on sedimentation and accommodation space in basins are controlled by the interactions of climate, tectonics and sea level changes (Fig. 8). Eustasy is mainly controlled by tectonics and climate, whereas climate is mainly controlled by global orbital forcing or possible local tectonism (e.g., formation of thrust belts). Tectonics is driven by the Earth's internal dynamics (plume and plate tectonic processes). The sediment supply is mainly controlled by climate, tectonism, transportation, and the nature of the provenance.

In Paper IV, the paleotectonic and plate-reconstruction of the studied sedimentary basin is studied by combining all of the available data. The reconstruction was based on the methods and tools described above.

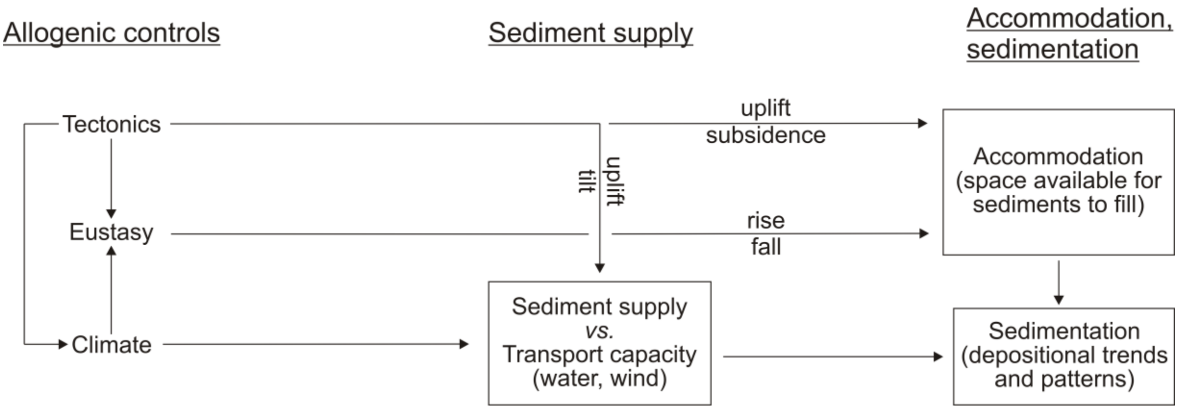

Fig. 8. Complex interplay of allogenic controls that affect to the sedimentary basin sedimentation, sediment supply, accommodation, and depositional trends and patterns (modified from Catuneanu et al., (2005). Eustasy, tectonic and climate mainly control sedimentation, whereas eustasy and tectonics are response to accommodation space.

5 Review of the original papers

Paper I

Paper I focuses on an area near the town of Rjukan, in Telemark, southern Norway (Fig. 3). The paper presents the results on the sub-Heddersvatnet unconformity and the volcanic-sedimentary Heddersvatnet and Vemork formations (Fig. 4). The main contributions of Paper I are (i) a revision of the nature of the sub-Heddersvatnet unconformity, (ii) a lithostratigraphic correlation of the Heddersvatnet and Vemork formations, and (iii) a geochemical and paleotectonic reconstruction of the Heddersvatnet formation basaltic lavas. The paper is based on sedimentological and geochemical laboratory work that was carried out in 2007–2008.

One of the most controversial problems of the Telemark supracrustal rocks is the nature and significance of the lithostratigraphic contacts between the Rjukan and Vindeggen groups and between the Tuddal, Vemork and Heddersvatnet formations (Wyckoff, 1934; Dons, 1960a, 1960b; Dahlgren, 1990a; Starmer, 1993; Menuge and Brewer, 1996; Brewer and Menuge, 1998). Earlier studies concluded that a regionally large angular unconformity exists between the Rjukan and Vindeggen Groups (Wyckoff, 1934; Dons, 1960a, 1960b), but this conclusion was subsequently called into question by Starmer (1993), Menuge and Brewer (1996), and Brewer and Menuge (1998). Dahlgren et al. (1990a) stated that the Vemork Formation represents the initial volcanism and sedimentation of the Vindeggen Group. Brewer and Menuge (1998) consider the Rjukan and Vindeggen groups to be one succession, within which the discordance of individual units is a function of the mode of deposition in the context of important tectonic changes in the evolution of the Rjukan Rift Basin. Recently, Laajoki (2005) studied the areal distribution and nature of the sub-Heddersvatnet unconformity, and Laajoki and Corfu (2007) subdivided the Vemork Formation into smaller lithostratigraphic units while discussed its relationship with the Tuddal Formation and the Vindeggen Group. Paper I addresses this controversy with new field-based lithostratigraphic, sedimentological and geochemical evidence, which also provided the framework for Paper II.

In Paper I, 14 basaltic lava samples were collected from the Heddersvatnet Formation to characterize their geochemical signature. The XRF results were used to compare these signatures to the Vemork Formation basalts and to build a paleotectonic reconstruction of the sedimentary environment. The geochemistry of the basaltic lavas indicated that the magmatic and tectonic evolution of the Heddersvatnet Formation was associated with a syn-rift tectonic phase, with more evolved magmas and crustal contamination following in the late stage of the volcanism. The samples show similar geochemical signatures as the one of the Vemork Formation basalts, and also some of the continental flood basalts. The composition indicated deep intra-plate melting compatible with a continental within-plate paleotectonic setting. The paper suggests that the termination of the volcanism indicates a gradual change from the syn-rift to post-rift stage.

The evidence presented in Paper I supports the idea that the Heddersvatnet and Vemork formations are time-equivalent strata volcanic-sedimentary rocks that change laterally from one type to another within a zone that comprises two distinct types of formations. Although the nature of the contact between the Tuddal and Vemork formations cannot be established with certainty, the angular unconformity may exist. Paper I suggests that the formation and nature of the sub-Heddersvatnet unconformity may reflect fault block rotations inside the sedimentary basin.

Paper II

Paper II focuses to the volcanic-sedimentary Heddersvatnet Formation in area near town of Rjukan, Telemark, southern Norway (Figs. 3, 4). The main contributions of Paper II include the following: (i) a detailed description of the sedimentology of the Mesoproterozoic conglomerate, sandstone and mudstone sequences; (ii) a coherent paleotectonic reconstruction; (iii) information about the relationships between alluvial fan and braidplain sedimentation; (iv) a description of how primary sedimentary structures can be preserved in ancient metamorphosed and deformed bedrock, which allows alluvial fan and braidplain systems to be recognized and a coherent sedimentation model to be built. Paper II is based on a study of physical features, including textural, compositional, and lithofacies type criteria, in combination with studies of clastic petrofacies analysis and geochemistry. The sedimentological and geochemical studies were carried out in 2007–2008.

Precambrian alluvial sedimentation patterns can display complex interactions between tectonics, different sedimentation processes, climate, metamorphic imprinting, and source rock composition. Ancient alluvial deposits can form thick, complex strata, but recognizing and distinguish between alluvial fan, braided fluvial, or braidplain deposits in the sedimentary record is often difficult, especially if the paleoslope of the channel(s) is unknown (e.g., Els, 1998; Eriksson et al., 2006; Bose et al., 2008). The depositional environments are usually sensitive to both tectonic activity and changing climatic conditions. However, they tend to have some characteristic facies assemblages.

The Heddersvatnet Formation is composed of volcaniclastic breccias and conglomerates, sandstones, associated mudstones, and subaerial basaltic lavas, which were divided into major genetic lithofacies associations and minor lithofacies. The sedimentological studies and basin analysis support the interpretation of an alluvial fan and possible associated braidplain deposit: (i) a deposition close to the source area; (ii) slightly divergent paleoflows; (ii) high-energy flows with waning flood-cycles; (iv) an abundance of poorly sorted and laterally extensive subaerial debris flows along with related streamflows, possible sheetfloods, hyperconcentrated flows, and their associations; (v) a large distribution of grain size and lithofacies changes in proximal *vs.* distal parts; (vi) a limited suite of sedimentary structures (cross-stratification, ripple-marks, and desiccation cracks); (vi) a fault bounded basin (graben) with a hanging wall close to uplifted flank(s); (viii) a paleoslope estimation indicating at least moderate paleotopographic heights; (ix) colluvial and scree apron breccias; (x) a lack of any typical braided stream channel fill conglomerates and floodplains; and (xi) channelized sediment bodies lacking extensive lateral continuity. The paleogeographical model suggests that the proximal part of the formation is dominated by colluvial and scree apron breccias and subaerial debris flows with associated streamflows and hyperconcentrated flows or sheetfloods representing waning-flood cycles. The distal part of the Heddersvatnet Formation is dominated by traction current deposits, which were interrupted by the fluctuating pulses of subaerial lava that flowed down the rift valleys, diverting the subsequent flow. Small-scale intra-rift faulting may have caused sub-environment development and lateral lithofacies changes to climatically or seasonally control intrafan ponded-lake sedimentation with playa type cycles.

The compositions of mudstone and sandstone samples indicate a passive rifted continental setting with moderate paleoweathering, which is possible in a semi-arid/arid paleoclimate. The clastic petrofacies suggest a locally uplifted and syn-rift tectonic setting toward the post-rifting stage of the sedimentary basin. These results correspond with the geochemical signatures presented in Paper I. The coherent sedimentation model suggests that the Heddersvatnet Formation was controlled by a tectonic base level fall near the paleotopographic high of the uplifted flank(s) of the sedimentary basin. This was combined with an intensive erosion of the basement in the pre-vegetation landscape, which formed an abundance of gravelly material available from the source area for entrainment by flood onto the sedimentation cone. Paper II supports the idea that a combination of detrital and geochemical records of clastic sedimentary rocks provides important information about the weathering, provenance, climate, and tectonism of ancient sedimentary basins.

Paper III

Paper III presents results of the Brattefjell Formation, in the mountain Brattefjell, Svafjell, and Mefjell areas, southern Norway (Figs. 3, 4). The paper is based on sedimentological and laboratory work carried out in 2005 and 2008–2009. The main contributions of this study are twofold: (i) providing the sedimentology of a Mesoproterozoic tidal sedimentation system and a reconstruction of its depositional history; and (ii) illustrating how tidal and nearshore sedimentation patterns correspond with fluctuating base level changes during the post-rift stage of a rift basin.

Precambrian epeiric sea paleoenvironments record information about ancient tidal conditions and nearshore sedimentation patterns. The recognition of various tidal cycles from the stratigraphic record has been a major contribution to the interpretation of ancient tidally influenced environments and to the understanding of rates of sediment accumulation and preservation. Studies of ancient tidal systems have been used to calculate Earth-Moon dynamics, anomalistic months and tidal effects on basin sedimentation patterns (e.g., Williams, 1989, 1990; Eriksson and Simpson, 2000). Most of the inferred Precambrian tidal deposits are subtidal sandwave deposits with tidal sandstone channel fills, which usually lack intertidal zones, barrier islands and associated tidal inlets and deltas (e.g., Eriksson et al., 1998). Associated shallow nearshore settings are characterized by uniform sedimentation suites with thick, well-sorted sandstone successions, a lack of clear vertical trends, and a lack of mudstone (e.g., Soegaard and Eriksson, 1985; Eriksson et al., 1998). It is thought that these tidal and nearshore environments during the Precambrian were generally high energy and were wider and shallower than their Phanerozoic counterparts (see Eriksson et al., 1998, 2005; Eriksson and Simpson, 2004).

The Brattefjell Formation is subdivided into three members based on its distinct lithofacies assemblages (Fig. 4). As a whole, the Brattefjell Formation consist diagnostic criteria of an ancient tidal influence in a marine nearshore setting. These criteria are the following: (i) bi-polar sedimentary structures (herringbone); (ii) double mud drapes; (iii) sandstone foresets bounded by mudstone couplets or mudstone drapes and re-activation surfaces reflecting flood-ebb cycles; and (iv) alternations of successive thick and thin bundles reflecting a diurnal variation. Although tidal bundles in the ancient rock record can be disturbed by later erosion, the bundle measurements suggest that at least 16–18 bundles were formed during the neap-spring cycle, which is suggestive of mixed semidiurnal tides. Paper III concludes that in the early stage of the lower Brattefjell member sedimentation, the regional subsidence caused marine conditions to cover wider areas, which gave rise to an early stage of transgression and a minor landward migration of the shoreline, forming shallowing upward stacking pattern cycles. The paper suggests that these cycles represent autogenic water level changes in a sedimentation basin caused by regional subsidence water level changes. The lithofacies assemblages are suggestive of subtidal settings, where tidal currents and wave actions form complex combinations. The sedimentation at the early stage of the middle Brattefjell member was characterized mainly by tidal sand flats, tidal channels, sandbars, and lagoon-estuarine developments likely protected by sandy barrier ridges. An ebb-dominant bedload transport was widespread over suspensions and sandbars, and reactivation surfaces were common. A rise of the relative base level during sedimentation of the middle Brattefjell member deposited interlayered mudstone and sandstone beds, suggesting alternating deposition from suspension and traction currents. Suspension settling occurred during tidal slacks, while traction characterized ebb and flood currents.

Paper III concludes that the sedimentary structures, abundance of interfingering mudstone and sandstone beds, lack of fluvial channel sediments, ooids, weak tides, and wave-dominated deposits are suggestive of a subtidal lagoon-estuary environment and relatively rapid sedimentation. The estuary sedimentation system indicated transgressive events of the basin and the drowning of fluvial channels. The transgression and wave scouring during the sedimentation of the upper Brattefjell member was characterized by the accumulation of a ravinement lag and, probably, barrier island drowning. The lithofacies assemblages and associated sedimentary structures indicate that the upper Brattefejll Formation forms a sequence in which relics of shoreface-offshore sediments and, probably, a washover fan were preserved in a transgressing coast. The Brattefjell Formation records millions of years of fluctuating water levels with an overall trangressive trend, indicating allocyclic patterns caused by regional subsidence. Abundance of ripple-marked beds, lack of storm related beds (hummocky), and lack of deep offshore-muds indicate that the Brattefjell Formation deposited above the fairweather wave base (ca. <20 m). The formation is interpreted as representing a tidally influenced clastic epeiric sea in which shallow water levels extended over part of a continent. The shoreface was fed sediment by along shore and coastal current drifts during shoreface transgressive erosion, in a low shoreline gradient with reduced sediment input and lack of major braided-fluvial channel(s).

Paper IV

Paper IV combines all of the data from the basin analysis, and it contributes to the provenance studies by building a structural-sedimentological evolution model for the Rjukan Rift Basin, i.e., the Vestfjorddalen Supergroup (Fig. 4). This study was based on sedimentological fieldwork in the Telemark area, mostly during 2005–2008, and laboratory work carried out in 2008–2009.

U-Pb geochronology of detrital zircon has become the standard method in provenance studies. The modern laser ablation techniques permit *in situ* analyses of Lu-Hf isotopes and trace elements from zircon to further assist in determining provenance. Zircon is particularly important for Precambrian source area research because it usually survives multiple erosion and transport processes and even metamorphic events. By integrating zircon provenance studies with sedimentary lithofacies, a better picture of basin evolution should emerge. Thus, a multifaceted approach is necessary to understand a sedimentary basin as a dynamic system. Paper IV provides evidence for the origin of the Rjukan Rift Basin by combining the detrital zircon age patterns with the sedimentary lithofacies to create a paleotectonic reconstruction and depositional model and to determine the source areas. The rift-filling model presented in Paper IV allows correlations to be made with other similar supracrustal rocks in southern Norway.

The provenance of the sampled sediments was evaluated from *in situ* U-Pb and Lu-Hf analysis of detrital zircon grains by LA-ICP-MS. Six samples was selected. They are distributed in all formations of the Vindeggen Group made of coarse clastic sediment, i.e. containing coarse zircon grains suitable for analysis. They represent, from bottom to top, the Heddersvatnet, Gausta, Skottsfjell, Vindsjå, and Brattefjell formations (from two different members). The sedimentary rocks and U-Pb age patterns of the Rjukan Rift Basin can be explained by a continental rift basin tectonic model. This model shows the development from syn-rift to post-rift stages, and it includes marine incursions. The subsidence and sedimentation rates were more intensive at the syn-rift stage, and this stage involved coarse clastic alluvial sedimentation with a distinct local provenance. In the detrital zircon record, grains older than ca. 1500 Ma are evidence of a pre-rifting basement source. These grains were probably brought into the basin by an axial river or along the rift margin ramps. During the post-rift stage, the basin was completely filled, and an epicontinental sea covered southern Norway. The trend of a diminishing local signal is seen in the detrital zircon pattern throughout the rift infill. Paleoproterozoic rocks were important sources in the basin's history, and matching rocks can be found in the southern Fennoscandia and northeastern Laurentia. Thus, Paper IV suggested that the Rjukan Rift Basin was situated closer to the Laurentia and later moved to its present location along a sinistral strike-slip fault. Based on the Hf isotope data and striking overlapping ages, the zircon grains came from the same source during the entire rift infilling history. Other Mesoproterozoic quartzites in south Norway were probably deposited after the Rjukan Rift Basin was completely filled and the sediments "spilled over" the rift margins. A correlation with these sediments is supported by a similar U-Pb age pattern and shallow marine sedimentological characteristics.

Paper V

Paper V describes and interprets the fracture zone and basal breccias that are associated with the sub-Svinsaga unconformity (Fig. 4). The study focuses on the mount Svafjell and Brattefjell areas, and the work was mainly carried out in 2005 (Fig. 3). The sub-Svinsaga unconformity is the most significant regional unconformity within the Telemark supracrustal rocks, and it separates the package into the Vestfjorddalen Supergroup and an overlying succession of early Sveconorwegian units. The isotopic datings show that a depositional hiatus of at least 170 Ma is associated with this unconformity. The unconformities and associated deposits record valuable information about the paleoclimate and paleosedimentology, and this information is the main contribution of the Paper V. Paper V proves that the origin of the sub-Svinsaga unconformity is probably associated with periglacial cold-climate processes and environments.

Paleoweathering can provide valuable information about the formation of different rocks units and the paleoclimatic conditions during their deposition. Thus, frost weathering is a fundamental geomorphic process operating in periglacial environments. Periglacial refers to the non-glacial processes, conditions, and landforms associated with cold-climates. In general, descriptions of Mesoproterozoic deposits ascribed to a periglacial cold-climate are rare. This rarity is possibly due to the deposits of that age being affected by diverse tectonic and metamorphic processes and, later, weathering and erosion. This can make the recognition of any typical periglacial cold-climate indicators, like sand wedges, frost-shattered blocks, or frost fractures, difficult or even impossible. However, it is probable that ancient periglacial and glacial deposits were produced by similar processes to those operating and observed in the Phanerozoic rock record (e.g., Eriksson et al., 1998, 2004). Thus, the recognition of cold-climate periglacial features from Precambrian deposits should be based on an assemblage of indicators and detailed lithofacies analyses.

Paper V concludes that the irregular features of the fractures, fracture patterns, microfractures, shattered quartz arenite clasts, and mudstone fills indicate that periglacial alteration processes played an important role in the genesis of the fracture system associated with the sub-Svinsaga unconformity. The characteristics of the fracture zone indicate rapid freezing and volumetric expansion. The role of frost shattering is also supported by the fracture zone passing upward to the *in situ* breccia zone and then to a debris-mantled block or a blockslope accumulation with sharp fragments and several–meters-large blocks. The sorting and nature of the breccia fragments and blocks support a formation by block accumulation in cold climate conditions with operative freeze-thaw processes combined with minor block ploughing and solifluction. The sedimentological studies show that the overlying conglomerate and subarkose beds were deposited over block accumulation by later fluvial processes and worked their way down into the interspaces between the fragments and blocks. The block accumulation affected the sedimentation patterns of the overlying fluvial Svinsaga Formation.

The paleogeographic reconstruction in Paper V indicates that in the early stage of the basin's evolution, the rapid subsidence was associated with different sedimentation processes and bedrock frost weathering, frost heaving, mass wasting, and blockfield and/or block slope accumulation. In the later stage, the newly formed geomorphic features were adjusted by fluvial incision on the fractured bedrock, associated with lacustrine and/or marine deposits and volcanism. Paper V and previous studies (e.g., Laajoki, 2002) suggest that the Telemark supracrustal rocks may have experienced significant frost weathering during the Mesoproterozoic Era.

Paper VI

Paper VI focuses on the Svinsaga Formation in the Mount Svafjell, Brattefjell and Meien areas (Fig. 3). The paper contributes to a better understanding of the Precambrian fluvial deposition by studying the Svinsaga Formation sedimentation patterns and depositional processes and by calculating the paleohydrological parameters. The studied formation was deposited in a basin with a strike-slip influence, which was affected by periglacial cold-climate weathering before, and possibly during, the sedimentation. The sedimentological fieldwork and laboratory work were carried out in 2005 and 2010.

Ancient braided fluvial systems were affected by a lack of binding vegetation, under variable paleoclimatic conditions, and possible characterized by unique fluvial styles during the Precambrian. In many settings, source rock material was subjected to intensive weathering, which caused an abundance of bedload material and hyperconcentrated debris flows due to channel bank instability. Thus, a braided fluvial style is generally seen as the most dominant for pre-vegetational paleoenvironments (e.g., Tirsgaard and Øxnevad, 1998; Long, 2004, 2006; Eriksson et al., 2006). Ancient fluvial systems occur in a wide range of paleotectonic settings, and they form an important part of the Precambrian rock strata. Therefore, the paleohydrological investigations are important in interpreting ancient fluvial systems and comparison different fluvial styles/systems during the Precambrian.

Fluvial systems display channel patterns that can be systematically related to sediment types that describe channel banks, sediment loads, and streamflow characteristics. Braided stream systems tend to usually have laterally confined channels with well-defined geomorphological elements (channels, banks, floodplains), which result in complex facies assemblages, and they are thus part of a continuous series of fluvial forms that develop in quasi-equilibrium with external controls on the river system. The analysis of fluvial deposits usually comprises variations in flow patterns, sediment transport rate, stream flow velocity and depth control of bedform textures and structures, stratification patterns, lithofacies characteristics, and possible large-scale evolutionary architectural elements. By utilizing sedimentology and the paleohydraulic reconstruction of events, the processes operating in ancient fluvial systems can be better understood.

The sedimentology of the ancient braided stream sedimentation systems and channel-fills, in different tectonic settings, has been described in many studies (e.g., Eriksson et al., 2006, 2008; Long, 2006), but only very few paleohydrological studies have been made on ancient fluvial deposits (e.g., Van Der Neut and Eriksson, 1999; Eriksson et al., 2006, 2008; Davidson and Hartley, 2010). Eriksson et al. (2006, 2008) reported and discussed a possibly unique fluvial style from the Proterozoic (ca. 2.0 – 1.8 Ga) deposits, in the Kaapvaal Craton. This study contributes to this discussion of ancient fluvial systems and brings new paleohydrological and sedimentological data from the ca. 1.17 Ga-old fluvial deposits. These parameters have some sedimentological significance as a comparative tool for other ancient deposits, within sedimentary basins, or comparing paleohydrological data within formations to estimate differences in paleohydrological patterns in the proximal and distal parts of the formation.

Eleven different sedimentary lithofacies and five lithofacies associations were recognized from the Svinsaga Formation. The lithofacies assemblages indicate that the formation represents a relatively high-energy braided fluvial environment. Massive breccias, massive and inversely to normally graded conglomerates, stratified sandstones and laminated and rippled mudstones, were transported by traction currents, sediment gravity flows and by suspension. The proximal part of the formation contains blockfield / blockslope accumulations and waning flood-flow cycles. These are overlain by hyperconcentrated and debris flow deposits, and ephemeral high-energy bedforms. The distal part of the formation contains dune bedforms and channel lag deposits, which indicate waning discharge fluctuations.

The paleohydrological calculations from the channel-fill conglomerates and sandstone bedforms correlate with lithofacies assemblages. The estimation of paleoslope and discharge values support the presence of a fluvial stream rather than an alluvial fan environment. The stream power and water velocity systematically decreases towards the distal parts of the formation.

The abundance of waning flood-flow cycles, ephemeral high-energy sedimentary deposits, and hyperconcentrated and debris flow deposits is a possible indicator of periglacial melt waters in basin margin strike-slip fault evolution. This melt water combined with abundantly available debris from the non-vegetated high-topographic landscape.

6 Discussion

6.1 Applicability of the used methods

Precambrian rock strata often show a lack of lateral and vertical outcrops, which presents a major problem in lithostratigraphic correlation. The unexposed and sheared contacts between formations are often highly problematic because they may hide some of the information of the strata. To tackle these difficulties, it is important to use of geochemistry as supplementary data and to understand which parts of the sedimentary basin (e.g., proximal *vs.* distal and axial *vs.* flank) successions are preserved and exposed.

The principles of Phanerozoic facies models are mainly based on the basic principles of actualism, the natural law of the limited number of depositional environments, Walther's Law of vertical successions, and the assumption of the uniformitarianism of recent analogues in the past. However, when studying Precambrian sedimentary environments, at least two different "hypotheses" of facies models must be taken into account. First, the assumption of Walther's Law is that the vertical succession of facies may reflect a lateral juxtaposition of depositional environments. However, this fundamental law only applies when there have been no significant changes in factors that control sedimentation patterns. In other words, it only applies to successions without major breaks in sedimentation, which can be complicated to prove in Precambrian strata. Second, Phanerozoic facies models represent a snapshot of the lateral relationships of sedimentary environments and facies over a limited amount of time. In addition, due to geological, atmospheric and biological differences in the Precambrian, some of the sedimentary basin conditions in the past may not have analogues today, and non-uniformitarian models may have to be used. Thus, it is import to recognize, from the study area facies scheme, what is actually local and what is global. Usually, unit and bed contacts are an important part of facies studies (e.g., sharp, gradual) because they can record significant breaks in sedimentation. Although it is difficult to apply a 3D facies architecture analysis to Precambrian strata, lithofacies analysis is a fundamental tool in Precambrian basin analysis because it helps clarify the sedimentation processes at local, regional, and possibly global scales. The lithofacies assemblages and paleohydrological parameters presented in the six papers suggest that the Phanerozoic sedimentation models differ, at least partly, from the Precambrian models and systems, probably due to intensive weathering, rapid basin subsidence, and the lack of binding vegetation. Therefore, the established lithofacies scheme used in this thesis was modified for local sedimentation model purposes.

The lithostratigraphic mapping and lithofacies analysis can be seen as an essential component of Precambrian sequence stratigraphy. Sequence stratigraphy allows an improved understanding of stratigraphic cyclicity and allogenic controls in sedimentary basin-fills, and allows the recognition of single or multiple cycles within sedimentary environments or within an entire basin (see Papers III and IV). The papers suggest that these cycles and their bounding surfaces are closely associated with changes in accommodation space and that they correspond with fluctuating water levels and changes in the base level. The limitations of the outcrop data in Precambrian sequence stratigraphy is mainly related to preservation potential and amount of data available (see Catuneanu and Eriksson, 2007; Catuneanu et al., 2009).

The clastic petrofacies analysis can be an effective tool as supplementary data for geochemistry, and it was used in Paper II. The main limitations of the method on Precambrian sedimentary rocks are biasing of the detrital framework and composition due to pseudomatrix, diagenesis, and multiple provenance sources, mixed transport history, paleoclimate, and metamorphosis. However, these problems can be partly avoided by using a combination of whole-rock geochemistry for tectonic reconstruction and detrital zircons for provenance studies on the same sedimentary deposits, as in Paper II. The problems with the Gazzi-Dickson modal analysis method are mainly related to cases in which there is a true mineralogical difference in grain size (Ingersoll et al., 1983). In fact, no point counting methods can adequately address this problem. However, the method does allow the maximization of source rock data, and counting of poorly sorted and coarse-grained sandstones is fast. As noted by Ingersoll et al. (1983), the modal composition does not change due to the simple breakage of grains; that is, the weathering of grains still produces the same minerals, no matter the grain size. The modal analysis in Paper II shows that modal analysis results correspond with the geochemical results and the tectonic evolution of the basin.

Geochemistry still is an important tool in ancient basin analysis. In particular, the combination of facies analysis, clastic petrofacies analysis, and geochemical data of siliciclastic sedimentary rocks provides important information about the lithostratigraphic correlation, weathering, provenance, paleoclimate, and paleotectonic settings of ancient sedimentary basins. However, the chemical composition of the provenance is probably the major control on the geochemistry of sedimentary rocks. This information can be distorted and biased by hydraulic sorting, post-depositional diagenetic reactions, metamorphosis, and weathering. XRF analysis, which was used in Papers I and II, is important for determining the paleogeographical model and tectonic setting and for comparing results from previous local studies. The main problems associated with the analyses were probably related to post-depositional diagenesis, metamorphisms, and weathering. These issues were mainly reflected as a potassium addition by metasomatism. Therefore, it is important to identify the different mechanisms before evaluating geochemical data and building tectonic models for ancient sediments.

The LA-ICP-MS techniques have permitted rapid *in situ* analysis of Lu-Hf isotopes and trace elements from zircon to further assist in determining provenance. Precambrian shield areas are often extensively soil-covered and vegetated. Furthermore, the rocks themselves can be highly deformed, which hinders detailed sedimentological observations, presenting a severe obstacle for Precambrian sedimentology and basin analysis. Therefore, isotope geochemical analyses are a “must” for fully understanding ancient sedimentary basin evolution. The main problems in Paper IV were likely related to the lack of comparable Lu-Hf data from the possible provenance sources, although a successful plate reconstruction and provenance history was achieved in Paper IV. Paper IV shows that it is important to fully understand the lithofacies assemblages and depositional environment where the detrital zircon sample is taken. Only this knowledge allows the building of coherent basin models and an evaluation of the provenance histories of the basin.

Many of the modern basin types are rarely found in the ancient record because of uplift, erosion, and/or deformation and destruction. In addition, sedimentary basin subsidence history is difficult to estimate due to the limited use of the backstripping method and limited seismic data for ancient basins. The use of backstripping and seismic data would allow the removal of the sediment load from basin to reveal the tectonic driving mechanism of the basin’s subsidence history. The recognition of ancient sediment basins is usually based on the study and usage of lithofacies assemblages, sequence stratigraphy, and geochemistry. However, despite the limitations, it is still possible to build a coherent tectonic-sedimentary history of a basin by using a multifaceted approach and by following the basin analysis flow chart from the bottom up, as in this thesis.

6.2 Tectonic-sedimentary evolution of the Telemark basin-fills

There is a general consensus, on a global scale, that present day southwest Norway was moved into its present location during the Sveconorwegian orogeny. The main debate has concerned two possible models for terrane/block assembly at the onset of the Sveconorwegian Orogeny (e.g., Åhäll et al., 1998; de Haas et al., 1999; Bingen et al., 2001, 2005, 2008b; Andersen et al., 2002b; Corfu and Laajoki, 2008 and references therein). Based on geochronology, isotope geochemistry, and metamorphic events, the *exotic* model suggests that the Telemark block evolved outside (proto)Baltica and welded with the Baltica during the Sveconorwegian Orogeny. Arguments for the *exotic* model are mostly based on a widespread 1.22–1.13 Ga magmatism in the Telemark block without equivalents in nearby terranes, and on a gabbro-tonalite complex (ca. 1.20–1.18 Ga) in the Bamble terrane, which has a geochemical signature indicating that the Telemark block subduction prevailed at the margin or the outboard of the Baltica (see Bingen et al., 2005, 2008b and references therein; Corfu and Laajoki, 2008). The *indigenous* model, however, suggests that the Telemark block was attached to the Baltica, either as a peripheral or as part of the margin. The indigenous model is supported by the geochronology of different magmatic suites, with equivalents in cratonic Fennoscandia, isotopic compositions of magmatic and sedimentary rocks and detrital isotope geochemistry showing the Paleoproterozoic felsic provenances in the Baltica (de Haas et al., 1999; Andersen et al., 2001; Bingen et al., 2001, 2003, 2005, 2008b; Andersen et al., 2002b; Laajoki and Corfu, 2007).

The analyzed U-Pb and Lu-Hf data presented in Paper IV suggest that the depositional basin for the Telemark supracrustal rocks was situated closer to the Laurentia supercontinent and later moved to its present location along a sinistral strike-slip fault (Fig. 9). This scenario was also suggested by authors such as Torske (1985), de Haas et al. (1999) and Bingen et al. (2005). In Paper IV, the majority of the analyzed U-Pb ages in the sediments can be matched with known basement rocks in both Fennoscandia and Laurentia. The exceptions are a peak at ca. 1730 Ma and a gap of ages between 1600 and 1500 Ma in the samples, which are discussed in more detail in Paper IV. If the Telemark block was not attached to the Baltica before the Sveconorwegian Orogeny, the thrusting of the Bamble and Kongsberg blocks onto Telemark block at ca. 1.10 Ga sets a minimum age for the docking of the Telemark to Baltica (Bingen et al., 2005; Bogdanova et al., 2008).

6.2.1 Rjukan Rift Basin

On a more regional and local scale, the term "Rjukan Rift Basin," for the Vestfjorddalen Supergroup, was introduced by Sigmond et al. (1997). Sigmond et al. (1997) argued that the field relations between the large volumes of felsic volcanic rocks within fault boundaries indicate deposition in a rift basin. A rift basin origin had already been suggested based on geochemical grounds (Menuge and Brewer, 1996). This concept has been supported by further geochemical and sedimentological studies presented by Brewer and Menuge (1998) and by Papers I, II, and IV. Structurally, the Rjukan Rift Basin is mostly oriented N-S. It is about 200-km-long and 60-km-wide, and it records a sedimentation history of ca. 170 Ma. Continental rift basins are complex features defined by large-scale structural components (e.g., border-faults, uplifted flanks, transfer zones) and by small-scale fault structures within the basin. Such structures must have affected the depositional patterns of the Rjukan Rift Basin by creating local sites of uplift and erosion, which controlled the sediment transport and defined the accommodation space for deposition. A summarizing schematic figure of the Rjukan Rift Basin and the overlying succession's structural-sedimentological evolution is presented in Figure 10. The syn-rift stage was characterized by abundant bimodal volcanism followed by abundant continental flood basalts and coarse-grained alluvial fan-fluvial sedimentation in different parts of the basin, which was defined by pure extensional rifting (studied in Papers I and II). Crustal extension and rifting in the Telemark was related to the mantle plume event or Dalopolonian Orogeny, which possible related to collision between the Mesoproterozoic EEC and another continent, presumably Amazonia or some other South American terranes (Bogdanova, 2001). The sedimentation of the basin was mostly affected by the local intensive erosion and weathering of the felsic lavas. The sediment deposits suggest high subsidence rates for the basin and an equally rapid erosion of rising rift shoulders during the syn-rift stage. The sedimentation basin subsidence was caused by tectonism, sediment-volcanic loading and crustal densification. The basin entered the late syn-rift stage gradually, where the connection between the rift structure and shallow marine waters was established and the volcanism terminated. At the late syn-rift stage, the transgression and associated erosion reworked the underlying sediments, and a newly formed bay may have acted as a sediment sink for clastic detritus transported by alongshore currents in a shoreline. This was followed by tidal sedimentation, and the cooling of the lithosphere eventually caused the basin subsidence to slow. The basin then entered its post-rift stage. The crust, including the basin, continued to subside on a larger scale. The fluvial incision and sedimentation indicate a base level drop, the filling of the basin and a shoreline advancing further to the sea. At the end of the early post-rift stage and the late post-rift stage, the shallow marine conditions returned and covered wide areas accompanied by base level transgression and the landward migration of the shoreline. The late syn-rift stage was characterized by subtidal and high-energy nearshore sedimentation patterns in an overall trangressive setting, which was studied in Paper III. A delicate balance between sediment supply and accommodation space creation was achieved, which resulted in sediment accumulations several kilometers thick. The whole rift was buried under shallow shelf deposits.

When comparing the Rjukan Rift Basin to, for example, the East African Rift (Frostick et al., 1986) and mid Jurassic Alp rift basins (Loup, 1993), notable differences in sedimentation patterns appear, including a lack of deep water (turbidites, olistostromes, and megabreccias) and carbonate sediments. The lack of a deepwater sedimentation prism and oceanic crust as well as the non-evolution to passive margin setting could indicate that the rifting in the Rjukan Rift Basin failed to complete the break-up of the continental crust. The high input of terrigenous siliciclastic sediments, possible cold-climate conditions, and other factors prevented the ignition of the carbonate factor in the Rjukan Rift Basin. The erosional unconformity (sub-Heddersvatnet unconformity), clastic sedimentation starvation and voluminous bi-modal volcanism in the syn-rift stage indicate an active rift model (Sengör and Burke, 1978; Frostick and Steel, 1993). In an active rifting setting, the surface deformation is associated with the impingement of a thermal plume or sheet on the base of the lithosphere. Although the dip of bounding faults is difficult to estimate, the thick accumulation of sediments (ca.

8 km) and the lack of frequently interrupting unconformities favor a simple shear rift model rather than a pure shear. Estimations of sedimentation rates in the East African Rift Basin vary from 10 cm/ka to several 100 cm/ka, which could be also the case in the Rjukan Rift Basin. The sedimentation rates were probably much higher during the base level drop and the syn-rift phase due to the intensive erosion of the uplifted flanks. Comparing the Rjukan Rift Basin e.g., to the well-studied Paris Basin, it is known that the rifting in the Paris Basin lasted for ca. 60 Ma (Allen and Allen, 1990), which could be the maximum rifting age (or less) of the Rjukan Rift Basin.

It is obvious that the sub-Svinsaga unconformity represents a significant depositional hiatus and that it marks the boundary of evolution in tectonic regimes. The sub-Svinsaga unconformity may also record an unusually periglacial paleoclimate, which was studied in Paper V. The nature of the sub-Svinsaga unconformity varies from angular in the south to more conformable in the north, indicating that the tectonic deformation and evolution was more intensive in different localities.

6.2.2 Early Sveconorwegian strike-slip basin

Based mostly on geochemical studies of the basalts, Brewer et al. (2002) suggested a continental back-arc setting for the Höydalsmo Group, which is part of the early Sveconorwegian units in the Telemark supracrustal rocks (Figs. 4 and 10). The lack of deep-marine basin-fills and evidence of contemporaneous tectonics argues against this suggestion. In fact, the abrupt lateral lithofacies variations, coarse-grained alluvial fan sedimentation, intrabasinal unconformities, bi-modal volcanism, and basin margin faults strongly suggest a strike-slip influence (cf. Hathaway, 1993; Mueller and Corcoran, 1998). However, the sedimentation environments and patterns of the overlying early Sveconorwegian units are not well known. The evolution possibly contains a sedimentary-volcanic transpression or extension stage to a non-volcanic and sedimentary dominated transtensional stage. Overall, the evolution records sedimentation at ca. 80 Ma in a strike-slip influenced basin generated by the releasing bend of transformal faults. The preliminary depositional evolution of the early Sveconorwegian units is illustrated in Figure 10. The first strike-slip phase was probably related to transpression and mantle volcanism, which was followed by a colder transtensional stage that mostly accumulated only coarse conglomerates and sandstones. The crust was thicker, and the faults did not penetrate into the mantle, thereby creating any associated volcanism. It is likely that strike-slip movements created several individual basins during the deposition. The lack of any volcaniclastic material in the Svinsaga Formation (Figs. 4, 9), which was studied in Paper VI, probably indicates that the deep faulting and volcanism was activated later and/or that it was only active in certain individual basins. Generally, in strike-slip basins, the reported sedimentation rates are high (ca. 0.5–4 m/ka, e.g., Einsele, 2000 and references therein), and the subsidence is rapid. The abundance of coarse-grained conglomerates and alluvial fan sedimentation in the early Sveconorwegian units could also support this conclusion.

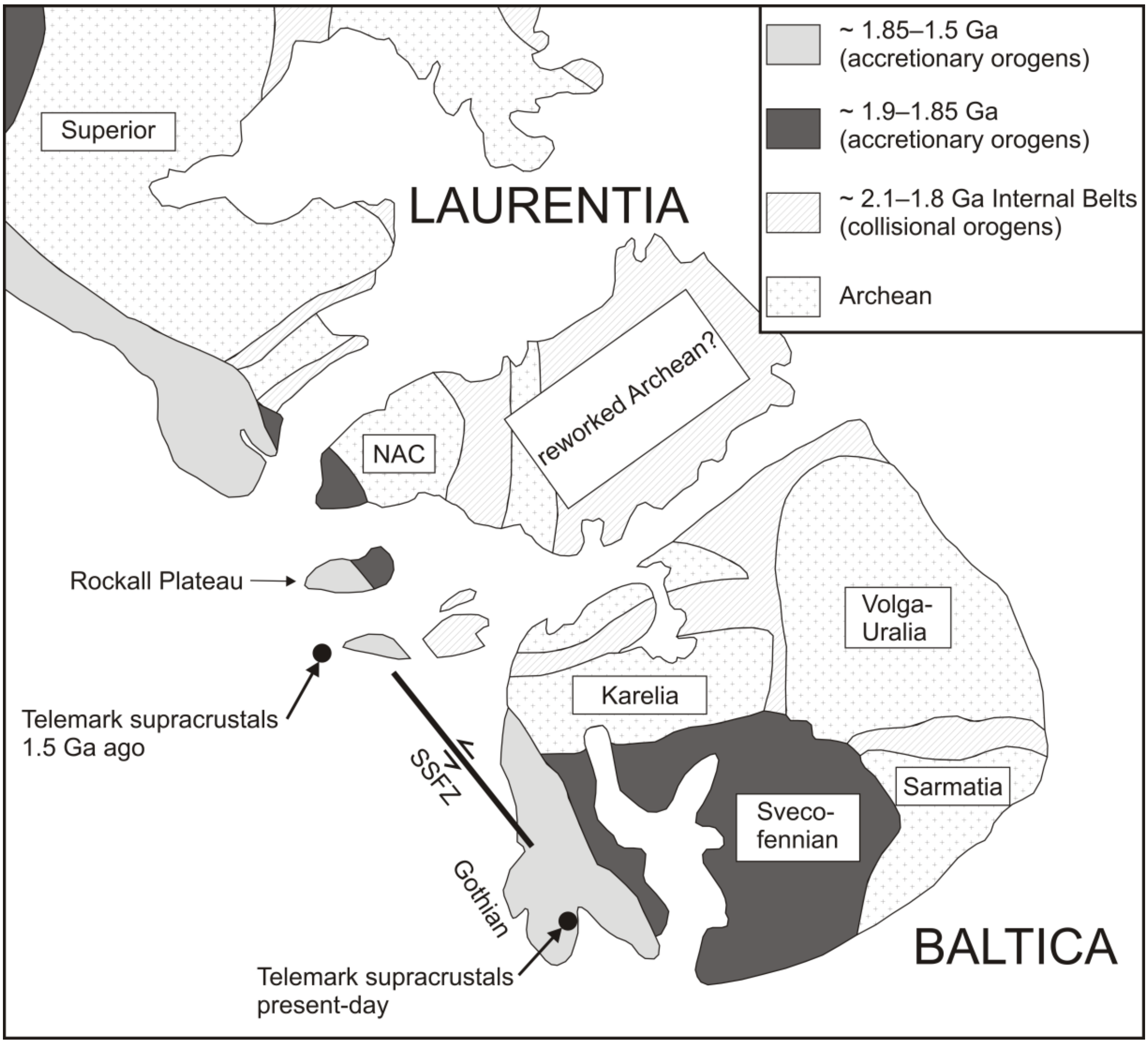

Fig. 9. Paleogeographic plate reconstruction of the Laurentia and Baltica during the Mesoproterozoic (modified from Buchan et al., 2000). Telemark block was possible located near Rockall Plateau and Laurentia, and displaced into current location along a strike-slip fault zone. NAC: North Atlantic Craton, SSFZ: strike-slip fault-zone.

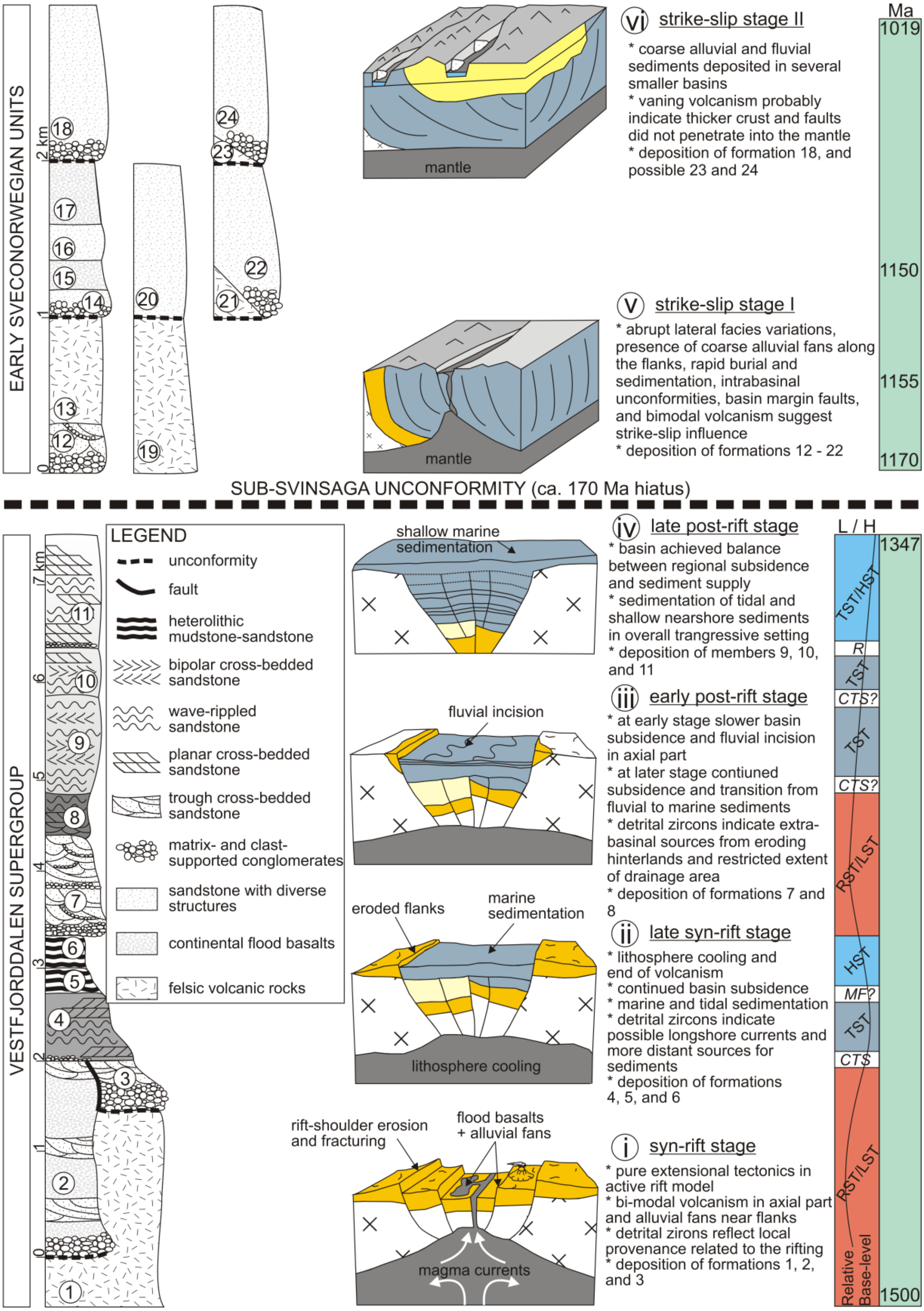

Fig. 10. Schematic summary of tectonic-sedimentary evolution of the Telemark basin-fills. Tectonism and sedimentation can be subdivided into the six different stages. See text for discussion. Formations: (1) Tuddal, (2) Vemork, (3) Heddersvatnet, (4) Gausta, (5) Bondal, (6) Lauvhovd, (7)

Skottsfjell, (8) Vindsjå, (9) Brattefjell lower member, (10) Brattefjell middle member, (11) Brattefjell upper member, (12) Svinsaga, (13) Ljosdalsvatnet & Robekk, (14) Røynstaul, (15) Morgedal, (16) Dalaå, (17) Gjuve, (18) Eidsborg, (19) Brunkeberg, (20) Transtaulhøgdi supracrustals, (21 & 22) Vallar bru & Heksfjellet, and (23 & 24) Skogsåa porphyre & Heddal Gr sediments. RST/LST: regressive/lowstand system tract, CTS: conformable trangressive surface, TST: transgressive system tract, MF: maximum flooding surface, HST: highstand system tract, R: transgressive ravinement surface.

7 Conclusions

The conclusions summarize the sedimentological basin analysis presented in the thesis and main results achieved from the Telemark basin-fills.

I The Telemark basin-fills represent a tectonic-sedimentary evolution from the extensional continental rift to the strike-slip influenced tectonic setting. The provenance studies indicate that the sedimentation basin was likely located near the Laurentia supercontinent and moved to its present location along sinistral strike-slip fault.

II The evolution of the Rjukan Rift Basin can be subdivided into (i) syn-rift, (ii) late-syn rift, (iii) early-post rift, and (iv) late-post rift stages. Each stage was characterized by different volcanic-sedimentary patterns, where a fluctuating basin subsidence created an accommodation space for basin-fills during the pure extensional tectonics. The accumulated basin-fills indicate sedimentation in alluvial fan, braidplain, fluvial, estuarine-lagoon, shallow marine and tidal environments. The lack of a deepwater sedimentation prism and oceanic crust, and the non-evolution to passive margin setting strongly indicate that the rifting failed to complete the break-up of the continental crust.

III The Telemark basin-fills strata are truncated by the sub-Svinsaga unconformity, which represents a ca. 170 Ma hiatus in the stratigraphic record, marking the boundary of evolution in the tectonic regimes. The sedimentological studies indicate that this boundary was closely associated with periglacial cold-climate processes and that the tectonic deformation and evolution was likely more intensive in different localities.

IV The abrupt lateral lithofacies variations, coarse-grained alluvial fan sedimentation, intrabasinal unconformities, bi-modal volcanism, and basin margin faults strongly suggest a strike-slip influenced setting for the early Sveconorwegian units. The evolution possibly contains a sedimentary-volcanic transpression or extension stage to a non-volcanic and sedimentary dominated transtensional stage. The faulting and volcanism was probably activated either at a later stage during the basin evolution or in certain individual basins.

V The integration of several different methods, including regional mapping and lithostratigraphy, facies analysis, sequence stratigraphy, clastic petrofacies analysis, and geochemistry, is essential when studying Precambrian sedimentary successions. It is crucial to understand a sedimentary basin as a dynamic system to reveal ancient tectonic settings, depositional environments, and depositional processes for building a coherent tectonic-sedimentary model.

VI Some Phanerozoic sedimentation models may oversimplify Precambrian sedimentary deposits, and uniformitarianism applied to individual sedimentary systems is not always valid. Thus, the ancient sedimentary environment should first be understood as an individual system before considering it to more modern schemes. Although Precambrian bedrock is often deformed and metamorphosed, and outcrops are often limited, it is possible to perform a reliable sedimentological and basin analysis and to build valid paleotectonic reconstructions of ancient sedimentary basins.

References

Åhäll, K.-I., Connelly, J.N., 2008. Long-term convergence along SW Fennoscandia: 330 m.y. of Proterozoic crustal growth. *Precambrian Research 161, 452–472.*

Altermann W., Corcoran, P.L., 2002. Precambrian sedimentary environments: a modern approach to ancient depositional systems. *IAS Special Publication 33: vii-xi.*

Allen, P.A., Allen, J.R., 1990. Basin analysis: principles and applications. *Blackwell Scientific Publication.*

Altermann, W., 2004. Precambrian stromatolites: problems in definition, classification, morphology and stratigraphy. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) *The Precambrian Earth: Tempos and Events. Elsevier – Developments in Precambrian Geology 12, 564–574.*

Andersen, T. 2005. Terrane analysis, regional nomenclature and crustal evolution in southwestern Fennoscandia. *GFF 127, 157–166.*

Andersen, T., Sylvester, A.G., Andersen, A., 2002a. Age and petrogenesis of the Tinn granite, Telemark, South Norway, and its geochemical relationship to metarhyolite of the Rjukan group. *Norges Geologiske Undersøkelse Bulletin 440, 19–26.*

Andersen, T., Griffin, W.L., Pearson, N.J. 2002b. Crustal evolution in the SW part of the Baltic Shield: The Hf isotope evidence. *Journal of Petrology 43, 1725–1747.*

Andersen, T., Laajoki, K., Saeed, A. 2004a. Age, provenance and tectonostratigraphic status of the Mesoproterozoic Blefjell quartzite, Telemark sector, southern Norway. *Precambrian Research 135, 217–244.*

Andersen, T., Griffin, W.L., Jackson, S.E., Knudsen, T.L., Pearson, N.J. 2004b. Mid- Proterozoic magmatic arc evolution at the southwest margin of the Baltic shield. *Lithos 73, 289–318.*

Andersen, T., Griffin, W.L., Sylvester, A.G., 2007. Sveconorwegian crustal underplating in southwestern Fennoscandia: LAM-ICPMS U-Pb and Lu-Hf isotope evidence from granites and gneisses in Telemark, southern Norway. *Lithos 93, 273–287.*

Arndt, N.T., 2004. Crustal Growth Rates. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) The Precambrian Earth: Tempos and Events. *Elsevier – Developments in Precambrian Geology 12, 155–158.*

Atkin, B.P., Brewer, T.S., 1990. The tectonic setting of basaltic magmatism in the Kongsberg, Bamble and Telemark sectors, Southern Norway. In: Gower, C.F., Rivers, T., Ryan, B. (eds.) Mid-Proterozoic Laurentia-Baltica. *Geological Association of Canada, Special Paper 38, 471–483.*

Bauluz, B., Mayayo, M.J., Fernandez-Nieto, C., Lopez, J.M.G., 2000. Geochemistry of Precambrian and Paleozoic siliciclastic rocks from the Iberian Range (NE Spain): Implications for source-area weathering, sorting, provenance, and tectonic setting. *Chemical Geology 168, 135–150.*

Bingen, B., Birkeland, A., Nordgulen, Ø., Sigmond, E.M.O., 2001. Correlation of supracrustal sequences and origin of terranes in the Sveconorwegian orogeny of SW Scandinavia: SIMS data on zircon clastic metasediments. *Precambrian Research 108, 293–318.*

Bingen, B., Mansfeld, J., Sigmond, E.M.O., Stein, H., 2002. Baltica-Laurentia link during the Mesoproterozoic: 1.27 Ga developments of continental basins in the Sveconorwegian orogeny, southern Norway. *Canadian Journal of Earth Sciences 39, 1425–1440.*

Bingen, B., Nordgulen, Ø., Sigmond, E.M.O., Tucker, R., Mansfeld, J., Högdahl, K., 2003. Relations between 1.19–.1.13 Ga continental magmatism, sedimentation and metamorphism, Sveconorwegian province, S Norway. *Precambrian Research 124, 215–241.*

Bingen. B., Øyvind, S., Marker, M., Sigmond, E.M.O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R.D., Liegeois, J.-P., 2005. Timing of continental building in the Sveconorwegian orogeny, SW Scandinavia. *Norwegian Journal of Geology 85, 87–116.*

Bingen, B., Andersson, J., Söderlund, U., Möller, C., 2008a. The Mesoproterozoic in the Nordic countries. *Episodes 31, 29–34.*

Bingen, B., Nordgulen, Ø., Viola, G., 2008b. A four-phase model for the Sveconorwegian orogeny, SW Scandinavia. *Norwegian Journal of Geology 88, 43–72.*

Black, L.P., Gulson, B.L., 1978. The age of the MudTank carbonatite, Strangways Range Northern Territory. *Journal of Australian Geology and Geophysics 3, 227–232.*

Black, L.P., Kamo, S.L., Allen, C.M., Davis, D.W., Aleinikoff, J.N., Valley, J.W., Mundil, R., Campbell, I.H., Korsch, R.J., Williams, I.S., Foudoulis, C., 2004. Improved 206Pb/238U microprobe geochronology by the monitoring of a trace-element-related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. *Chemical Geology 205, 115–140.*

Bogdanova, S.V., 2001. Tectonic setting of 1.65–1.4 Ga AMCG magmatism in the western East European Craton. *EUG-11 meeting, Strasbourg, France. Journal of Conference Abstracts 8, 769.*

Bogdanova, S.V., Bingen, B., Gorbatschev, R., Kheraskova, T.N., Kozlov, V.I., Puchkov, V.N., Volozh, Y.u.A., 2008. The East European Craton (Baltica) before and during the assembly of Rodinia. *Precambrian Research 160, 23–45.*

Bose, P.K., Sarkar, S., Mukhopadhyay, S., Saha, B., Eriksson, P., 2008. Precambrian basin-margin fan deposits: Mesoproterozoic Bagalkot Group, India. *Precambrian Research 162, 264–283.*

Bose, P.K., Eriksson, P.G., Sarkar, S., Wright, D.T., Samanta, P., Mykhopadhyay, S., Mandal, S., Banerjee, S., Altermann, W., 2010. Sedimentation patterns during the Precambrian: A unique record? *Marine and Petroleum Geology, doi:10.1016/j.marpetgeo.2010.11002.*

Brewer, T.S., Atkin, B.P., 1987. Geochemical and tectonic evolution of the Proterozoic Telemark supracrustals, southern Norway. In: Pharaoh, T.C., Beckinsale, R.D., Richard, D.T. (eds.) Geochemistry and mineralization of Proterozoic volcanic suites. *Geological Society Special Publication 33, 471–487.*

Brewer, T.S., Atkin, B.P., 1989. Elemental mobilities produced by low-grade metamorphic events: a case study from the Proterozoic supracrustals of southern Norway. *Precambrian Research 45, 143–158.*

Brewer, T.S., Menuge, J.F., 1998. Metamorphic overprinting of Sm-Nd isotopic systems in volcanic rocks: the Telemark Supergroup, southern Norway. *Chemical Geology 145, 1–16.*

Brewer, T.S., Åhäll, K.-I., Darbyshire, D.P.F., Menuge, J.F., 2002. Geochemistry of late Mesoproterozoic volcanism in southwestern Scandinavia: implications for Sveconorwegian/Grenvillian plate tectonics models. *Journal of Geological Society 159, 129–144.*

Buchan, K.L., Mertanen, S., Park, R.G., Pesonen, L.J., Elming, S.-A., Abrahamsen, N., Bylund, G., 2000. Comparing the drift of Laurentia and Baltica in the Proterozoic: the importance of key palaeomagnetic poles. *Tectonophysics 319, 167–198.*

Bugge, C., 1931. Geologiske undersøkelse i Telemark. *Norks Geologisk Tidsskrift 12, 149–170.*

Bugge, J.A.W., 1943. Geological and petrological investigations in the Kongsberg-Bamble formation. *Norsk Geologiske Undersøkelse, 160.*

Catuneanu, O., 2001. Flexural partitioning of the Late Archean Witwaterstand foreland system, South Africa. *Sedimentary Geology 141/142, 95–122.*

Catuneanu, O., 2006. Principles of sequence stratigraphy. *Elsevier, Amsterdam.*

Catuneanu, O., Martins-Neto, M.A., Eriksson, P.G., 2005. Precambrian sequence stratigraphy. *Sedimentary Geology 176, 67–95.*

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. *Earth-Science Reviews 92, 1–33.*

Christie-Blick N., Biddle, K.T., 1985. Deformation and basin formation along strike-slip faults. In: Biddle, K.T., Christie-Blick, N. (eds.) Strike-slip deformation, basin formation, and sedimentation. *SEPM Special Publication 37, 1–34*

Condie, K.C., 1998. Episodic continental growth and supercontinents: a mantle avalanche connection*? Earth Planetary Scientific Letters 163, 97–108.*

Condie, K.C., 2002. Episodic continental growth models: afterthoughts and extensions. *Tectonophysics 322, 153–162.*

Condie, K.C., 2004. Precambrian superplume events. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) *The Precambrian Earth: Tempos and Events. Elsevier – Developments in Precambrian Geology 12, 163–173.*

Condie, K.C., Dengate, J., Cullers, R.L., 1995. Behavior of rare earth elements in a paleoweathering profile on granodiorite in the Front Range, Colorado, USA. *Geochimica et Cosmochimica Acta 59/2, 279–294.*

Corcoran, P.L., Mueller, W.U., 2004. Aggressive Archean Weathering. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) The Precambrian Earth: Tempos and Events. *Elsevier – Developments in Precambrian Geology 12, 494–505.*

Corcoran, P.L., Mueller, W.U., 2004. Archean Sedimentary Sequences. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O., (eds.) *The Precambrian Earth: Tempos and Events. Elsevier – Developments in Precambrian Geology 12, 613–625.*

Corfu, F., Laajoki, K., 2006. The Skardfoss Formation, its age and bearing on the lithostratigraphy of the Telemark supracrustals, south Norway. In: Peltonen, P., Pasanen, A. (eds.) *Bulletin of the Geological Society of Finland, Special Issue 1, 24.*

Corfu, F., Laajoki, K., 2008. An uncommon episode of mafic magmatism at 1347 Ma in the Mesoproterozoic Telemark supracrustals, Sveconorwegian orogeny – implications for stratigraphy and tectonic evolution. *Precambrian Research 160, 299–307.*

Cullers, R.L., Bock, B., Guidotti, C., 1997. Elemental distributions and neodymium isotopic compositions of Silurian metasediments, western Maine, USA; redistribution of the rare earth elements. *Geochimica et Cosmochimica Acta 61/9, 1847–1861.*

Dahlgren, S., Heaman, L., Krogh, T., 1990a. Geological evolution and U-Pb geochronology of the Proterozoic Telemark area, Southern Norway. *Geonytt 17, 39–40.*

Dahlgren, S., Heaman, L., Krogh, T., 1990b. Precise U-PB zircon and baddeleyite age of the Hesjåbutin gabbro, Central Telemark area, southern Norway. *Geonytt 17, 38.*

Dahlgren, S., Heaman, L., 1991. U-Pb constrains for the timing of middle Proterozoic magmatism in the Telemark region, Southern Norway. *Proceedings of the Geological Association of Canada – Mineralogical Association of Canada 16, A28*

des Marais, D.J., 1994. The Archean atmosphere: its composition and fate. In: Condie, K.C. (ed.) *Archean Crustal Evolution. Elsevier, Amsterdam.*

Dickinson, W.R., Suczek, C.A., 1978. Plate tectonics and sandstone compositions. *American Association of Petroleum Geologists 63 (12), 2164–2182.*

Dickinson, W.R., Beard, L.S., Brakenridge, G., Robert, E.J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of American Bulletin 94 (2), 222–235.*

Dons, J.A., 1959. Fossils(?) of Precambrian age from Telemark, southern Norway. *Norks Geologisk Tidsskrift 39, 249–269.*

Dons, J.A., 1960a. Telemark supracrustals and associated rocks. In: Holtedahl, O. (ed.) Geology of Norway. *Norges Geologiske Undersøkelse Bulletin 208, 49–58.*

Dons, J.A., 1960b. The stratigraphy of supracrustal rocks, granitization and tectonics in the Precambrian Telemark area, Southern Norway. *Norges Geologiske Undersøkelse Bulletin 212, 1–30.*

Dons, J.A., 1962. The Precambrian Telemark area in south central Norway. *Geologische Rundschau 62, 261–268.*

Dons, J.A., 1963. Precambrian rocks of Central Telemark, Norway: Ripple marks and mud cracks. *Norsk Geologisk Tiddskrift 43, 477–495.*

de Haas, G.J.L.M., Andersen, T., Vestlin, J., 1999. Detrital zircon geochronology: new evidence for and old model for accretion of the SW Baltic Shield. *Journal of Geology 107, 569–586.*

Ebbing, J., Afework, Y., Olesen, O., Nordgulen, Ø., 2005. Is there evidence for magmatic underplating beneath the Oslo Rift? Terra Nova 17, 129–134.

Einsele, G., 2000. Sedimentary basin: Evolution, facies, and sediment budget. *Springer.*

Els, B.G., 1998. The auriferous Late Archaean sedimentation systems of South Africa: unique palaeoenvironmental conditions? *Sedimentary Geology 120, 205–224.*

Eriksson, P.G., Cheney, E.S., 1992. Evidence for the transition to an oxygen-rich atmosphere during the evolution of red beds in the Lower Proterozoic sequences of southern Africa. *Precambrian Research 54, 257–269.*

Eriksson, K.A., Simpson, E.L., 2000. Quantifying the oldest tidal record: the 3.2 Ga Moodies Group, Barberton greenstone Belt, South Africa. *Geology 28, 831–834.*

Eriksson, P.G., Condie, K.C., Tirsgaad, H., Mueller, W.U., Altermann, W., Miall, A.D., Aspler, L.B., Catuneanu, O., Chiarenzelli, J.R., 1998. Precambrian clastic sedimentation systems. *Sedimentary Geology 120, 5–53.*

Eriksson, P.G., Martins-Neto, M.A., Nelson, D.R., Aspler, L.B., Chiarenzelli, J.R., Catuneanu, O., Sarkar, S., Altermann, W., Rautenbach, C.J.de.W., 2001. An introduction to Precambrian basins: their characteristics and genesis. *Sedimentary Geology 141/142, 1–35.*

Eriksson, P.G., Catuneanu, O., Nelson, D.R., Mueller, W.U., Altermann, W., 2004. Towards a synthesis. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) *The Precambrian Earth: Tempos and Events. Elsevier – Developments in Precambrian Geology 12, 739–762.*

Eriksson, P.G., Catuneanu, O., Sarkar, S., Tirsgaad, H., 2005. Patterns of sedimentation in the Precambrian. *Sedimentary Geology 176, 17–42.*

Eriksson, P.G., Bumby, A.J., Brümer, J.J., Van der Neut, M., 2006. Precambrian fluvial deposits: enigmatic palaeohydrological data from the c. 2–1.9 Ga Waterberg Group, South Africa. *Sedimentary Geology, 190, 25–46.*

Eriksson, P.G., Banerjee, S., Catuneanu, O., Sarkar, S., Bumby, A.J., Mtimkulu, M.N., 2007. Prime controls on Archean-Paleoproterozoic sedimentation: Change over time. *Gondwana Research 12, 550–559.*

Eriksson, P.G., Long, D., Bumby, A., Eriksson, K., Simpson, E., Catuneanu, O. 2008. Palaeohydrological data from the ca. 2.0 to 1.8 Ga Water Group, South Africa: discussion of possibly unique Paleoproterozoic fluvial style. *South African Journal of Geology 111, 281–304.*

Eriksson, P.G., Rautenbach, C.J. de W., Wright, D.T., Bumby, A.J., Catuneanu, O., Moster, P., van der Neut. M., 2009. Possible evidence for episodic epeiric marine and fluvial sedimentation (and implications for palaeoclimatic conditions), c. 2.3–1.8 Ga, Kaapvaal craton, South Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology 273, 153–173.*

Frimmel, H.E., 2004. Formation of a Late Mesoproterozoic Supercontinent: The South Africa – East Antarctica Connection. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) The Precambrian Earth: Tempos and Events. *Elsevier – Developments in Precambrian Geology 12, 240–255.*¨

Frostick, L.E., Steel, R.J., 1993. Sedimentation in divergent plate-margin basins. *IAS Special Publication 20, 111–128.*

Frostick, L.E., Renaut, R.W., Reid, I., Tiercelin, J.J., 1986. Sedimentation in the African rifts. *Geological Society of London – Special Publication 25.*

Gaál, G., Gorbatschev, R., 1987. An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Research 35, 15–52.*

Gorbatschev, R., Bogdanova, S., 1993. Frontiers in the Baltic shield. *Precambrian Research 64, 3–21.*

Gorbatschev, R., 2004. The Transscandinavian Igneous Belt – Introduction and background. In: Höghdahl, K., Andersson, U.B., Eklund, O. (eds) The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geological Survey of Finland, Special Paper 37, 9–13.*

Grotzinger, J.P., James, N.P., 2000. Precambrian carbonates: evolution of understanding. In: Grotzinger, J.P., James, N.P. (eds.) Carbonate Sedimentation and Diagenesis in the Evolving Precambrian World. SEPM Special Publication 67, 3–20.

Grauch, R.I., 1989. Rare earth elements in metamorphic rocks. In: Lipin, B.R., McKay, G.A. (eds.) Geochemistry and mineralogy of rare earth elements. *Mineralogical Society of America – Reviews in Mineralogy 21, 147–167.*

Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., van Achterbergh, E., O'Reilly, S.Y., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta 64, 133–147.*

Hathaway, B., 1993. The Nadai Basin: Neogene strike-slip faulting and sedimentaion in a fragmented arc. Western Vitu Levu, Fiji. *Journal of Geological Society London 150, 563–581.*

Hunt, D., Tucker, M., 1992. Stranded parasequences and the forced regressive wedge system tract: deposition during base-level fall. *Sedimentary Geology 81, 1–9.*

Högdahl, K., Andersson, U.B., Eklund, O. (eds.) 2004. The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution. *Geological Survey of Finland Special Paper 37, 125.*

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., Sares, S.W., 1984. The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method. *Journal of Sedimentary Petrology 54, 103–106.*

Ingersoll, R.V., Busby, C.J., 1995. Tectonics of sedimentary basins. In: Busby, C.J., Ingersoll, R.V. (eds.) Tectonics of sedimentary basins. *Blackwell Science.*

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology. *Chemical Geology 211, 47–69.*

Joo, Y.J., Lee, Y.I., Bai, Z., 2005. Provenance of the Qingshuijian Formation (Late Carboniferous), NE China: implications for tectonic processes in the northern margin of the North China Block. *Sedimentary Geology 177/1–2, 97–114.*

Köykkä, J., 2006. Mesoproterotsooisen Svinsagan muodostuman sedimentologia, Telemark, Etelä-Norja. MSc thesis. *University of Oulu, Department of Geosciences.*

Köykkä, J, Laajoki, K., 2006a. Fracture and talus breccia zone at the base of the Svinsaga Formation, central Telemark, south Norway: indicators of Mesoproterozoic frost weathering action. In: Peltonen, P., Pasanen, A. (eds.) *Bulletin of the Geological Society of Finland, Special Issue 1, 81.*

Köykkä, J., Laajoki, K., 2006b. The Mesoproterozoic Svinsaga Formation, central Telemark, south Norway; sedimentological researches and paleocurrent analysis indicate periglaciofluvial braided river depositional environment affected by talus breccia input. In: Peltonen, P., Pasanen, A. (eds.) *Bulletin of the Geological Society of Finland, Special Issue 1, 82.*

Laajoki, K., 1998. Stratigraphic and tectonic significance of the Vallar Bru and Eidet conglomerates of the middle Proterozoic Seljord Group, southern Telemark, Norway. *Nordic Geological Winter Meeting 23, 167.*

Laajoki, K., 2000. Primary and tectonic relationships between the Middle Proterozoic Svinsaga formation (Bandak group) and the Seljord group, southern Telemark, Norway. *Geonytt 1, 114.*

Laajoki, K., 2002. The Mesoproterozoic sub–Heddal unconformity, Sauland, Telemark, south Norway. *Norsk Geologisk Tiddskrift 82, 139–152.*

Laajoki, K., 2003. Basal parts of the middle Proterozoic Svinsaga formation on the Svafjell, Meien, and Sjånuten mountains, Telemark, South Norway. *NGF Abstracts and Proceedings 1, 51.*

Laajoki, K., 2005. The Mesoproterozoic sub–Heddersvatnet unconformity, Telemark, South Norway. *Bulleting of the Geological Society of Finland 77, 49–63.*

Laajoki, K., 2006a. Lithostratigraphy of the Mesoproterozoic Oftefjell group, central Telemark, Norway. *Res Terrae A24. Publications of the Department of Geosciences, University of Oulu.*

Laajoki, K., 2006b. The Mesoproterozoic sub–Lifjell unconformity, central Telemark, Norway. *Bulletin of the Geological Society of Finland 78, 41–70.*

Laajoki, K., 2006c. The Mesoproterozoic sub-Røynstaul unconformity, central Telemark, Norway. *Norsk Geologisk Tiddskrift 86, 29–40.*

Laajoki, K., 2009. The Mesoproterozoic sub–Svinsaga unconformity, central Telemark, Norway. Res Terrae A26. *Publications of the Department of Geosciences, University of Oulu.*

Laajoki, K., Corfu, F., Andersen, T., 2002. Lithostratigraphy and U–PB geochronology of the Telemark supracrustals in the Bandak-Sauland area, Telemark, South Norway. *Norwegian Journal of Geology 82, 119–138.*

Laajoki, K., Lamminen, J., 2004. Role of the Mesoproterozoic Telemark supracrustals in the assembly of Rodinia. *32nd IGC Florence Scientific Sessions 1/2, 872.*

Laajoki, K., Corfu, F., 2007. Lithostratigraphy of the Mesoproterozoic Vemork formation, central Telemark, Norway. *Bulletin of the Geological Society of Finland 79, 41–67.*

Lahtinen, R., Korja, A-K., Nironen, M., 2005. Paleoproterozoic tectonic evolution. In: Lehtinen, M., Nurmi, P.A., Rämö, O.T. (eds.) Precambrian Geology of Finland – Key to Evolution of the Fennoscandian Shield. *Elsevevier, Amasterdamn, 481–532.*

Lambert, M.B., Beaumont-Smith, C., Paul, D., 1992. Structure and stratigraphic successions of an Archean stratovolcano, Slave Province, Northwest Territories. *Geological Survey of Canada 92–1C, 189–200.*

Lamminen, J., 2004. Facies analysis of the Mesoproterozoic Røynstaul Formation, Haugset, Telemark, south Norway. *Congres Geologique International, Resumes 32, 1290.*

Lamminen, J., 2005. Mesoproterotsooinen Haugsetin alluviaalinen viuhka ja hiekkainen palmikoiva joki, Telemark, Etelä-Norja. *MSc thesis. University of Oulu, Department of Geosciences*

Lamminen, J., 2006. The Mesoproterozoic Brattefjell Formation, Telemark, South Norway: a tidally influenced shoreline. In: Peltonen, P., Pasanen, A. (eds.) *Bulletin of the Geological Society of Finland, Special Issue 1, 87.*

Lamminen, J., Andersen, T., Nystuen, J.P., 2009a. Rapid crustal movements during the Sveconorwegian orogeny: U-Pb zircon evidence for strike–slip basin tectonic setting in southeast Telemark, South Norway. *NGF Vinterkonferansen, Bergen, Abstracts and Proceedings of the Geological Society of Norway, 60.*

Lamminen, J., Köykkä. J., Andersen, T., Nystuen, J.P. 2009b. From extension to transtension: the Telemark supracrustals, ca. 400 Ma sedimentary record of variable tectonics before and during the Sveconorwegian (Grenvillian) Orogeny. *AGU Joint Assembly, Toronto, 13A–04.*

Lecuyer, C., Gruau, G., Fruech-Green, G.L., Picard, C., 1996. Hydrogen isotope composition of early Proterozoic seawater. *Geology 24/4, 291–294.*

Long, D.F.G., 2004. Precambrian rivers. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) *The Precambrian Earth: Tempos and Events. Elsevier – Developments in Precambrian Geology 12, 660–663.*

Loup, B., 1993. Sea-level changes and extensional tectonic in the Lower Jurassic (northern Helvetic realm, Switzerland). *IAS Special Publication 20, 129–159.*

Ludwig, K.R., 2003. Isoplot 3.00. *Berkeley Geochronology Center Special Publication 4.*

McLennan, S.M., Hemming, S., McDaniel, D.K., Hanson, G.N., 1993. Geochemical approaches to sedimentation, provenance, and tectonics. In: Johnsson, M.J., Basu, A. (eds.) Processes controlling the composition of clastic sediments. *Geological Society of America – Special Paper 284, 21-40.*

McLennan, S.M., 1989. Rare earth elements in sedimentary rocks: Influence of provenance and sedimentary process. In: Lipin, B.R., McKay, G.A. (eds.) Geochemistry and Mineralogy of Rare Earth Elements. *Mineralogical Society of America – Reviews in Mineralogy, 169–200.*

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Miall, A.D. (ed.) Fluvial Sedimentology. *Canada Society of Petroleum Geology Memoir 5, 597–604.*

Miall, A.D, 2000. Principles of sedimentary basin analysis. *Springer-Verlag Berlin Heidelberg.*

Milodowski, A.E., Zalasiewicz, J.A., 1991. Redistribution of rare earth elements during diagenesis of turbidite/hemipelagite mudrock sequences of Landovery age from central Wales. *Geological Society of Special Publications 57, 101–124.*

Menuge, J.F., Brewer, T.S., 1996. Mesoproterozoic anorogenic magmatism in southern Norway. In: Brewer, T.S. (ed.) Precambrian crustal evolution in the North Atlantic regions. *Geological Society Special Publications 112, 275–295.*

Mueller, W.U., Corcoran, P.L., 1998. Late-orogenic basins in the Archean Superior Province, Canada: characteristics and interferences. *Sedimentary Geology 120, 177–203.*

Mueller, W.U., Corcoran, P.L., 2001. Volcano–sedimentary processes operating on a marginal continental arc: the Archean Raquette Lake Formation, Slave Province, Canada. *Sedimentary Geology 141/142, 169–204.*

Myers, J.S., 2001a. Protoliths of the 3.8–3.7 Ga Isua greenstone belt, west Greenland. *Precambrian Research 105, 129–141.*

Myers, J.S., 2001b. Earth's oldest known volcanic and sedimentary rocks: origin and tectonic evolution of the > 3.8–3.7 Ga Isua Greenstone belt, southwest Greenland. In: Cassidy, K.F., Dunphy, J.M., van Kranendonk, M.J. (eds.) *Extended Abstract Volume – 4th International Archean Symposium.*

Nelson, D.R., 2004. Earth's Formation and First Billion Years. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) The Precambrian Earth: Tempos and Events. *Elsevier – Developments in Precambrian Geology 12, 3–27.*

Nesbitt. H.W., 1979. Mobility and fractionation of rare earth elements during weathering of a granodiorite. *Nature 279/5710, 206–210.*

Nijman, W., de Vries, S.T., 2004. Early Archean Crustal Collapsed Structures and Sedimentary Basin Dynamics. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Muellerler, W.U., Catuneanu, O., (eds.) The Precambrian Earth: Tempos and Events. *Elsevier – Developments in Precambrian Geology 12, 139–155.*

Nilsen, T.H., McLaughlin, R.J., 1985. Comparision of tectonic framework and depositional patterns of the Nornelen strike-slip basin of Norway and the Ridge and Little Sulphur Creek strike-slip basins of California. In: Biddle, K.T., Christie-Blick, N. (eds) Strike-slip deformation, basin formation, and sedimentation. *SEPM Special Publication 37, 79–103.*

Nordgulen, Ø., 1999. Geologisk kart over Norge, Berggrunnskart HAMAR, M 1:250,000. *Norges geologiske undersøkelse.*

Nutman, A.P., Friend, C.L., Bennet, V.C., 2002. Evidence for 3650–3600 Ma assembly of the northern end of the Itsaq Gneiss Complex, Greendland: implication for early Archean tectonics. *Tectonics 21, 1005.*

Osae, S., Asiedu, D.K., Banoeng-Yakubo, B., Koeberl, C., Dampare, S.B., 2006. Provenance and tectonic setting of late Proterozoic Buem sandstones of southeastern Ghana; evidence from geochemistry and detrital modes. *Journal of African Earth Sciences 44/1, 85-96.*

Padget, P., Brekke, H., 1996. Geologisk kart over Norge, berggrunnskart Arendal, 1:250,000. *Norges Geologisk Undersøkelse, Trondheim.*

Patchett, J., Kouvo, O., 1986. Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes and U-Pb zircon ages in the Svecokarelian terrain of South Finland. *Contributions to Mineralogy and Petrology 92, 1–12.*

Pease, V., Daly, J.S., Elming, S-A., Kumpulainen, R., Moczydlowska, M., Puckov, V., Roberts, D., Saintot, A., Stephenson, R., 2008. Baltica in the Cryogenian, 850–630 Ma. *Precambrian Research. 160, 46–65.*

Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988. Eustatic controls on clastic deposition. I. Conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, CG.St.C, Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (eds.) Sea Level Changes-An Integrated Approach. *SEPM Special Publication 42, 110–124.*

Scherer, E., Münker, C., Mezger, K., 2001. Calibration of the Lutetium-Hafnium clock. *Science 293, 683–687.*

Sengör, A.M.C., Burke, K., 1978. Relative timing of rifting and volcanism oon Earth and its tectonic implications. *Geophysical Research Letters 5, 419–421.*

Sengör, A.M.C., Görur, N., Saroglu, F., 1985. Srike-slip faulting and related basin formation in zones of tectonic escapes: Turkey as a case study. : In Biddle, K.T., Christies-Blick, N. (eds.) Strike-slip deformation, basin formation, and sedimentation. *SEPM Special Publication 37, 227–264.*

Singh, U.B., 1969. Precambrian rocks of the Telemark area in South Central Norway: Primary sedimentary structures in Precambrian quartzites of Telemark, southern Norway, and their environmental significance. *Norsk Geologisk Tiddskrift 49, 1–31.*

Sigmond, E.M.O., 1985. The Mandal-Ustaoset line, a new discovered major fault zone in south Norway. In: Tobi, A.C., Touret, J.L.R. (eds.) The Deep Proterozoic Crust in the North Atlantic Provinces. *NATO Advanced Study Institute Series C 158, 323–330.*

Sigmond, E.M.O., Gjelle, S., Solli, A., 1997. The Rjukan Proterozoic rift basin, its basement and cover, volcanic and sedimentary infill, and associated intrusions. *Norges Geologiske Undersøkelse Bulletin 433, 6–7.*

Starmer, I.C., 1993. The Sveconorwegian Orogeny in Southern Norway, relative to deep crustal structures and events in the North Atlantic Proterozoic supercontinent. *Norsk Geologisk Tidsskrift 73, 109–132.*

Starmer, I.C., 1996. Accretion, rifting, rotation and collision in the North Atlantic supercontinent, 1700–950 Ma. In: Brewer, T.S. (ed.) Precambrian Crustal Evolution in the North Atlantic Region. *Geological Society of London Special Publications 112, 219–248.*

Stephens, M.B., Wahlgren, C.H., Weijermars, R., Cruden, A.R., 1996. Left lateral Transpressive Deformation and its Tectonic Implications, Sveconorwegian Orogen, Baltic Shield, Southwestern Sweden. *Precambrian Research 79, 261–279.*

Soegaard, K., Eriksson, K.A., 1985. Evidence of tide, storm, and wave interaction on a Precambrian shelf: the 1.7 Ga Ortega Group, New Mexico. *Journal of Sedimentary Petrology 55, 672–684.*

Söderlund, U., Möller, C., Andersson, J., Johansson, L., Whitehouse, M., 2002. Zircon geochronology in polymetamorphic gneisses in the Sveconorwegian Orogen, SW Sweden: ion microprobe evidence for 1.46–1.42 and 0.98–0.96 Ga reworking. *Precambrian Research 113, 193–225.*

Söderlund, U., Patchett, P.J., Vervoort, J.D., Isachsen, C.E., 2004. The ^{176}Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters 219, 311–324.*

Tirsgaard, H., Øxnevad, I.E.I., 1998. Preservation of pre-vegetational fluvio-aeolian deposits in a humid climatic setting: an example from the Middle Proterozoic Eriksfjord Formation, southwest Greenland. *Sedimentary Geology 120, 295–317.*

Torske, T., 1985. Terrane displacement and Sveconorvegian rotation of the Baltic Shield: a working hypothesis. In: Tobi, A.C., Touret, J.L.R. (eds.) The Deep Pro- terozoic Crust in the North Atlantic Provinces. *NATO Advanced Study Institute Series, Series C 158, 333–343.*

Walker, R.G., 1992. Facies, facies models and modern stratigraphic concepts. In: Walker, R.G., James, N.P. (eds.) Facies models – Response to sea level changes. *Geological Association of Canada.*

Werenskiold, W., 1910. Om Øst-Telemarken. *Norges Geologiske Undersøkelse Bulletin 53, 5–70.*

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., von Quadt, A., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards Newsletter 19, 1–23.*

Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M., 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature 409, 175–178.*

Williams, G.E., 1989. Tidal rhytmites: geochronometers for the ancient Earth–Moon system. *Episodes 12, 162–172.*

Williams, G.E., 1990. Tidal rhytmites: key to the history of the Earth's rotation and lunar orbit. *Journal of Physics of the Earth 38, 475–491.*

Williams, I.R., 1999. Geology of the Muccan 1:100000 Sheet. Western Australian. *Geological Survey – 1:100000 Geological Series Explanatory Notes.*

Windley, B.F., 1995. The Evolving Continents. *John Wiley and Sons, Chichester.*

Woodhead, J.D., Hergt, J.M., 2005. A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. *Geostandards and Geo–analytical Research 29 (2), 183–195.*

Wyckoff, D., 1934. Geology of the Mt. Gausta Region in Telemark, Norway. *Norsk Geologisk Tiddskrift 13, 1–72.*

Young, G.M., 2004. Earth's Two Great Precambrian Glaciations: Aftermath of the "Snowball Earth" Hypothesis. In: Eriksson, P.G., Altermann, W., Nelson, D.R., Mueller, W.U., Catuneanu, O. (eds.) The Precambrian Earth: Tempos and Events. *Elsevier – Developments in Precambrian Geology 12, 440–448.*

Original papers

I Köykkä, J., 2010. Lithostratigraphy of the Mesoproterozoic Telemark supracrustal rocks, South Norway: revision of the sub-Heddersvatnet unconformity and geochemistry of basalts in the Heddersvatnet Formation. *Norwegian Journal of Geology 90, 49–64.*

II Köykkä, J., 2011. Precambrian alluvial fan and braidplain sedimentation patterns: example from the Mesoproterozoic Rjukan Rift Basin, southern Norway. *Sedimentary Geology 234, 89–108.*

III Köykkä, J., Lamminen, J., 2011. Tidally influenced clastic epeiric sea at a Mesoproterozoic continental margin, Rjukan Rift Basin, southern Norway. *Precambrian Research 185, 164–182.*

IV Lamminen, J., Köykkä, J., 2010. The provenance and evolution of the Rjukan Rift Basin, Telemark, south Norway: the shift from a rift basin to an epicontinental sea along a Mesoproterozoic supercontinent. *Precambrian Research 181, 129–149.*

V Köykkä, J., Laajoki, K., 2009. Mesoproterozoic frost action at the base of the Svinsaga Formation, central Telemark, South Norway. *Norwegian Journal of Geology 89, 291–303.*

VI Köykkä, J., in press. The sedimentation and paleohydrology of the Mesoproterozoic stream deposits in a strike-slip basin (Svinsaga Formation), Telemark, southern Norway. *Sedimentary Geology, doi:10.1016/j.sedgeo.2011.01.010.*