Chapter 1

Introduction to the lithotectonic framework of Sweden and organization of this Memoir

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Abstract: The solid rock geology of Sweden comprises three principal components: (1) Proterozoic and (locally) Archean rocks belonging to the western part of the Fennoscandian Shield; (2) Phanerozoic and (locally) Neoproterozoic sedimentary cover rocks deposited on top of this ancient crust; and (3) the early to mid-Paleozoic (0.5–0.4 Ga) Caledonide orogen. Earlier compilations have applied different principles for the subdivision of the geology in the Fennoscandian Shield and the Caledonide orogen. A uniform lithotectonic framework has been developed here. Crustal segments affected by orogenesis have been identified and their ages determined by the youngest tectonothermal event. Four ancient mountain belts and six orogenies are preserved. Solid rocks outside the orogens have been assigned to different magmatic complexes or sedimentary successions based on their time of formation and tectonic affiliation. This approach allows relicts of older mountain-building activity to be preserved inside a younger orogen – for example, the effects of the Archean (2.8–2.6 Ga) orogeny inside the 2.0–1.8 Ga Svecokarelian orogen and Paleo–Mesoproterozoic (1.7–1.5 and 1.5–1.4 Ga) mountain-building processes inside the 1.1–0.9 Ga Sveconorwegian orogen. Sweden’s five largest mineral districts are addressed in the context of this new lithotectonic framework, which forms the architecture to the contents of the chapters in this Memoir.

Supplementary material: Whole-rock geochemical data from Proterozoic and Neoarchean magmatic rocks in the Fennoscandian Shield, Sweden used to generate the diagrams that illustrate the composition and tectonic affinity of different magmatic suites in different lithotectonic units throughout the Memoir are available at https://www.geolsoc.org.uk/Publications/Books/Memos/Memoir50data

Principles for the subdivision of the geology using a tectonic perspective

The primary focus of interest in earlier compilations of the Fennoscandian Shield has been on the timing of the crystallization or deposition of rocks and crustal growth. Archean (3.2–2.6 Ga and possibly older) and early Paleoproterozoic (2.5–2.0 Ga) rocks, included in the so-called Karelian Province, and an ‘orogenic sequence’ of supracrustal and intrusive rocks with an age of formation of 2.0–1.8 Ga, referred to as the Svecofennian Domain, have traditionally been separated from each other (e.g. Gaál & Gorbatschev 1987; Gorbatschev & Bogdanova 1993; Nironen 1997; Lahtinen et al. 2009). Magmatic rocks with a similar composition that formed at c. 1.8 and 1.7 Ga, referred to as the Transscandinavian Igneous Belt (see, for example, Gaál & Gorbatschev 1987; Patchett et al. 1987; Larson & Berglund 1992; Gorbatschev & Bogdanova 1993; Gorbatschev 2004) have been included in a third crustal segment.

Common use of the term ‘Svecofennian’ in both a lithodemic and tectonic context (the Svecofennian Domain and Svecofennian orogeny, respectively, in, for example, Gaál & Gorbatschev 1987) creates some confusion. For example, identification of the reworking and incorporation of older Archean and early Paleoproterozoic rocks inside the 2.0–1.8 Ga orogen lacks focus or is simply ignored. In addition, use of the lithodemic term ‘Transscandinavian Igneous Belt’ in a tectonic context obscures the significant change that took place during the long time period of nearly 200 million years when this magmatic supersuite formed. Cratonization of the solid rock that is close to, or exposed at, the ground
surface in the eastern part of Sweden occurred at 1.8–1.7 Ga and is marked by a transition from conspicuous ductile strain and metamorphism to predominantly brittle deformation with little or no metamorphic overprint (Viola et al. 2009; Saintot et al. 2011). As addressed later in this Memoir, the 1.8 Ga and older rocks in the ‘Transscandinavian Igneous Belt’ developed during a late stage of the 2.0–1.8 Ga orogeny, while the 1.7 Ga suite formed afterwards.

The principles used in this approach are in marked contrast with those traditionally applied in the 0.5–0.4 Ga Caledonide orogen (Kulling 1972; Gee & Sturt 1985; Gee et al. 1985). The primary focus in compilations of this younger orogenic belt has been on the timing of its latest, regionally significant tectonothermal evolution and on the internal tectonostratigraphic framework established at that time. Use of a terminology in the Caledonide orogen that emphasizes the latest mountain-building activity, rather than the timing of formation of the rocks affected by it, is the key difference. The principles adopted in the Caledonide orogen allow the reworking and incorporation of components that are pre-orogenic with respect to the Caledonian tectonic evolution, yet bear relicts, for example, of an earlier, pre-Caledonian mountain-building phase.

The geological architecture established in this Memoir reflects first and foremost the sequence of major tectonic events that has affected the solid rock in Sweden, building on that used by Bergman et al. (2012). The principles used to construct the architecture in the Caledonide orogen are also applied to the Fennoscandian Shield. A subdivision into separate lithotectonic units (Neuendorf et al. 2005) is adopted. The approach used to construct the lithotectonic framework has been to identify the crustal segments affected by mountain-building activity and the time when the solid rock in each segment ceased to be affected by orogenesis, thereby attaining a cratonic status. Subsequently, the remainder of the solid rock in Sweden, outside these orogens and not affected by mountain-building activity, has been subdivided into different magmatic complexes or sedimentary successions based on the timing of their emplacement or deposition and their tectonic affiliation.

Orogens and solid rocks situated outside them

The adoption of these working procedures has resulted in a spatial breakdown of the bulk of the solid rock in Sweden into four orogens (Figs 1.1 & 1.2). The volumetrically most important ancient mountain belt in the eastern part of Sweden (57% of the land area beneath Quaternary drift), referred to as the Svecofennian orogen (see discussion of terminology in the following paragraph), as well as the Blekinge–Bornholm (1%) and Sveconorwegian (16%) orogens in the southeasternmost and southwestern parts of the country, respectively, form part of the Fennoscandian Shield; the fourth component (17%), in the northwestern part of Sweden, consists of the Caledonide orogen. The latest orogeny in these four major
Deformation zone, type and sense of movement not specified

Terranes from outboard of the continent Baltica, mainly oceanic volcano-sedimentary successions

Shortened margin to continent Baltica

Cover on crystalline basement

Tonian–Paleogene sedimentary and Permo–Carboniferous magmatic rocks

FENNOSCANDIAN SHIELD

Sveconorwegian orogen

Syn-orogenic intrusive rock (1.0–0.9 Ga)

Pre-orogenic, metamorphosed intrusive and supracrustal rocks (1.7–1.1 Ga)

Pre-orogenic, metamorphosed intrusive and supracrustal rocks (1.9–1.2 Ga)

Blekinge–Bornholm orogen

Syn-orogenic intrusive rock (1.47–1.43 Ga)

Pre-orogenic, metamorphosed intrusive and supracrustal rocks (1.8 Ga)

Post-Svecokarelian rocks in the foreland to the Blekinge–Bornholm and Sveconorwegian orogens

Dolerite, subordinate clastic sedimentary rock (0.98–0.95 Ga)

Dolerite (1.27–1.25 Ga)

Clastic sedimentary rock and basalt (Mesoproterozoic prior to 1.3 Ga)

Granite, quartz syenite, nepheline syenite, gabbro, anorthosite, dolerite (1.8–1.4 Ga)

Granite, quartz syenite, monzodiorite and supracrustal rock (1.7 Ga)

Svecofennian orogen

Syn-orogenic rock

Intrusive and subordinate supracrustal (mainly volcanic) rocks (c. 1.83–1.75 Ga)

Varibly metamorphosed, intrusive and subordinate volcanic rocks (c. 1.88–1.83 Ga)

Metamorphosed volcanic and intrusive rocks (c. 1.91–1.87 Ga), subordinate limestone and quartzite in south-central Sweden

Metamorphosed intrusive and volcanic rocks (c. 1.96–1.93 Ga)

Metamorphosed siliciclastic sedimentary and subordinate volcanic rocks (c. 1.96 Ga or older to 1.82 Ga)

Pre-orogenic rock

Metamorphosed Archean (2.8–2.6 Ga and possibly older) and early Paleoproterozoic (2.5–2.0 Ga) plutonic and supracrustal rocks

Fig. 1.2. Simplified bedrock geological map of Sweden generated using the 1:1 million national bedrock database at the Geological Survey of Sweden (Bergman et al. 2012).
lithotectonic units, including ductile deformation, metamorphism and syn-orogenic sedimentation and magmatic activity, took place at 2.0–1.8, 1.5–1.4, 1.1–0.9 and 0.5–0.4 Ga, respectively (Figs 1.3 & 1.4). Moderately to steeply dipping structures constitute a significant component in the Proterozoic orogens, whereas flat-lying allochthons emplaced during east-vergent thrusting dominate the Caledonide orogen (Fig. 1.4).

The mountain-building processes during the time frame 2.0–1.8 Ga affected, to variable extents, all three crustal segments inside the 1.8 Ga and older part of the Fennoscandian Shield identified by, for example, Gaál & Gorbatschev (1987). Pre-orogenic (Karelian Province) and syn-orogenic (Svecofennian Domain and the 1.8 Ga part of the Transscandinavian Igneous Belt) components with respect to the 2.0–1.8 Ga mountain-building phase can be identified (Fig. 1.2). For these reasons, use of the more embracing term ‘Svecokarelian’ rather than ‘Svecofennian’ for the oldest orogeny, as used by Sveriges geologiska undersökning (the Geological Survey of Sweden), is adopted in this Memoir.

Relicts of older phases of tectonothermal activity are preserved inside each of the four orogens identified here, accounting for the influence of six orogenies in the tectonic evolution of Sweden (Fig. 1.3). Relicts of an Archean (2.8–2.6 Ga) orogeny (Lopian) are preserved in the northernmost part of the Svecokarelian orogen in Sweden; relicts of the Svecokarelian mountain-building phase (2.0–1.8 Ga) are present in the Blekinge–Bornholm, Sveconorwegian (eastern part) and Caledonide orogens; and Proterozoic orogenies at 1.7–1.5 Ga (Gothian) and 1.5–1.4 Ga (Hallandian) are overprinted by the Sveconorwegian tectonothermal evolution in the western and eastern parts of the Sveconorwegian orogen, respectively (Fig. 1.3). Pre- and syn-orogenic components are distinguished inside each of the three Proterozoic orogenic belts (Fig. 1.2). A division according to the inferred provenance of the allochthons, from the shortened margin of the continent Baltica or from terranes derived from outside of this margin, has been adopted for the Caledonide orogen (Fig. 1.2).

Fig. 1.3. Synthesis of the tectonic evolution in different crustal segments in Sweden, emphasizing the timing of terminal orogeny and the development of a cratonic setting. (a, b, c) Fennoscandian Shield in eastern, southeastern and southwestern Sweden with the terminal orogeny at 2.0–1.8, 1.5–1.4 and 1.1–0.9 Ga, respectively. (d) Caledonide orogen in northwestern Sweden with the terminal orogeny at 0.5–0.4 Ga.
The remaining part of the solid rock in Sweden, not affected by orogenic activity and placed or deposited on previously cratonized crustal segments (Fig. 1.3), has been assigned to different magmatic complexes or sedimentary successions (9% of the land area beneath Quaternary drift: Figs 1.1 & 1.2). Proterozoic (1.7–0.9 Ga) components belonging to the Fennoscandian Shield, emplaced into or deposited on top of the solid rock in the Svecokarelian orogen (Figs 1.3 & 1.4), are exposed in the foreland to the Blekinge–Bornholm, Sveconorwegian and Caledonide orogens. Tonnian–Paleogene, mainly sedimentary, successions (Fig. 1.3) lie unconformably on top of (Fig. 1.4), or are down-faulted against, the older Proterozoic solid rock.

The excellent coverage of the country by airborne magnetic field and ground gravity measurements (see Appendix A1) provides strong support for this lithotectonic framework. For example, a contrast in the trends of anomalies on both the magnetic (Fig. 1.5a) and Bouguer gravity (Fig. 1.5b) maps highlights the boundary between the Svecokarelian and Sveconorwegian orogens, exposed in southeastern and southwestern Sweden, respectively (cf. Fig. 1.2). Furthermore, the spatial distribution of the post-Svecokarelian, 1.7 Ga magmatic complex south of Östersund, in the central part of Sweden (Fig. 1.2), corresponds to positive anomalies on the magnetic map (Fig. 1.5a) and negative anomalies on the gravity map (Fig. 1.5b). These anomalies can be traced several hundred kilometres northwards beneath the Caledonide orogen, emphasizing the regional importance of this magmatic complex. Inspection of these maps also reveals marked contrasts in the anomaly patterns inside both the Svecokarelian and Sveconorwegian orogens in the Fennoscandian Shield (cf. Figs 1.2 & 1.5). These contrasts are addressed when a more detailed internal division of the orogens into subordinate lithotectonic units is presented in the relevant chapters later in this Memoir.

Mineral districts in the context of the lithotectonic framework

Mining and mineral processing have been part of industrial development in Sweden for many hundreds of years. Five major mineral districts are present (Fig. 1.6). All the mines currently in operation and four of the major mineral districts occur in the 2.0–1.8 Ga Svecokarelian orogen; the fifth district lies inside the Caledonide orogen (Fig. 1.6). A compilation of the mineral deposits and metallogeny in Fennoscandia was presented by Eljä (2012).

Three mines are currently in operation in central Sweden (Bergslagen mineral district; Fig. 1.6). Carbonate- or skarn-hosted replacement-style Zn–Pb–Au–Ag sulphide deposits (Garpenberg), stratiform Zn–Pb–Ag–Cu sulphides (Zinkgruvan and Lovisagruvan), skarn- or carbonate-hosted Fe oxide and Kiruna-type apatite–Fe oxide deposits, all hosted or spatially associated with 1.9 Ga syn-orogenic volcanic rocks, form the important deposit types in this district (Fig. 1.6). Production of ore at Garpenberg was documented in the Middle Ages and this is the oldest mining area in Sweden still in operation.

Cu–Zn–Fe–Ag–Au volcanogenic massive sulphide and orogenic Au deposits are clustered in two separate mineral districts (Skellefte and Gold line) further north in the Svecokarelian orogen (Fig. 1.6). The volcanogenic massive sulphide deposits are hosted once again by syn-orogenic volcanic rocks belonging to a 1.9 Ga magmatic suite. Four mines with base metal sulphides (e.g. Kristineberg) and one with Au (Björkdal) are currently operating in the Skellefte district (Fig. 1.6). The fourth mineral district in the Svecokarelian orogen (Norrbotten) occurs in the northemmost part of the country (Fig. 1.6). Kiruna-type apatite–Fe oxide (e.g. Kirunavaara), skarn-related Fe oxide (Kaunisvaara) and epigenetic Cu–Au deposits (Aitik), again associated with magmatic
Fig. 1.5. Geophysical anomaly maps covering Sweden extracted from geophysical databases at the Geological Survey of Sweden. (a) Magnetic total field after subtraction of the geomagnetic reference field (DGRF 1965.0).
Fig. 1.5. Continued. (b) Bouguer gravity field. The white lines on each map show the boundaries between the different geological units discussed in this chapter. Maps generated by Ildikó Antal Lundin (Geological Survey of Sweden).
Fig. 1.6. Main groups of metallic mineral deposits classified according to commodity and significant mineral districts in Sweden. The relationship of these districts to the major lithotectonic units, discussed in the text, is shown using the background geological information (see Fig. 1.2 for the legend to the base geological map). Character and location of the deposits extracted from the mineral resource database at the Geological Survey of Sweden.
activity at c. 1.9 Ga, form the important types in this district; stratiform–stratatable base metal sulphide deposits are also present. Seven mines are currently in operation (Fig. 1.6).

The major mineral district inside the Caledonide orogen (Fig. 1.6) is situated close to the border with Norway in central Sweden and continues westwards into Norway (the Groner–Stekenjokk mineral district). Zn–Cu–(Ph–Au–Ag) sulphide deposits are hosted by both 0.5 Ga felsic volcanic rocks and stratigraphically overlying calcareous turbidites. These synorogenic rocks were derived from terranes formed outboard of the continent Baltica. No mining activity is currently ongoing.

Motivation for a national compilation

The solid rock geology of Sweden provides a significant complementary and, in some cases, unique insight into the tectonic evolution of northern Europe. Attention to some of these aspects of the country’s geology is provided in this section, bearing in mind a need to motivate the choice of a national compilation in this Memoir with its intrinsic limitations. Focus on such a compilation is also warranted by the significance Sweden has as a supplier of metallic raw materials.

The northernmost part of Sweden shares with Finland a continental lithosphere comprising Archean (2.8–2.5 Ga and possibly older) crust overlain by early Paleoproterozoic (2.0–1.8 Ga) orogeny (the Svecokarelian orogen, Fig. 1.1). However, compared with neighbouring countries, the geology in Sweden provides the most comprehensive insight into the evolution during the youngest part of this mountain-building phase at c. 1.8 Ga and even later at c. 1.7 Ga after its completion. The solid rock geology in southeasternmost Sweden and on the small island of Bornholm in Denmark is unique in northern Europe. Deformation, metamorphism and magmatic activity at c. 1.5–1.4 Ga (Hallandian), unaffected by younger orogeny, can be examined directly at the ground surface (the Blekinge–Bornholm orogen in Fig. 1.1).

Sweden shares with Norway evidence for the tectonic reworking of older continental crust during a 1.1–0.9 Ga orogeny in its southwestern part (the Sveconorwegian orogen, Fig. 1.1) and an early to mid-Paleozoic (0.5–0.4 Ga) mountain-building evolution in the NW (the Caledonide orogen, Fig. 1.1). However, significant or, in some cases, unique geological aspects are preserved in the Swedish part of both these orogenic belts. It is vital that these aspects are taken into account when conceptual tectonic models for the orogenic evolution of these two ancient mountain belts are proposed.

In the Sveconorwegian orogen, high-pressure metamorphism with the formation of eclogite is only preserved in the Swedish part, where the processes along the eastern frontal part of the orogen are also available for study over a strike length of >600 km. As will be emphasized in the part of this Memoir addressing the Caledonian orogeny, the Swedish segment has historically provided evidence for the major thrusting of the allochthons and the attenuation of thrust complexes westwards from the foreland. The Caledonide orogen in Sweden also provides a far better possibility of studying the earlier rifted and subsequently shortened margin to the continent Baltica than the attenuated and highly deformed allochthonous relicts of this tectonic regime in the hinterland in Norway. Evidence for ultrahigh- or high-pressure metamorphism at 0.5 Ga, in the allochthons derived from the outermost part of this continental margin, is also restricted to the Swedish part of the Caledonide orogen. This tectono-thermal phase took place prior to the terminal collision between Baltica and Laurentia and a second phase of high- or ultrahigh-pressure metamorphism at 0.4 Ga in the hinterland in Norway.

Organization of this Memoir

Figure 1.4 shows which chapter (or chapters) in this Memoir addresses a particular phase of the tectonic evolution of Sweden. Different phases are preserved in different parts of the country, a feature that is obscured in the highly schematic view in Figure 1.4. The chapters are grouped into eight parts, this structure being steered by the tectonic evolution.

1. 2.0–1.8 Ga (Svecofennian) orogeny, eastern Sweden (Part I, Chapters 2 (Stephens & Bergman 2020), 3 (Bergman & Weihed 2020), 4 (Skyttä et al. 2020), 5 (Hög dahl & Bergman 2020), 6 (Stephens & Janss on 2020), 7 (Wahlgren & Stephens 2020a) and 8 (Stephens 2020a)).

2. Far-field responses to accretionary tectonic activity at 1.7–1.4 Ga, Sweden (Part II, Chapters 9 (Ripa & Stephens 2020a) and 10 (Ripa & Stephens 2020b)).

3. 1.5–1.4 Ga (Hallandian) orogeny, southeastern Sweden (Part III, Chapter 11 (Stephens & Bergman 2020)).

4. Intracratonic rifting at 1.27–1.25 Ga, c. 1.14 Ga and 0.98–0.95 Ga, Sweden (Part IV, Chapters 12 (Ripa & Stephens 2020c) and 13 (Ripa & Stephens 2020d)).

5. 1.1–0.9 Ga (Sveconorwegian) orogeny, southwestern Sweden (Part V, Chapters 14 (Stephens et al. 2020), 15 (Stephens & Wahlgren 2020a), 16 (Bergröm et al. 2020) and 17 (Stephens & Wahlgren 2020b)).

6.onian–Cryogenian intracratonic rifting and passive margin sedimentation, Sweden (Part VI, Chapter 18, Wickström & Stephens 2020).

7. 0.5–0.4 Ga (Caledonian) orogeny, northwestern Sweden (Part VII, Chapters 19 (Gee & Stephens 2020a), 20 (Gee & Stephens 2020b), 21 (Gee et al. 2020), 22 (Stephens 2020b) and 23 (Gee 2020).


The parts addressing the volumetrically more important ancient mountain belts (Svecokarelian, Sveconorwegian and Caledonian) open with a presentation of the internal lithotectonic or, in the case of the Caledonide orogen, tectonostratigraphic framework (Chapters 2 (Stephens & Bergman 2020), 14 (Stephens et al. 2020) and 19 (Gee & Stephens 2020a), respectively). The broader regional geological context is also presented there. Each of these parts closes with an assessment of the orogenetic evolution, as inferred in the published geoscientific literature and following an evaluation of the compilation presented in this Memoir (Chapters 8 (Stephens 2020a), 17 (Stephens & Wahlgren 2020b) and 23 (Gee 2020), respectively).

As one of the principal aims of this Memoir is to place the Proterozoic geological evolution in a plate tectonic perspective (see Preface), secondary processes involving polyphase deformation and metamorphism are presented prior to the protolith character of the rocks in the chapters addressing different lithotectonic units inside the Proterozoic orogens (Chapters 3–7 (Bergman & Weihed 2020; Hög dahl & Bergman 2020; Skyttä et al. 2020; Stephens & Jansson 2020; Wahlgren & Stephens 2020a) in Part I, Chapter 11 (Wahlgren & Stephens 2020b) in Part III and Chapters 15 (Stephens & Wahlgren 2020a) and 16 (Bergröm et al. 2020) in Part V). To help the reader, a brief general overview of the geology in the particular lithotectonic unit opens each of these chapters, as well as the chapters dealing with different sets of thrust sheets in...
the Caledonide orogen (Chapters 20–22 (Gee & Stephens 2020b; Gee et al. 2020; Stephens 2020b) in Part VII).

Mineral and bedrock resources inside a lithotectonic unit are addressed in a separate section in virtually all the chapters. In this way, the resource geology is linked to the character of the host rock to the deposits and to the inferred tectonic evolution. All the chapters provide some concluding remarks bearing on the broader tectonic implications of the character of the solid rock in that particular lithotectonic unit. The review presented in this Memoir has also identified key issues for future geoscientific research, which are summarized in their own sections in most of the chapters.

Tectonic evolution and disposition of the text

Magmatism and sedimentation related to rifting succeeded the completion of orogenic activity in a particular crustal segment when the crust had attained a cratonic status (Fig. 1.3). Evidence for long periods (400–500 million years) of rift-related magmatism and sedimentation is also preserved between mountain-building phases. These include the 2.5–2.0 Ga interval during tectonic evolution in the northern part of the Svecokarelian orogen, the 1.5–1.1 Ga interval in the southwestern part of the Sveconorwegian orogen and the 0.9–0.5 Ga interval between the Sveconorwegian and Caledonian orogenies (Fig. 1.3). A broadly westwards shift of the tectonic evolution in time is also apparent (see also, for example, Gaál & Gorbatsevich 1987). There has been considerable debate concerning the type of mountain-building processes in connection with plate convergence during the Svecokarelian (2.0–1.8 Ga) and Sveconorwegian (1.1–0.9 Ga) orogenies (Figs 1.3a, c & 1.4). Discussion has focused around the relative roles of accretionary and continent–continent collisional processes, as defined in Cawood et al. (2009). Different tectonic models for these two major mountain-building phases are discussed and evaluated in the closing chapters of Part I (Chapter 8, Stephens 2020a) and Part V (Chapter 17, Stephens & Wahlgren 2020b), respectively.

Part II of this Memoir discusses whether the late Paleoproterozoic and Mesoproterozoic solid rock, emplaced or deposited after the Svecokarelian orogeny, in connection with intracratonic rifting (Figs 1.3a & 1.4), is not only coeval with, but also formed in connection with, orogenic processes in a far-field tectonic realm. The plate tectonic settings of Mesoproterozoic orogenies, preserved in southeastern (Blekinge–Bornholm orogen) and southwestern (reworked components in the Sveconorwegian orogen) Sweden (Figs 1.3b, c & 1.4), are of relevance in this context; they are addressed in Part III (Chapter 11, Wahlgren & Stephens 2020b) and Part V (Chapters 15 (Stephens & Wahlgren 2020a) and 16 (Bergström et al. 2020)), respectively. Broader tectonic implications of the possible connection between intracratonic rifting and the Mesoproterozoic orogeny, in the context of an indigenous outboard or exotic character of some lithotectonic units inside the Sveconorwegian orogen, are also discussed in Part V (Chapter 17, Stephens & Wahlgren 2020b).

An important issue addressed in Part IV (Chapter 12, Ripa & Stephens 2020c) concerns the tectonic setting of the intracratonic rifting at 1.27–1.25 Ga (Figs 1.3 & 1.4). Rifting linked to the break-up of the supercontinent Columbia and the opening of an ocean between the cratons in Fennoscandia and Greenland, prior to Sveconorwegian plate convergence, constitutes one of the possibilities discussed in this chapter.

In contrast with the Proterozoic orogenies, there is currently a broad consensus that plate convergence during early to mid-Paleozoic Caledonian mountain-building (Figs 1.3d & 1.4) was taken up by subduction-related accretionary processes at 0.5 Ga and terminal collision between the continents Baltica and Laurentia at 0.4 Ga. Evidence for earlier Cryogenian–Ediacaran extension, resulting in the separation of Baltica from Rodinia and the birth of the Iapetus Ocean, is well preserved in the Swedish part of the Caledonide orogen. Part VII provides details and a broader synthesis of the character and timing of these tectonic processes. The synthesis (Part VII, Chapter 23, Gee 2020) also addresses the main features of the Caledonide orogen in Sweden in relation to the hinterland part in Norway. This integration provides a basis for evaluating the orthogonal or oblique character of the 0.4 Ga continent–continent collision.

Far-field responses to Caledonian orogenesis as well as to the earlier rifting and drift tectonics are preserved in the Toronian–Silurian sedimentary successions east of, and structurally beneath, the thrust sheets of the Caledonide orogen (Fig. 1.4). These successions are presented in Part VI. The Memoir closes in Part VIII with focus on the Mesozoic sedimentary succession exposed in southern Sweden (Fig. 1.4) related to different tectonic events, including the progressive break-up of the supercontinent Pangaea.

Appendix A1: Sources of information in this Memoir

Published geoscientific papers are the primary source of information in the various chapters in this Memoir. As a consequence, the Memoir provides an extensive source of previously published literature concerned with the geology of Sweden. Several of the chapters addressing the geology of the Svecokarelian and Caledonide orogenies contain figures showing reflection seismic profiles along lines close to the eastern coast of Sweden – in the Bothnian Bay, Bothnian Sea and Baltic Sea (Fig. 1.1) – and along traverses across the Caledonide orogen in central Sweden (Fig. 1.1). These profiles have been constructed using data acquired by the BABEL Working Group (1990, 1993) for the Svecokarelian orogen and are based on published information in Palm et al. (1991), Juhojuntti et al. (2001), Hedin et al. (2012) and Juhlin et al. (2016) for the Caledonide orogen. The timescale adopted throughout this Memoir is the International Chronostratigraphic Chart drafted for the International Commission on Stratigraphy and published during August 2018 (Cohen et al. 2013; updated August 2018).

A second major source of information has materialized after the evaluation of cartographic interpretations and geodata from a selection of the publicly available databases at the Geological Survey of Sweden. Many of the figures and tables in this Memoir have been generated using this information. These include the various geological and geophysical anomaly maps in the different chapters, the structural orientation data presented in maps and equal-area stereographic projections on the lower hemisphere, geochronological data in tables and figures, and data bearing on the lithogeochemistry and mineral resources in various graphics. An attempt has been made to maintain uniformity in the presentation of these figures and tables to provoke a comparison between similar sets of data in different lithotectonic units. The geographical content of the maps is based on open geodata from Lantmäteriet (the Swedish mapping, cadastral and land registration authority), available according to the open data licence Creative Commons, CC0.

Acknowledgements are made in the Preface to the geoscientists who helped generate the reflection seismic profiles (2015), extracted the digital information from the databases at the Geological Survey of Sweden (2013–14) and generated the geophysical anomaly maps (2013–14). Some comments on the databases, based on information provided by the Geological Survey of Sweden, and their use in this Memoir, complete Appendix A1.
**Geological maps and 3D model**

Geological maps constitute a key component in all the chapters in this Memoir. The more detailed maps of Sweden were generated using the current national bedrock map database compiled by the Geological Survey of Sweden, designed for use at a scale of 1:1 million. The coordinate grid drawn on both these maps and the geophysical anomaly maps (see later) corresponds to a part of the National SWEREF 99 TM coordinate system. A map product generated from this database (Bergman et al. 2012) and supportive geophysical anomaly maps (Jönberger 2012; Wedmark 2012), covering the entire country, have also been printed at the scale 1:1 million.

The bedrock map database and its map product provide a 2D model for the spatial distribution of solid rock units and more significant deformation zones (ductile shear zones and faults) on the ground surface over the whole country, extending to the border of the Swedish economic zone in the offshore part. Each rock unit in the database was assigned to a specific major lithotectonic unit (e.g. orogen) or sub-unit and consists of one or more lithologies, the timing of formation of which is also indicated. Use of the term ‘deformation zone’ for localized high-strain zones has been used because zones affected by ductile shear, brittle or combined ductile and brittle deformation have not been distinguished. The base information used in the compilation work (see following paragraph) is significantly generalized. This

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**Fig. A1.1.** Sources of cartographic, geological and geophysical information used in this Memoir. (a) Coverage of solid rock map information in Sweden and its recommended usage at different scales (based on information from the Geological Survey of Sweden). This coverage differs slightly from that used in the development of the national bedrock map database (1:1 million) published during 2012 (Bergman et al. 2012) and used in this Memoir. (b) Flight line spacing and flight direction of airborne geophysical measurements in Sweden. The focus in this Memoir is placed on airborne magnetic data and, in some chapters, radiometric data. (c) Gravity measurement sites in Sweden. The tendency to develop a dark tone in several areas reflects the greater density of measurement sites. The flight lines and measurement sites of the geophysical datasets show the situation during 2013–14 when the geophysical maps included in this Memoir were generated. Both geophysical maps were supplied by Ildikó Antal Lundin (Geological Survey of Sweden).
simplification has the consequence, for example, that the true width of the deformation zones is not shown.

The base sources of information used to generate the 1:1 million map comprise two regional map databases constructed by the Geological Survey of Sweden: one for the Caledonide orogen and the Tonian–Paleogene rocks east of this orogen (Fredén 1994) and the other for the part of the Fennoscandian Shield in Sweden (Koistinen et al. 2001). The information presented in these two compilations was systematically updated using the results of later geological mapping varying in scale between 1:50 000 and 1:250 000, carried out by, and currently stored in the bedrock map database labelled BMOD, at the Geological Survey of Sweden (Fig. A1.1a).

A 3D model for the entire country has recently been developed (Curtis et al. 2018) that makes use of the lithotectonic framework for Sweden and information bearing on the geometric relationships between the shield (including its various sub-units), the younger sedimentary cover successions on the older continental crust and the gently dipping tectonics in the Caledonide orogen.

**Geophysical anomaly maps**

Magnetic and Bouguer gravity anomaly maps, based on airborne magnetic field and ground gravity measurements, respectively, are presented in the parts of the Memoir addressing the lithotectonic units inside the Fennoscandian Shield. These geophysical anomaly maps are included to support the identification and character of various lithological and structural features discussed in the text. Radiometric anomaly maps, focusing on the spatial distribution of uranium in the uppermost part of the solid rock mass and drift, are also provided in some chapters. The radiometric anomaly maps are based on airborne natural gamma ray measurements.

Airborne magnetic and radiometric data have been acquired along flight lines, commonly in a north–south or east–west direction and with different line spacings in different parts of the country (Fig. A1.1b). Measurements are currently carried out at a flight altitude of 60 m, although earlier flights (prior to 1994) used an altitude of 30 m. After subtraction of the geomagnetic reference field DGRF 1965.0, the acquired data were stored in databases at the Geological Survey of Sweden, most measurements being carried out systematically by this state authority since 1960. The coverage of quality airborne geophysical data is generally poor in the Caledonide orogen in the northwestern part of the country (Fig. A1.1b).

At the time when the Bouguer gravity anomaly maps for this Memoir were generated (2013), gravity data from nearly 300 000 measurement points were available in the respective database at the Geological Survey of Sweden (Fig. A1.1c). Many of these measurements were acquired in a denser pattern around exploration targets, mainly in the 1970s and 1980s. The digital gravity data include the observed g-value, free-air and Bouguer anomalies and, for a large part of the material, terrain corrections. The database includes measurements made by the Geological Survey of Sweden and other organizations – for example, Lantmäteriet.

**Geochronological information**

Geochronological information provides a vital part of the compilation in this Memoir and is presented in the form of standard tables and figures in most of the chapters. Ages providing the timing of crystallization of magmatic rocks, and the timing of metamorphism and subsequent cooling are distinguished in the figures.

Information was extracted initially (2014) from the geochronological database at the Geological Survey of Sweden and organized according to lithotectonic unit. Ages not present in this database, or which emerged later in the published geoscientific literature, were included during the subsequent preparation of the various chapters. The attributes in the tables include: the lithology and sample coordinates (National SWEREF 99 TM coordinate system); the isotope system (principally U–Pb and ⁴⁰Ar–³⁹Ar); the method, mineral dated and age type obtained; the inferred age (2σ uncertainty); the geological interpretation; and a reference to where the background geochronological data are published.

**Orientation of mesoscopic structures and grade of metamorphism**

The bedrock map database BMOD provided the source for the structural orientation data presented in this Memoir. The trends of form lines, inferred to be coupled to the tectonic foliation in the rock mass, and information bearing on the grade of metamorphism are also shown cartographically on a regional scale. The form line and metamorphic information were extracted from a tectonic map database constructed by the Geological Survey of Sweden during 2015 and designed for use at the scale 1:5 million.

**Lithogeochronological data**

Published information in the geoscientific literature has been used when the composition and tectonic affinity of the dominant magmatic suites constituting many of the lithotectonic units are addressed. In the chapters addressing the rocks in the Fennoscandian Shield, this information has been complemented by an evaluation of the lithogeochronological data extracted from the corresponding database at the Geological Survey of Sweden, currently referred to there as the BLAB KEMI and previously as the LIKE database. In addition to the whole-rock geochemical data, attributes bearing on sample identification, sample coordinates (National SWEREF 99 TM coordinate system), lithology, lithostratigraphic framework and method of analysis are included in the database.

Analyses have been selected from the BLAB KEMI database for study on the basis that a sample can be linked with high confidence to a particular magmatic suite. A part of or all the selected samples, depending on the focus of interest in a particular chapter, were then included in the diagrams presented in this Memoir. Plots for trace elements either distinguish or only show samples apparently not affected by hydrothermal alteration involving the elements Na, K and Mg, on the basis of the chemical index value used in this study to assess such alteration (see later text). Chondrite-normalized rare earth element plots only include samples where values for all these elements (excluding Pr) are available. Anomalous outliers on some trace element diagrams or some of the samples showing highly irregular patterns on the chondrite-normalized plots have not been included because problems with the analytical results are suspected. The quality of the data in the BLAB KEMI database is variable and further work to evaluate this issue is needed.

Standard plots, comparable from chapter to chapter, have been completed using the selected data. The diagrams have been generated using the Geochemical Data Toolkit (GCD-kit) for Windows software (Janoušek et al. 2006). The data used to produce the figures are tabulated in Supplementary material files archived at https://www.geolsoc.org.uk/Publications/Books/Memoirs/Memoir50data.

**Mineral and bedrock resources**

An evaluation of mineral and bedrock resources is an essential part of several of the chapters in this Memoir, not least inside the lithotectonic units where the country’s five significant mineral districts are located. Relevant information has been derived from the mineral resource database at the Geological Survey of Sweden.
Acknowledgements

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Author contributions

MBS: writing – original draft (lead).

Correction notice

The Editors have revised Figures 1.2 and 1.6 to correct an error in the visualization of one of the map database codes, which resulted in the inclusion of some mafic intrusive rocks in the wrong age group. A large number of polygons coloured previously with yellow are now shown in pale brown.

References


BERGMAN, S. & WEIHED, P. 2020. Archean (>2.6 Ga) and Paleoproterozoic units and illustrated cartographically in the context of the geology of Sweden, complementing the material studied in the published geoscience literature. This database includes information on thousands of minor occurrences as well as on larger deposits where metals, industrial minerals or bedrock have been, or are being, exploited economically.

The amount and quality of information on each deposit in the database are highly variable. The following information is present for all of them: name of occurrence or deposit; position in space (national SWeref99 TM coordinate system); type of deposit; commodity; economic status; and reference to literature. Following the extraction of the data from the mineral resource database (2013), the deposits were arranged according to commodity groups inside each lithotectonic unit and illustrated cartographically in the context of the geology of the unit.

The following information is present for all metals, industrial minerals or bedrock have been, or are being, exploited economically, including sands of minor occurrences as well as on larger deposits where metals, industrial minerals or bedrock have been, or are being, exploited economically.

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