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Lithostratigraphic definition of the Anisian carbonate-ramp deposit of the Annaberg Formation (Middle Triassic, Northern Calcareous Alps, Austria)

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Abstract: Concerning the Middle Triassic stratigraphic succession of the Northern Calcareous Alps (NCA), a modern, litho- and biostratigraphic oriented evaluation of the early- and middle Anisian Annaberg Formation is presented. Due to the fact, that Middle Triassic formations are characterized by a wide distribution within the NCA, any lithostratigraphic definitions of these formations would be of great benefit for mapping geologists, engineers and hydrogeologists. The lithostratigraphic term Annaberg Formation may substitute former designations like "*Alpiner Muschelkalk*", "*Anisian Limestone and Dolomite*" or, partly, "*Gutenstein Limestone*". It is exclusively of Anisian age and earlier then the Steinalm and Reifling Formation. Mainly based on microfacies data and lithological data, we define the Annaberg Formation (former: Annaberg Limestone) as one of the most significant Middle Triassic lithostratigraphic units within the NCA. After a detailed description of the type area, findings gained in other areas of the NCA are incorporated to obtain the largest possible overview about the lithological variability and constituents of the Annaberg Formation. As a result, we can describe the Annaberg Formation as mainly organic-rich, medium bedded wackestone, containing remnants of crinoids, little bivalves and gastropods. Typically, fossil-rich layers with accumulations of bivalves and crinoids can often be observed within the Annaberg Formation. In contrast to the Gutenstein Formation no siliceous concretions or fossils (like radiolarians) appear and the fauna is in the main shallow marine. The rock-colour varies from dark- to medium-grey and the bench thicknesses are greater than within the Gutenstein Formation sensu stricto. The fossil content is also larger than in the essentially anaerobe Gutenstein Formation. With respect to the Virgloria Formation the Annaberg Formation is rather planar bedded, not so rich in bioturbation-structures and poor in silica and clay. Hence, the depositional environment of the Annaberg Formation can be described as a restricted carbonate ramp succession, with only minor water movement and separated from the open sea by a shoal with crinoid and brachiopod meadows. Breccias may be an indication for collapse-structures and slumping. In addition, knife-cavity structures ("Messerstichkalke") indicate an occasional hypersaline environment with precipitation of evaporite-minerals like gypsum. Fossil-rich layers with accumulations of molluscs and crinoids may indicate short-term storm affected sedimentation.

Keywords: Northern Calcareous Alps, stratigraphy, Middle Triassic, Anisian, Annaberg Formation, Alpiner Muschelkalk.

Introduction

The Northern Calcareous Alps (NCA) represent a prominent part of the East Alpine fold-and-thrust belt in Austria and comprise a wealth of classical Mesozoic stratigraphical sites (see Tollmann 1976a; Channell et al. 1992; Linzer et al. 1995; Mandl 2000). In spite of a suite of well-developed classical fossil assemblages and outcrops, which were described in a large quantity of publications, the Anisian, and all the other Middle Triassic lithostratigraphic units of the NCA, are still being discussed. This includes their paleogeographic relationships and chronostratigraphic variabilities within the whole area of the NCA. Hence, clear-cut lithostratigraphic definitions are pending. Especially the age, geometry and facies relations between Middle Triassic shallow water carbonate settings like Steinalm- and Wetterstein Formations and their adjacent slope and basin stratal units such as the Gutenstein, Reifling, Partnach and Raming Formations, are strongly debated. In many cases, the intensive polyphase deformation-history of the NCA since Late Jurassic or mid Cretaceous times has destroyed much of these facies connections. As a result, the Anisian carbonate-ramp deposits have lost much of their original facies and stratigraphical relationships due to tectonic overprint.

Tollmann (1966, p. 118 f) first introduced a valid lithostratigraphic definition of "*Annaberg Limestone*" and "*Annaberg Dolomite*", with the specification of a type locality, a type section and reference section. However, the initial definitions given by Tollmann (1966), reveal some uncertainties, especially in terms of the chronostratigraphic range, lithostratigraphic position and sedimentary depositional environment of the Annaberg Limestone. Therefore, the aim is accurate lithological descriptions of the Annaberg Formation, based on the first lithological descriptions by Tollmann (1966, p. 120). Additionally, a clear separation of the Annaberg Formation from all the other alpine formations of Middle Triassic age, especially those coming from the Anisian stage, is suggested here. Altogether, a correct lithostratigraphic, biostratigraphic and microfacies definition of the Annaberg Formation will be proposed in this paper, including its correct biostratigraphic dating. The old lithostratigraphic term "Alpiner Muschelkalk" (established by Gümbel 1860), which in part correlates with the appearance of the Annaberg Limestone and other Middle Triassic formations, should be abandoned. Additionally, a short overview about formations corresponding to the Annaberg Formation outside of the Eastern Alps, is attached.

Methods

One of the authors has tried to summarize all his experiences acquired through the detailed mappings of Middle Triassic Series within the eastern part of the NCA and to put down all his observations and data derived from these mappings. Naturally, an exact description of the Annaberg Formation at the type-locality has been of fundamental importance, but the aim was also to propose reference sections. The authors have tried to verify the kind of microfacies of the Anisian formations already in the field and underlined their observations in nature by further studies of many thin sections. An astonishing microfacies similarity could be detected between the various occurrences of the Middle Triassic formations inside and outside the NCA. For chronostratigraphic dating of the Anisian strata only biostratigraphic data, gained from different key-fossils like foraminifers and/or dasycladalean green algae, had been available. The determination of the fossils was supported mainly by Dr. Olga Piros in Budapest (Hungary) and Dr. Felix Schlagintweit in Munich (Bavaria). An exact fine stratigraphic subdivision of the Anisian stage into substages and biozones is not possible for the time span of the early and middle Anisian within the NCA. The localities, important for the definition of the Annaberg Formation, are given in Table 1.

The discrimination between the Annaberg Formation and other Middle Triassic formations

A long-awaited goal has been to get microfacies and biofacies criteria for the correct stratigraphic definition of the Annaberg Limestone sensu Tollmann (1966). Although the lithological criteria, which Tollmann (1966, p.118) cited, hitherto are clearly understandable, many mapping geologists did not get a satisfying answer to the question of how to differentiate the Annaberg Formation from other Middle Triassic formations like the Gutenstein Formation, Raming Formation and Steinalm Formation. For instance, the lithological development of the Raming Formation within the Tirolic Nappe System of the eastern NCA is a good example, of how stratigraphically completely different formations can be confused by mapping, when only lithological criteria are applied to distinguish them in the field. A clear differentiation between the single formations is available only when microfacies aspects, gained with the help of thin-sections, slabs or by looking on the rock-surface with a hand lens, are taken into account. In this way, detailed information about the lithology, fossil-content, sedimentary environment, microfacies and chronostratigraphy of all Middle Triassic formations will be necessary in future.

Geological setting

The thick thrust nappe stack of the NCA, first described in detail by Tollmann (1976b, p. 45; overview at Mandl 2000, p. 62), forms a main part of the Eastern Alps. Its deposition area was originally situated on the north-western margin of the Neo-Tethys-ocean (Fig. 1). During the Triassic Period, the NCA were part of a broad, low-latitude shelf belt, which expanded from the Middle European epicontinental marginal sea in the north to a southward carbonate dominated shelf including large reef and lagoonal systems (Mandl 2000, p. 64). The shelf was situated on the southern margin of the European/Eurasian continental plate until the Jurassic. During the Late Jurassic, the domain of the NCA became separated from the European continental plate by the narrow Penninic oceanic realm (Faupl & Wagreich 2000, p. 83), later forming an external part of the Adriatic plate. Starting from the Late Jurassic–Early Cretaceous Epoch onwards, the NCA were sheared off their Austroalpine Paleozoic crystalline basement and were thrusted as a broad nappe stack north-west- to northward onto the external (i.e. Penninic) tectonic units (Schmid et al. 2004, p. 105). The individual thrusted units of the studied area (Fig. 2) were firstly formed in the Late Cretaceous, including the Tirolic Ötscher Nappe System (first mentioned by Hahn 1912 and Kober 1912), subdivided by Spengler (1928) from bottom to top into the Reisalpen Nappe, Unterberg Nappe and Göller Nappe, and the Bajuvaric Nappe System (first mentioned by Hahn 1912), subdivided by Kober (1912), Spengler (1928) and Spengler (1951) from bottom to top into the Frankenfels Nappe, Lunz Nappe and Sulzbach Nappe. Afterwards, in the Paleogene and Neogene Period, the overthrust of all the tectonic units of the NCA had generally been reactivated after deposition of the Late Cretaceous and Paleogene clastic Gosau Group (Wagreich 1995, p. 66).

Within the NCA, the Mesozoic stratigraphic succession starts during the Lower Triassic Epoch with grey, greenish and violet slates, silty- and quarzitic sandstones of the mainly siliciclastic developed Werfen Formation (Tollmann 1976a, p. 57; Hess 1981 and Fig. 3). During the Anisian (early Middle Triassic) the sedimentation of carbonates began with evaporitic and shallow marine dolomitic/calcareous strata of the Reichenhall Formation (Frisch 1969; Tollmann 1976a, p. 66). This formation is stratigraphically positioned below the base of the early- to middle Anisian Gutenstein Formation (Flügel & Kirchmayer 1963; Tollmann 1976a, p. 72 and Fig. 3), which is widespread within the eastern part of the NCA (Türnitz and Gutenstein Alps, Fig. 4). On top of the Gutenstein Formation either transitional beds occur to the shallow marine middle Anisian Steinalm Formation (Pia 1924; Tollmann

Table 1: List of important sections for the definition of the Annaberg Formation.

Lithostratigraphic Unit	Locality	Status	Federal state	Tectonic Unit	Nappe System	Literature
Annaberg Limestone	Annaberg – forest road 'Spindelhof'	type-locality, type section	Lower Austria	Sulzbach Nappe	Bajuvaric Nappe System	Tollmann (1966, p. 118)
Annaberg Formation			Lower Austria	Sulzbach Nappe	Bajuvaric Nappe System	Moser (2019)
Annaberg Limestone	Annaberg – Lassing-gorge	type-locality, reference-section	Lower Austria	Sulzbach Nappe	Bajuvaric Nappe System	Tollmann (1966, p. 120)
Annaberg Limestone	Lassing – Scheibenberg, Palfau – Gamsstein	reference-section	Lower Austria/ Styria	Sulzbach Nappe	Bajuvaric Nappe System	Moser & Tanzberger (2015, p. 238) Krystyn et al. 2008
Annaberg Dolomite	Trübenbach – Teufelsriedel	type-locality	Lower Austria	Sulzbach Nappe	Bajuvaric Nappe System	Tollmann (1966, p. 114)
Annaberg Dolomite	St. Martin/Tennengebirge	studied area	Salzburg	Staufen–Höllengebirge Nappe	Tirolic Nappe System	Moser (2018, p. 148) Brunner (2013)
Annaberg Formation	Karwendel – Nordkette	studied area	Tyrol	Inntal Nappe	Tirolic Nappe System	Gruber (2016, p.305)
Annaberg Formation	Kleinzell – Hochstaff	variety	Lower Austria	Reisalpen Nappe	Tirolic Nappe System	Moser (2020)
Furth Limestone	Furth/Triesting	type-locality, synonyme	Lower Austria	Göller Nappe	Tirolic Nappe System	Tollmann (1966, p. 120)
Annaberg Limestone	Annaberg – Hocheck	type-area	Lower Austria	Sulzbach Nappe	Bajuvaric Nappe System	Hagenguth et al. (1982, p. 167)
Annaberg Limestone	Türnitz – Schwarzenberg	studied area	Lower Austria	Reisalpen Nappe	Tirolic Nappe System	Hagenguth et al. (1982, p. 167)
Alpiner Muschelkalk	Berchtesgaden, Bischofswiesen	type-area	Bavaria	Hallstatt/Berchtesgaden Nappe	Juvavic Nappe System	Gümbel (1860, p. 19)
Anisian Limestone/ Dolomite	Hallein – Bad Dürrnberg	variety	Salzburg	Hallstatt/Berchtesgaden Nappe	Juvavic Nappe System	Plöchinger (1955, p. 96)
	Gschöder – Hochtürnach, Riegerin	variety	Styria	Mürzalpen Nappe	Juvavic Nappe System	Moser et al. (1994, p. 481)
Mittlere Serie des Alpinen Muschelkalks	Innsbruck – Nordkette	synonyme	Tyrol	Inntal Nappe	Tirolic Nappe System	Sarnthein (1966, p. 41)
Virgloria Formation	Brand – Virgloriatobel	type-locality	Vorarlberg	Lechtal Nappe	Bajuvaric Nappe System	Richthofen (1859, p. 83)
Gutenstein Formation	Gutenstein – 'Passbrücke'	type-locality	Lower Austria	Göller Nappe	Tirolic Nappe System	Flügel & Kirchmayer (1963, p. 113)
Upper Gutenstein Formation/Kasberg Formation	Grünau/Almtal – Kasberg	variety	Upper Austria	Totengebirge Nappe	Tirolic Nappe System	Moser & Moshammer (2018)
Sulzkogel Member	Gosau – Sulzkogel	type-locality	Upper Austria	Hallstatt Nappe	Juvavic Nappe System	Gawlick et al. (2021, p. 423)
Rabenkogel Member	Bad Mitterndorf – Rabenkogel	type-locality	Styria	Hallstatt Nappe	Juvavic Nappe System	Gawlick et al. (2021, p. 431)
Vysoká Formation	Malé Karpaty	studied area	Slovakia	Vysoká Nappe	Krizna Nappe	Michalík et al. (1992)
"Gutenstein Formation"	Aggtelek mountains	studied area	Hungaria	Silicicum	Juvavic Nappe System	Piros (2002)

1976a, p. 81) or a sharp facies change occurs into the deeper marine pelagic Reifling Formation (Gessner 1963; Tollmann 1976a, p. 87). The latter comprises chronostratigraphically the late Anisian and different parts of the Ladinian stage (Fig. 3). The Annaberg Formation occupies the transitional beds between the Gutenstein and Steinalm Formations and consists of organic-rich outer, mid and inner ramp deposits. The distribution area of the Annaberg Formation is mainly located within the Bajuvaric Nappe System (Table 1) and is closely related to the occurrence of the middle Anisian (Pelsonian) Steinalm Formation. In certain profile-sections the Annaberg Formation seems to substitute the Steinalm Formation and so encompasses the whole Pelsonian substage up to the base of the Reifling Formation (Hagenguth et al. 1982, plate 1).

The history of research of the Annaberg Formation and relevant data from previous studies

Spengler (1931, p. 18) noticed during his geological recording of the area of the Türnitz- and Gutenstein Alps in Lower Austria (Fig. 5), that "*the Middle Triassic in the area of the map is appearing in a very different way*" and distinguished seven different types of facies (a–g), each of it comprising specific chronostratigraphic levels within the Anisian and Ladinian stage (middle Triassic epoch). Furthermore, he mentioned some facies transition between the different types of Middle Triassic rocks, which, however, were not investigated in terms of their microfacies characteristics and their fossil content until now. Nevertheless, Spengler (1931, p. 21) was one of the first, who separated "*thick-bedded, grey limestones*" (facies c) of Anisian age, which he was able to date correctly to the early Middle Triassic stage with the help of brachiopod and crinoid findings. Earlier, before him, Geyer (1911, p. 12*f*) had noticed, that, within the surroundings of the Ybbs and Lower Enns valley, the rocks beneath the cherty and nodular bedded Reifling Formation may be represented by "*massive, grey, coarse-splintery limestone*" of Anisian age. All these rocks, described in this way, differ considerably from the common lithological appearance of the Gutenstein Formation and were assigned by Spengler (1931) biostratigraphically correctly to the early and middle Anisian substage. Within the area of the Gutenstein Alps, Hertweck (1961, p. 13) observed a similar lithology of Anisian rocks, citing "*massive, hardly bedded, dark grey limestones with rough surfaces*", which may underly the Reifling Formation.

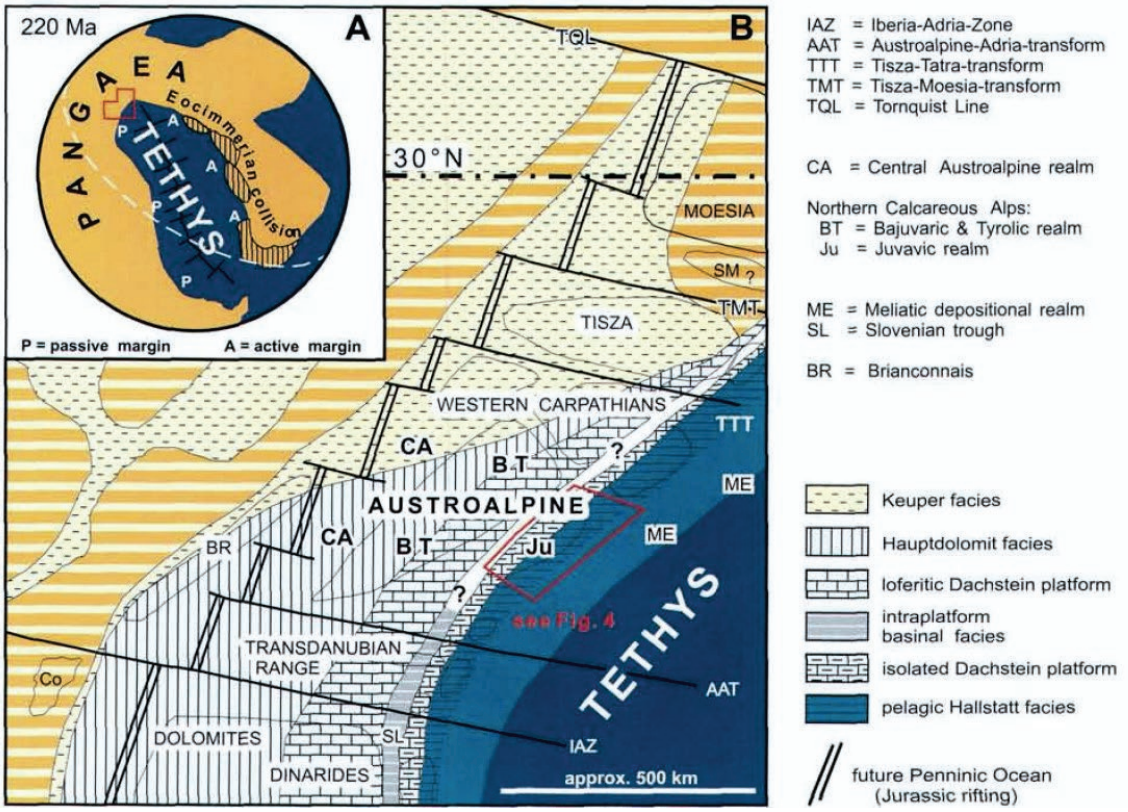

Fig. 1. Paleogeographic map with the paleogeographic position of the Austroalpine Triassic within the Tethyan realm (from Mandl 2000: fig. 2, with permission from the publisher).

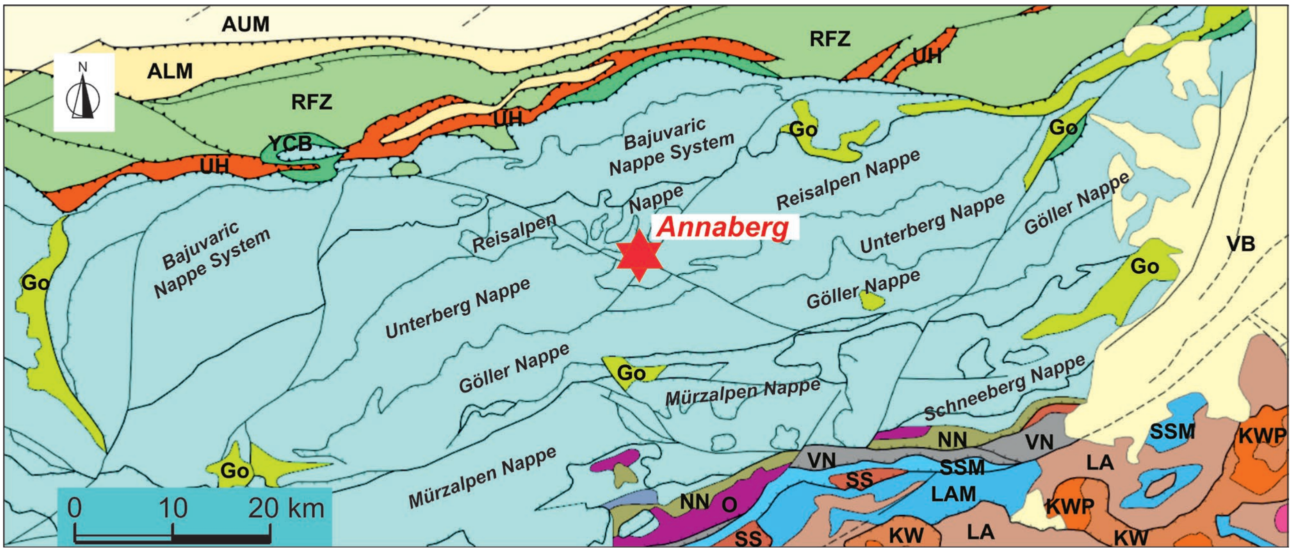

Fig. 2. Map with the geographic position of Annaberg and tectonic overview about the eastern part of NCA with (1) Bajuvaric Nappe System in the north, (2) Tirolic or Ötscher Nappe System (=Reisalpen Nappe, Unterberg Nappe, Göller Nappe) in the center, and (3) Juvavic Nappe System (=Mürzalpen Nappe, Schneeberg Nappe) in the south. Go=Gosau Basins, AUM=Authothone Molasse, ALM=Allochthone Molasse, RFZ=Rhenodanubian Flysch Zone, YCB=Ybbsitz Klippen Belt, UH=Helvetikum and Ultrahelveticum, NN=Noric Nappe, VN=Veitsch Nappe, O=Ordovician Blasseneck Porphyr, SS=Silvretta–Seckau Crystalline Unit with SSM=Mesozoic Cover, LA=Lower Austroalpine with LAM=Mesozoic Cover, KW=Koralpe-Wölz Crystalline Unit with KWP=Permian Orthogneiss (base map: Multithematische Geologische Karte von Österreich 1:1,000,000, Geological Survey of Austria).

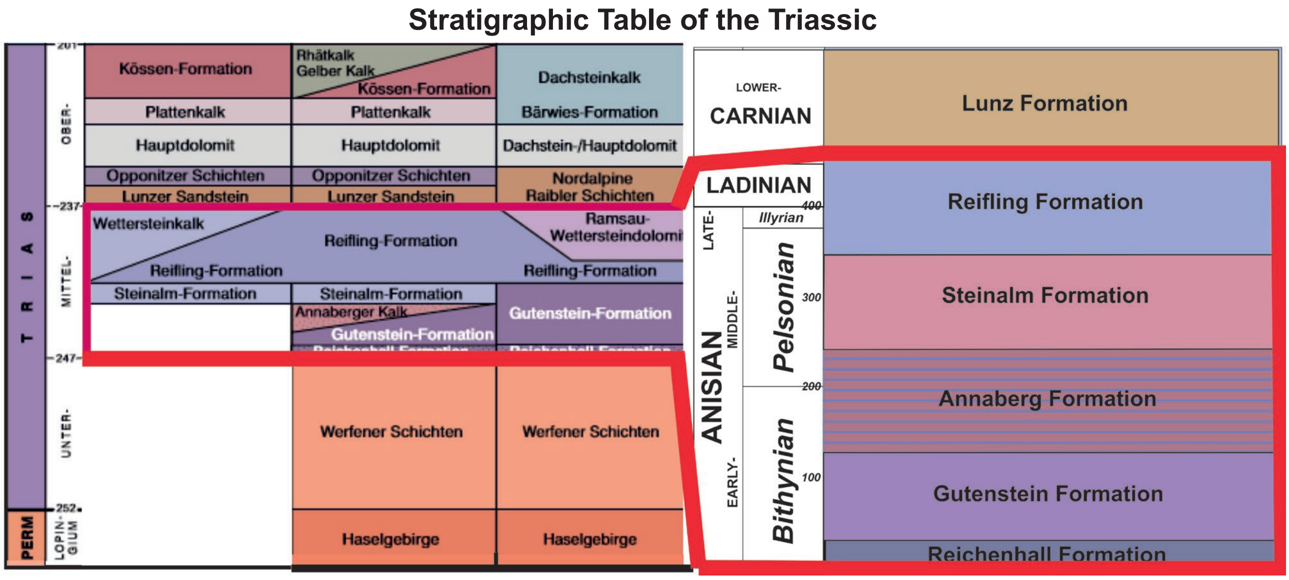

Fig. 3. Modified stratigraphic chart of the eastern NCA with the exact position of the middle Triassic stratigraphic succession of Annaberg on the right side (modified from Moser & Schnabel 2019, p. 228).

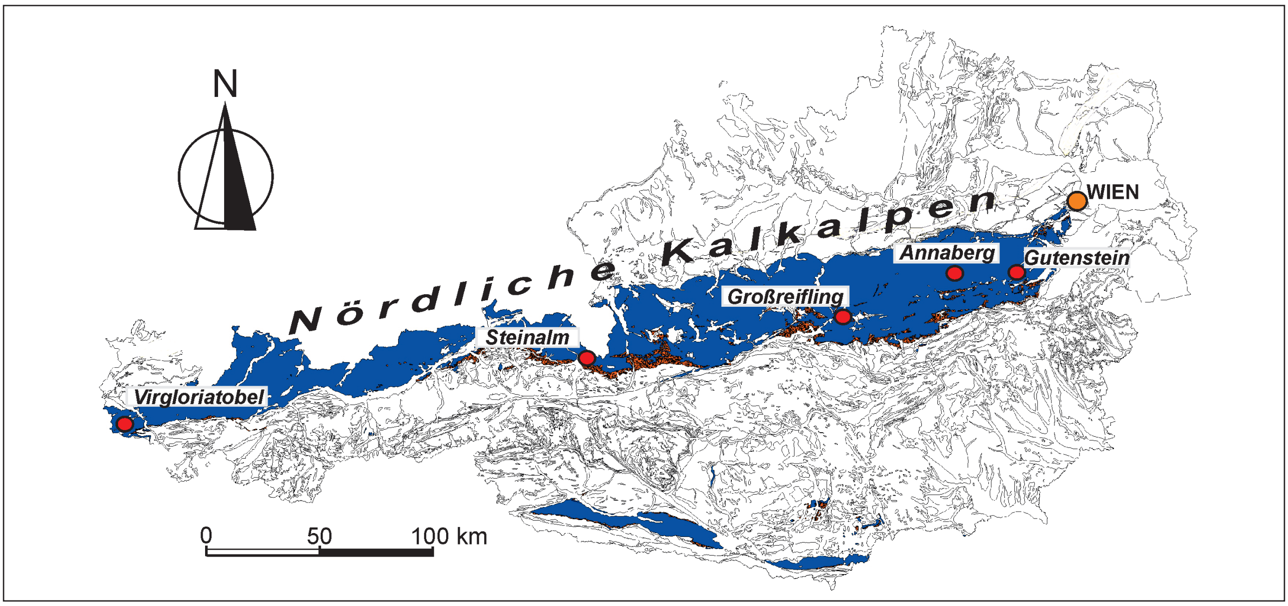

Fig. 4. Overview map with the location of the type-locality of the Annaberg Formation, the Gutenstein Formation, the Virgloria Formation, the Steinalm Formation, and the Reifling Formation (Großreifling) in Austria; modified from the base map "Multithematic Geological Map of Austria 1: 3,000,000", Geological Survey of Austria.

Only the renewed geological investigations of the Ötscher-region (Lower Austria) by Tollmann (1964–1966) allowed a refinement of the herein mapped Middle Triassic stratigraphic successions. Subsequently Tollmann (1966, p. 118) was able to distinguish a "*greyish, thick-bedded, fine-layered, massive limestone or dolomite*", which he termed "*Annaberg Limestone*" or "*Annaberg Dolomite*", from a general fine laminated and thin bedded, black-coloured limestone, originally termed as Gutenstein Formation by Hauer (1853).

To get a good overview of the whole lithology and facies variability of the Annaberg Formation, one may consider even more localities in addition to those defined by Tollmann (1966). During the first observations of the Gutenstein Formation in Gutenstein (Lower Austria), Flügel & Kirchmayer (1963, p. 113) recognized, that in Gutenstein itself, intercalations of thicker beds with "*organogenic detritus*" of crinoids may appear intercalated within the uppermost parts of the Gutenstein Formation (e.g. at quarry 'Passbrücke'). In this way the first microfacies characteristics of the Annaberg Formation had been recognized and, also, its age-related differentiation from the fine-grained calcilutitic lithotypes of the Gutenstein Formation. Hence, Flügel & Kirchmayer (1963, p.130) observed a shallowing upwards trend of the accommodation space within the Early Pelsonian portion of the Upper Gutenstein Formation. Referring to it, Summesberger & Wagner (1971, p. 354) stated at the very end of their publication about the Gutenstein Formation, that among the synonyms, they cite, including the Annaberg Limestone, "*transitions between Gutenstein Limestone and Steinalm Limestone*" will exist. In this way, these authors were among the first to realize that, in spite of the lack of biostratigraphic data, the Annaberg Formation represents a lithological connecting member between the Gutenstein and Steinalm Formations after all. Finally, Hagenguth et al. (1982, p. 167 f) was the first to describe the microfacies of the Annaberg Formation in the vicinity of its type-locality in Annaberg (Lower Austria). On the one hand, Hagenguth et al. (1982, p. 168) assigned the sedimentary environment of the Annaberg Formation to the "*margin of a basin, rich in biogenic detritus and with an infill from a neighbouring platform*" and, on the other hand, to a "*sub- and supratidal intra-platform-area*". Additionally, predominantly benthonic biogenic fragments such as crinoids, bivalves and ostracods had been identified by them as typical for the microfacies of the Annaberg Formation. From the facies point of view, they characterized bioclast bearing micrites (mudstones, wackestones), bioturbated micrites, poor in fossils and microsparitic limestones as well as intrabiosparites, showing (sub)rounded intraclasts and partially micritisized bioclasts. The correct chronostratigraphical assignment of the Annaberg Formation to the middle and early Anisian with the help of the following foraminifers and crinoids, collected and cited by Hagenguth et al. (1982, p. 169) is bio- and lithostratigraphically noteworthy:

Meandrospira dinarica KOCHANSKY
Meandrospira deformata SALAJ
Glomospira densa PANTIĆ
Pilaminella grandis SALAJ
Dadocrinus gracilis BUCH

Many of these taxa, characteristic for the Anisian stage, can be found along the whole Tethys-region (Salaj et al. 1983) and have been, for example, also cited by Ha et al. (2019, p. 11) in Indochina.

Hagenguth et al. (1982) interpreted the depositional environment of the Annaberg Formation correctly as being of shallow-marine and supra- to subtidal origin. Nevertheless, Hagenguth et al. (1982, p. 168) added the age of the Annaberg Formation beyond the Pelsonian to the "*Late Anisian and early Ladinian*", what was later corrected by Wessely (1984, see below).

In some case the appearance of the Annaberg Formation within the lithostratigraphy of the eastern NCA is hidden by old lithostratigraphic terms like "*Alpiner Muschelkalk*" (Gümbel 1860) or "*Anisian Limestone/Dolomite*" (Plöchinger 1955, p. 96) on existing geological maps. Kubanek (1969, p. 7*f*) has given a critical discussion of the origin and application of the old lithostratigraphic terms "Muschelkalk" and "Alpiner Muschelkalk". Equivalents to the Annaberg Limestone also appear in a similar manner within the western NCA. These include the "*Mittlere Serie des Alpinen Muschelkalks*", defined by Sarnthein (1966, p. 41) and Frisch (1968, p. 101), as well as portions of the *Virgloria Formation*, defined by Richthofen (1859) and Kobel (1969).

Recent investigations, trying to define some of the litho- and biostratigraphic characteristics of the Annaberg Formation, can be found in Nittel (2006, p. 97), Lein et al. (2010, 2012), Wessely & Krystyn (2013, p. 318), Moser & Piros (2015, p. 222), Moser & Tanzberger (2015, p. 237), Gruber (2016, p. 305), Moser (2018), Moser & Moshammer (2018) and, finally, Moser (2019).

Furth Limestone

Tollmann (1966, p. 120 f) originally proposed the lithostratigraphic designation "*Furth Limestone*" in terms of different medium- to dark grey coloured, thick bedded, dolomitic limestones and rauwackes in the distribution area of the Sulzbach Nappe (Bajuvaric Nappe System) near the location Sägemühle (1 km west of Annaberg, Lower Austria; see Fig. 5). Because of their dolomitic and "cellular-porous occurrence" he compared these rock series with the "*dolomitic limestones*" of the "*Anisian and Ladinian stage*", described by Hertweck (1961, p. 13) near Furth/Triesting within the Gutenstein Alps (Lower Austria, Fig. 5). We undertook an examination of this type of limestone in the surroundings of Furth/Triesting, in the area along the mountain-ridge between Ebelthal (with a small quarry), mount Ruhberg (634 m), Rittsteig farm, the cliffs on mount Groldenkogel (582 m) and mount Tannberg (677 m). The lithotypes found at these locations correspond largely to the lithotype of the Annaberg Formation, as described here (Fig. 6). The massive rocks are usually developed as more or less organic-rich, dark grey, brown grey or medium grey coloured, fine grained limestones, poor in fossils (Fig. 6F), as it can be seen at mount Ruhberg (634 m, 1 km south of the Furth/Triesting) and, also clearly visible, near the country road L 4034 0.5 km SE of Furth/Triesting (mount Groldenkogel). Characteristically, a small amount of tiny columnar plates of single crinoids (Fig. 7D) can be observed as biogenic fragments occasionally. Furthermore, the massive limestone draws attention through the formation of steep cliffs (e.g. on mount Groldenkogel). The rauwackes, described by Hertweck (1961, p. 13) and Tollmann (1966, p. 120) as characteristic for the "Furth Limestone", occur only subordinately and are probably of tectonic origin, since they do not form any stratigraphically definable horizon. At fresh breakage it is visible that the rauwackes consist of medium- to dark grey coloured, calcareous breccias, in which black and angular limestone lithoclasts float within a grey carbonatic matrix. Due to their

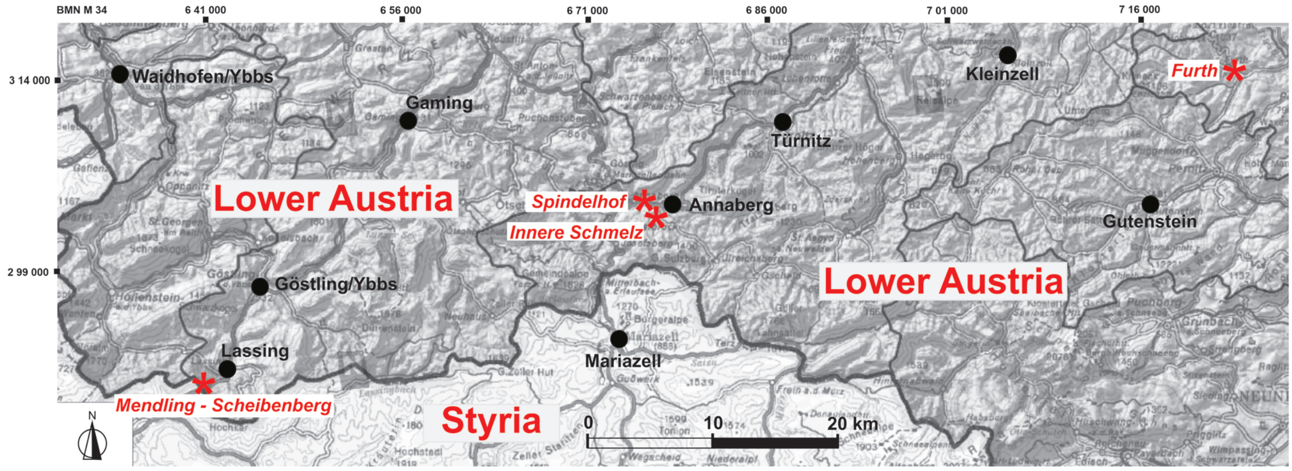

Fig. 5. Base map with the site of some locations important for the lithostratigraphic definition of the Annaberg Formation in Lower Austria base map: Lower Austria Atlas; © BEV.

position close to the front of the Göller Nappe and, thus, to an extensive basal thrust-plane, which is situated above Late Cretaceous Gosau Sediments ("*Gutenstein–Furth Line*"), the limestones are tectonically intensively stressed and hence preferentially fractured and brecciated. The apparently massive appearance of the originally thick bedded limestone could also be of tectonic origin. Fine stratification can be observed as distinct as in the limestones and dolomites of the Annaberg Formation. '*Messerstichkalke*' ("*knife-cavity*"*-limestones*, Fig. 7H) have also been described within the "Furth Limestone" (Moser & Piros 2018, p. 63) as shallow, puncture-like cavity structures, which may be regarded as an good indication of hypersaline depositional conditions, as we have discussed above. Hence, they are in any case a good indication that the "Furth Limestone" has been deposited in a shallow-marine paleoenvironment similarly to that of the Annaberg Limestone (Moser & Tanzberger 2015, p. 238). We support that the lithostratigraphic term "Furth Limestone" will represent a synonym of the valid stratigraphic term 'Annaberg Limestone' (Annaberg Formation) from now on.

Characteristics of the Annaberg Formation at its type-locality

The type-locality of the Annaberg Formation, proposed by Tollmann (1966, p. 119), follows a small creek between 850–900 metres in altitude, approximately 200 metres north of the Spindelhof farm (today: 'Spindlhof', house Lassingrotte 9), situated on the northern margin of the Lassingbach valley about 3 kilometres west of Annaberg (Lower Austria, with coordinates BMN M 34: 6 75 534/3 04 633 or WGS 84: 47°52'33"/15°20'12", Fig. 5). Here, the Annaberg Formation is developed as medium- to thick-bedded, rarely thin-bedded, dark grey, brown grey or medium grey coloured, often organic-rich, fine grained, also fine- and planar bedded limestone (Figs. 6A, 8), that occasionally bears some little crinoid-litter and small shells of bivalves. This lithological description is typical for the occurrence of the Annaberg Formation also at other locations and can considered to be valid for the definition of the holostratotype of the Annaberg Formation itself. However, this section is not really an adequate type-section, as it appears to be incomplete and no direct connection to under- or overlying lithostratigraphic units seem to be available until now (Fig. 9). Additionally, the specified region of Annaberg is characterized by strong tectonic deformation. Besides, a modern stratigraphic processing of the adjacent rock series (e.g. "*Wetterstein Limestone*" situated north of the type-section and "*Reichenhall Formation*" to the south, see Tollmann 1964) is missing until now. To its disadvantage, this type-section contains only a few clearly-recognizable sedimentary structures and microfacies elements, so that the whole sedimentological characteristics of the Annaberg Formation, visible in other places of the NCA, cannot really be met here.

Several thin sections, prepared from samples taken near the type-section, enable us to recognize one of the most common microfacies elements of the Annaberg Formation: dark grey coloured, fine grained wackestone (biomicrite, biopelmicrite) with tiny columnar plates of crinoids, small shells of bivalves, gastropods, ostracods and foraminifers. All these bioclasts float in a sometimes bioturbated micritic matrix (Fig. 10), which shows an index of bioturbation between 2 and 3 (Bromley 1999, p. 222). The appearance of small mollusc-shells (mostly cm-sized bivalves, less gastropods, Figs. 7E, 10A, B) and, also, the aggregation of fine and tiny crinoid fragments (Figs. 7A,D, 10C) can be considered characteristic for the whole fossil content of the Annaberg Formation. Additionally, fine bedded layers, which generally can be traced back to the resedimented supply of crinoid detritus, and furthermore the loss of sedimentary structures through intense bioturbation ('Wurstelkalke', vermicular limestone), caused by the feeding traces of crustaceans like *Thalassinoides* and *Rhizocorallium,* can generally be described as typical for the microfacies of the Annaberg Formation (Figs. 7C, 10C–F).

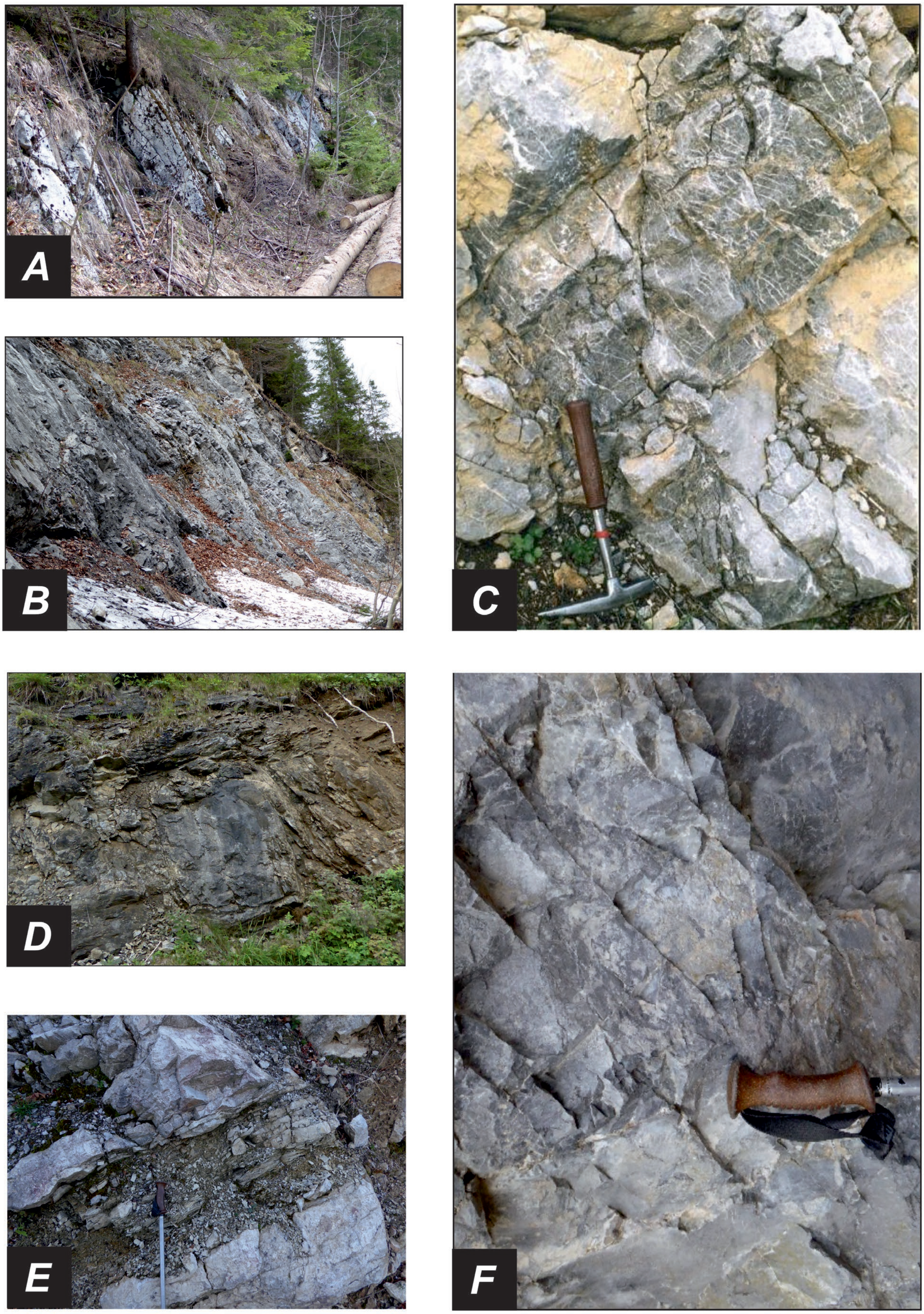
A
B
C
D
E
F

Fig. 6. A — Annaberg Formation at its type-locality in Annaberg (Lower Austria). Medium to thick- and planar bedded, organic-rich, dark grey colored limestone (mudstone, wackestone), poor in fossils, but often containing fine crinoid litter and, occasionally, small, only cm-sized shells of bivalves and gastropods; Location: road section on the forest road 200 meters north of farm Spindelhof, 3 km west of Annaberg (Lower Austria), positioned in the immediate vicinity of the type-locality defined by Tollmann (1966) at a creek 200 meters NW of Spindelhof; BMN M 34: 6 75 519/3 04 649; WGS 84: 47°52'34"/15°20'11"; **B** — Annaberg Formation within its type area in Annaberg (Lower Austria). Medium- to thick bedded, organic-rich, dark grey colored limestone with planar bedding-planes, poor in fossils. Location: section at both sides of the 'Lassing-george' ('Innere Schmelz'), 1.5 km south of Annaberg; **C** — Black colored, medium and planar bedded limestone of Annaberg Formation. Location: forest road 'Mendlingbauer' up to mount Scheibenberg (1400 m), 2.5 km WSW' Lassing (Lower Austria); **D** — Dark grey, organic-rich, alternating thin- and thick bedded dolomite with planar bedding planes, penetrated by steep inclined fault planes (Annaberg Dolomite or Formation). Location: forest road on mount 'Naßberg', 1322 m, Pongau, Salzburg; **E** — Annaberg Formation on mount Hochstaff, 1305 m (Gutenstein Alps, Lower Austria): alternation between medium bedded, dark-grey limestones, dolomitic marls and dolomites; **F** — Dark grey, bituminous, thick bedded and massive limestone of the Annaberg Formation (="Furth Limestone"), poor in fossils (Location: 'Stein' at mount Groldenkogel, 582 m, outcrops at the country road L 4034 shortly before the little village Furth/Triesting, Lower Austria); between the Annaberg- and Steinalm Formation are "knife-cavity"-limestones ("Messerstichkalke"). The crystal moulds may indicate a hypersalinar depositional environment (location: Furth/ Triesting, Lower Austria).

As another suitable type area of the Annaberg Formation, Tollmann (1966, p. 120) cites the location 'Lassing-Durchbruch' ("Lassing gorge") east of the settlement area 'Innere Schmelz' (about 1.5 kilometres south of Annaberg, Lower Austria, Fig. 5). At this point the lithological characteristics of the Annaberg Formation can be quoted similarly as medium- to thick-bedded, planar or wavy bedded, dark grey to brown grey coloured, fine grained, intensive bituminous and rarely slightly dolomitic limestones (Fig. 6B). These limestones sometimes show fine lamination and, also, tiny columnar plates of crinoids on the bedding-planes. Compared with the type-section at farm 'Spindelhof', this section ("reference section") has the benefit, that the stratigraphic overburden of the Annaberg Formation could be defined with the occurrence of the cherty limestones of the Lower Reifling Formation (Pober 1981). But downdip, the stratigraphic underlying beds are missing here again due to tectonic reduction. Only a few, well-recognizable sedimentary structures (such as fine bedding) and microfacies elements are developed. Hence, also in this comparative profile not too much more can be said in terms of the main characteristics of the Annaberg Formation.

Altogether, it can be deduced, that at the type-locality of the Annaberg Formation, proposed by Tollmann (1966, p. 119 f), most of the excavated rock packages correspond very well to the main lithological characteristics of the Annaberg Formation elsewhere, but let us see only a few microfacies elements. Additionally, the whole sections seem to be incomplete because of tectonic reduction and show a questionable stratigraphic positioning until now.

Concerning the exact chronostratigraphic age and lithostratigraphic position of the Annaberg Formation at its type-locality (section at forest road 'Spindelhof'), the modern mappings carried out by Moser (2019) have revealed, that the Annaberg Formation is overlain – in overturned position – by the middle Anisian (Pelsonian) Steinalm Formation (Figs. 8 and 9). This can be proved with help of a typical Anisian dasycladalean flora, containing *Physoporella pauciforata undulata* PIA (BYSTRICKÝ) and *Teutloporella peniculiformis* OTT, as well as by the occurrence of the Anisian foraminifer *Meandrospira dinarica* KOCHANSKY-DEVIDÉ, derived from two different locations, which are situated close to the Annaberg Formation at its type-locality (Fig. 9). The dasycladalean flora also predates the "Wetterstein Formation" sensu Tollmann (1964) into the (middle) Anisian. From the structural geological point of view the strike directions of all Anisian strata (Annaberg Formation, Steinalm Formation and Reifling Formation) correspond to each other and, hence, belong to the same stratigraphic succession as overturned part of the Bajuvaric Sulzbach Nappe, as it can be seen on the little geological map (Fig. 9). Downdip, the Annaberg Formation seems to be overlain (in overturned position) by rauwackes. But these rauwackes may be rather of tectonic origin because they are accompanied southwards by the nappe-boundary of the tectonically overlying Tirolic Reisalpen Nappe. Thus, we would expect, that the rauwackes may not represent the earliest Anisian Reichenhall Formation at this location (Figs. 8 and 9).

An exclusively early to middle Anisian age of the Annaberg Formation at its type-locality can be derived (Fig. 8) from the lithostratigraphic position of the Annaberg Formation within the Middle Triassic lithostratigraphic succession between the overlying Pelsonian Steinalm Formation and the underlying early Anisian Gutenstein- and Reichenhall Formations (Moser 2019), The chronostratigraphic range of the Annaberg Formation from the middle Anisian (Pelsonian) upwards to the late Anisian (Illyrian) or early Ladinian (Fassanian), as proposed by Tollmann (1966, p. 119), can certainly be ruled out as proven by our data.

New sections and occurrences

Further studies on the characteristics of the Annaberg Formation can be found in Moser & Tanzberger (2015, p. 238), based on microfacies data from the area of the Scheibenberg (1400 m)–Gamsstein (1770 m) mountain-range between Lassing (Lower Austria) and Palfau (Styria). In the process of the construction of a new forest road, leading from the 'Mendlingbauer' farm upwards to mount Scheibenberg (1400 m), a beautiful Middle Triassic profile section was exposed, with the various

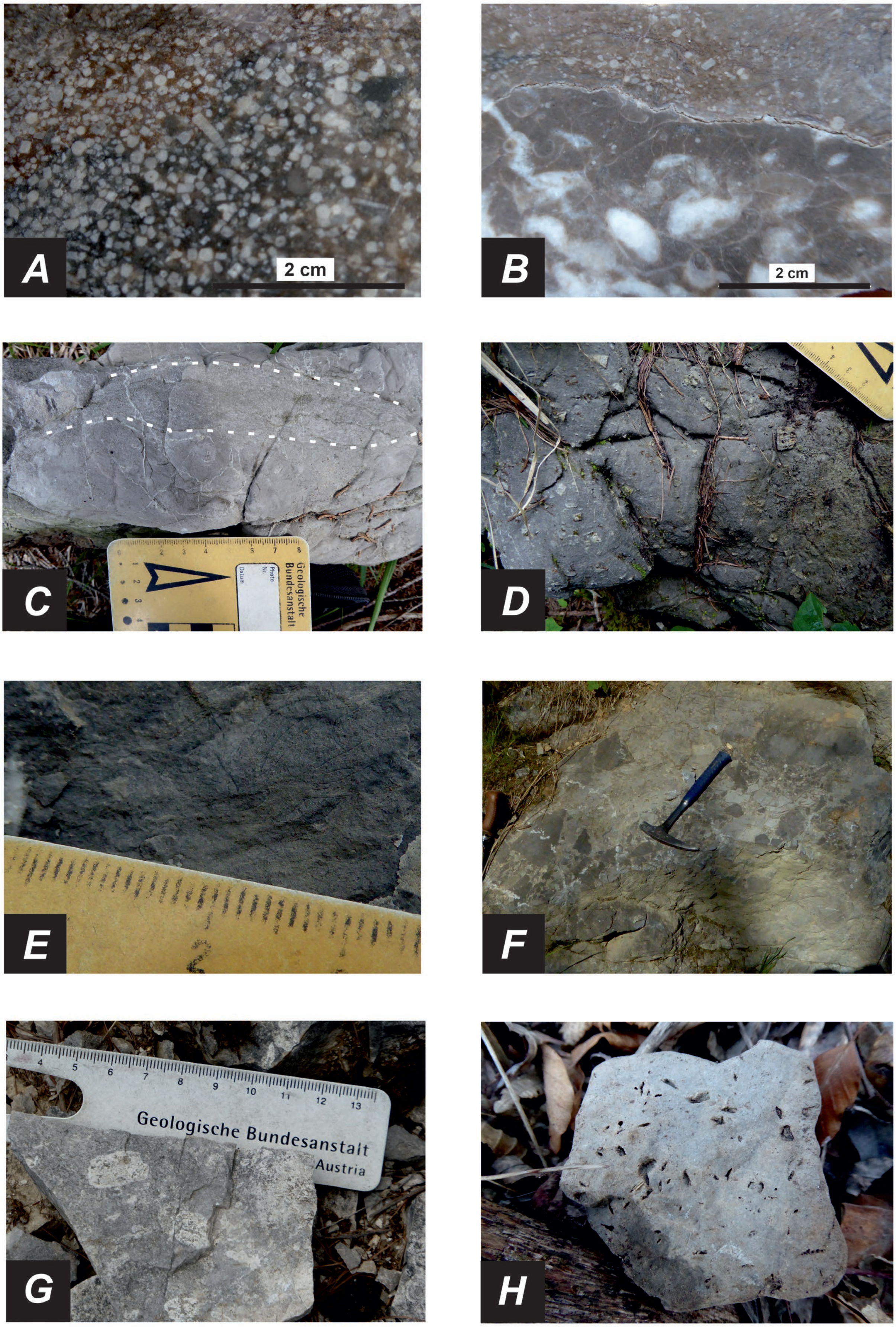
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Fig. 7. Facies of the Annaberg Formation. **A** — Dark grey, fine bedded bioclastic packstone, rich in crinoids (encrinite) (location: excavations at road 'Kasbergstraße' up to mount Kasberg (1747 m, Upper Austria). **B** — Thick bedded, detrital, medium grey colored, probably tempestitic crinoid-brachiopod packstone, showing another microfacies of Annaberg Formation, including resedimented bioclasts of brachiopods (location: mount 'Hochstein', 1405 m, Kasberg region, Upper Austria). **C** — Dark grey, fine-granular grain/packstone, showing some supply of crinoidal biodetritus as distinct layer (dashed lines) within the Annaberg Dolomite (location: southern flank of mount 'Höheneggkopf', 1431 m, Pongau, Salzburg). **D** — Dark grey wackestone, showing coarse stem plates of crinoids, which represent a typical microfacies of the Annaberg Formation (location: northern flank of mount 'Korein', 1850 m, Pongau, Salzburg). **E** — Small, cm-sized shells of bivalves, spilled together in a single layer within the Annaberg Formation (location: road to farmhouse 'Karnreith', 1.8 km west of Annaberg, Lower Austria). **F** — Coarse sized, debritic breccia, poor in matrix, intercalated into Annaberg Dolomite (Annaberg Formation), showing different grey, angular dolostone clasts within a fine-grained interstitial matrix infill (location: forest road, passing the creek 'Kargraben', Pongau, Salzburg). **G** — Representative for the transitional beds between the Annaberg- and Steinalm Formation. Slightly light colored, dolomitized limestones with dolomitic intraclasts, oncoids and cortoids (location: type-locality in Annaberg, Lower Austria). **H** — Characteristic for the transitional beds between the Annaberg- and Steinalm Formation are "knife-cavity"-limestones ("Messerstichkalke"). The crystal moulds may indicate a hypersalinar depositional environment (location: Furth/ Triesting, Lower Austria).

types of facies of the Annaberg Formation clearly visible due to the fresh and unweathered outcrops (Fig. 11). The mainly medium- and planar bedded, dark grey, organic-rich limestones of this section (Fig. 6C) have proved to be similar to those of Annaberg (type-locality) and have shown a characteristic benthonic fauna, consisting of crinoids, small bivalves, gastropods, ostracods and foraminifers. Typically, these biota float in a dark grey, fine grained, organic-rich and slightly bioturbated carbonatic sediment (wacke-, pack- and grainstones; Fig. 10B,C). In addition, this section contains other facies elements which were not described as characteristic for the formation until now: single beds, containing small bivalve-coquinas (pavements) of storm surges (tempestites), intercalations of ooidal sand shoals and, finally, fine bedded crinoidal calcarenites. All together these sedimentary rocks within the Annaberg Formation indicate a rather shallow marine environment, positioned generally above the storm wave base. The so-called '*Messerstichkalk*' ("knife-cavity"-limestone), first named in this way by Schmidegg (1951, p. 166) in the region of the Karwendel-mountains in Tyrol and also, in this sense, described by Hagenguth et al. (1982, p. 168) and Moser et al. (2007, p. 337) in other regions, can also be clearly assigned to the depositional environment of the Annaberg Formation. The indication of temporary hypersaline depositional conditions (elongated "knife wounds" will correspond to dissolved evaporite crystals) is often observable within the transitional beds between the Annaberg and Steinalm Formations. Similar types of this '*Messerstichkalk*' are also findable within the so-called "*Further Kalk*" (see above), a cavernous limestone, which corresponds lithologically and microfacially entirely to the Annaberg Formation (Moser & Piros 2018, Fig. 6F). Ooid-bearing limestones or ooliths have also been described from the Annaberg Formation (Frisch 1968, p. 77, Moser & Tanzberger 2015, p. 238). Together with the subrounded micrite-intraclasts (plasticlasts) and little coquinas, the ooids indicate occasionally strong currents and agitated shallow marine seawater, whereas the plasticlasts will prove the process of resedimentation of unlithified micritic internal sediments caused by turbulent water flow as a result of singular tides and storms (Tucker & Wright 1990, p. 12). Other characteristic features of the Annaberg Formation are organic-rich limestones with single beds showing intense bioturbation ('*Wurstelkalk*', "vermicular limestone"; Fig. 10 D,E). The trace fossils may indicate an occasionally somewhat higher oxygen content of the seabed.

With the help of all these facies-types, the Annaberg Formation can be characterized also in other sections of the NCA. For instance, within the Upper Gutenstein Formation of mount Kasberg (1747 m, Upper Austria) thick bedded limestones can be found, which show the following microfacies types (Moser & Moshammer 2018, p. 44): (1) biomicrite and bioturbated micrite (wackestone), showing fine crinoid-fragments and small bivalves, (2) crinoidal packstones, containing bioclasts of brachiopods (Fig. 7A,B), (3) thin bedded biosparite (grainstone), consisting of crinoids, bivalves, gastropods, brachiopods and foraminifers and (4) tempestitic crinoid–brachiopod-packstone (Fig. 7 B).

Within the middle part of the NCA, in the area of the '*Werfen –St. Martiner Schuppenzone*' ("*Werfen–St. Martin Imbricate Structure*", Pongau, Salzburg), situated within the southern part of the Tirolic Nappe System in the federal state of Salzburg, completely dolomitized equivalents to the Annaberg Formation can be mentioned. These were firstly described by Rossner (1972, p. 11) as "*dark grey, massive dolomite*" and, later, by Brunner (2013) and Moser (2018) as '*Annaberg Dolomite*'. Here, the Annaberg Formation is developed as dark grey, bituminous, thin-, medium- or thick- and planar bedded dolomite (Fig. 6D), in which only few fossil remains such as crinoids (Fig. 7D) and occasionally small bivalve-shells (Fig. 7E) and gastropods prevail. Sedimentary structures such as fine bedding can also be observed (Fig. 7C). This sedimentary structure may be due to supply of fine crinoid-detritus. Fine lamination may also be used as an indicator of lack of bioturbation, caused by at times very hostile and anaerobic depositional conditions on the water/sediment interface. However, some beds can appear as intensively bioturbated micrite (grade of bioturbation 3, after Nichols 2009, p. 176), with burrow mottled carbonate enclosed in it (Fig. 10F). The big size of some of these burrows suggests temporarily relative high levels of oxygen in the seawater overlying the bituminous sediments (Savrda & Bottjer 2014). These traces and burrows can be determined as *Thalassinoides*, *Palaeophycus* and *Planolites* (writ. com. R. Hofmann, 2018). These are most likely grazing traces and feeding burrows of

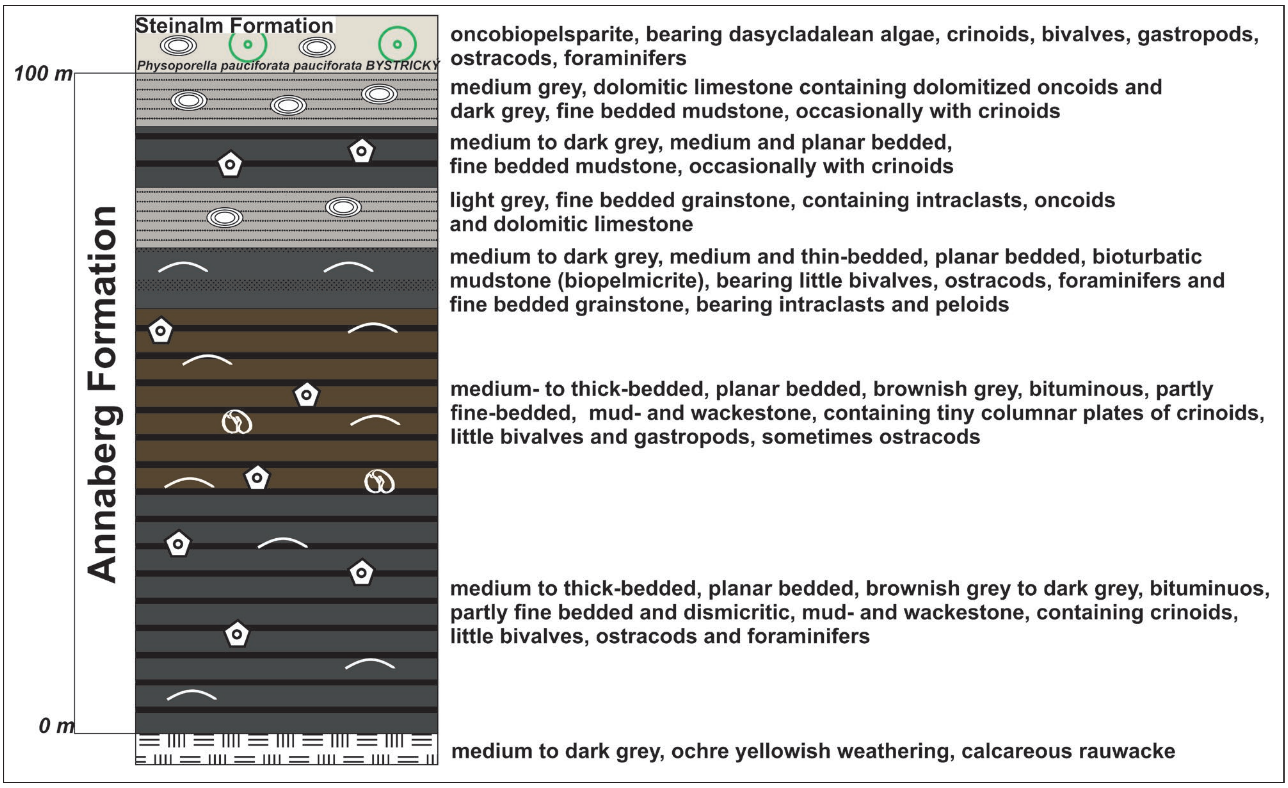

Fig. 8. Idealized columnar section through the Annaberg Formation at its type-locality, 3 km west of Annaberg (forest road 200 m north of the farm 'Spindelhof'): lower profile section (~70 m) showing microfacies characteristics of the Annaberg Formation, upper profile section (~30 m) showing the transitional beds between Annaberg and Steinalm Formation.

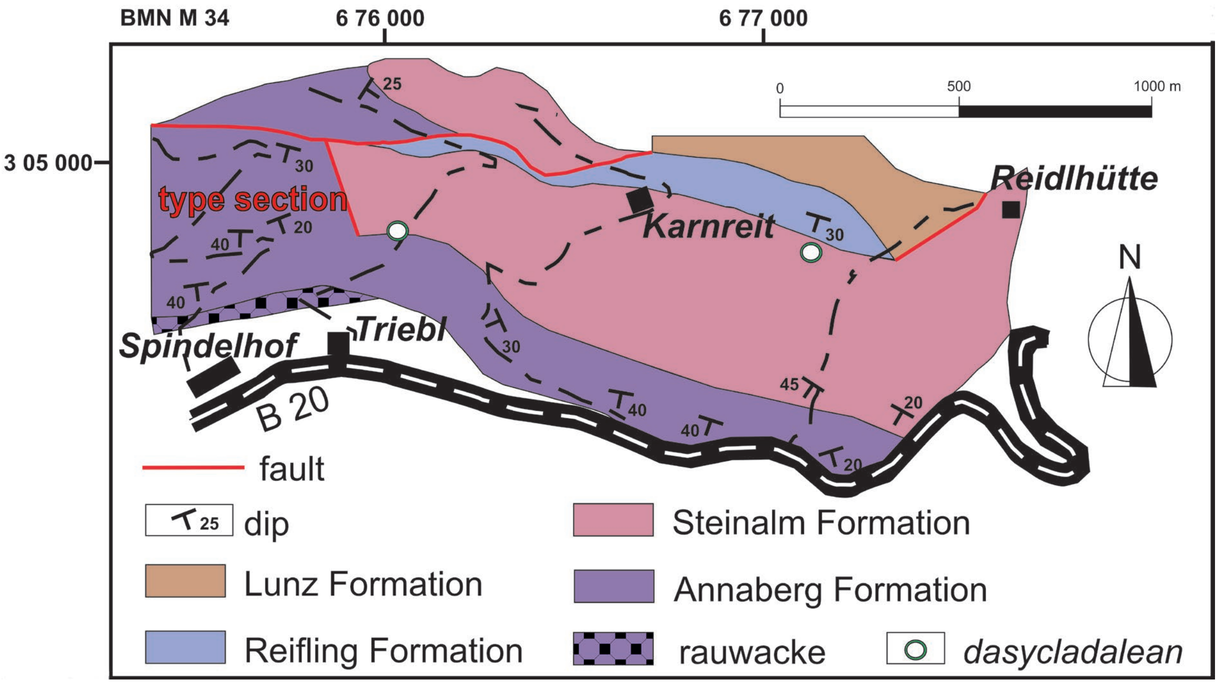

Fig. 9. Geological map, including the type-locality and type-section of the Annaberg Formation, situated about 3 kilometers west of Annaberg, Lower Austria (after Moser 2019).

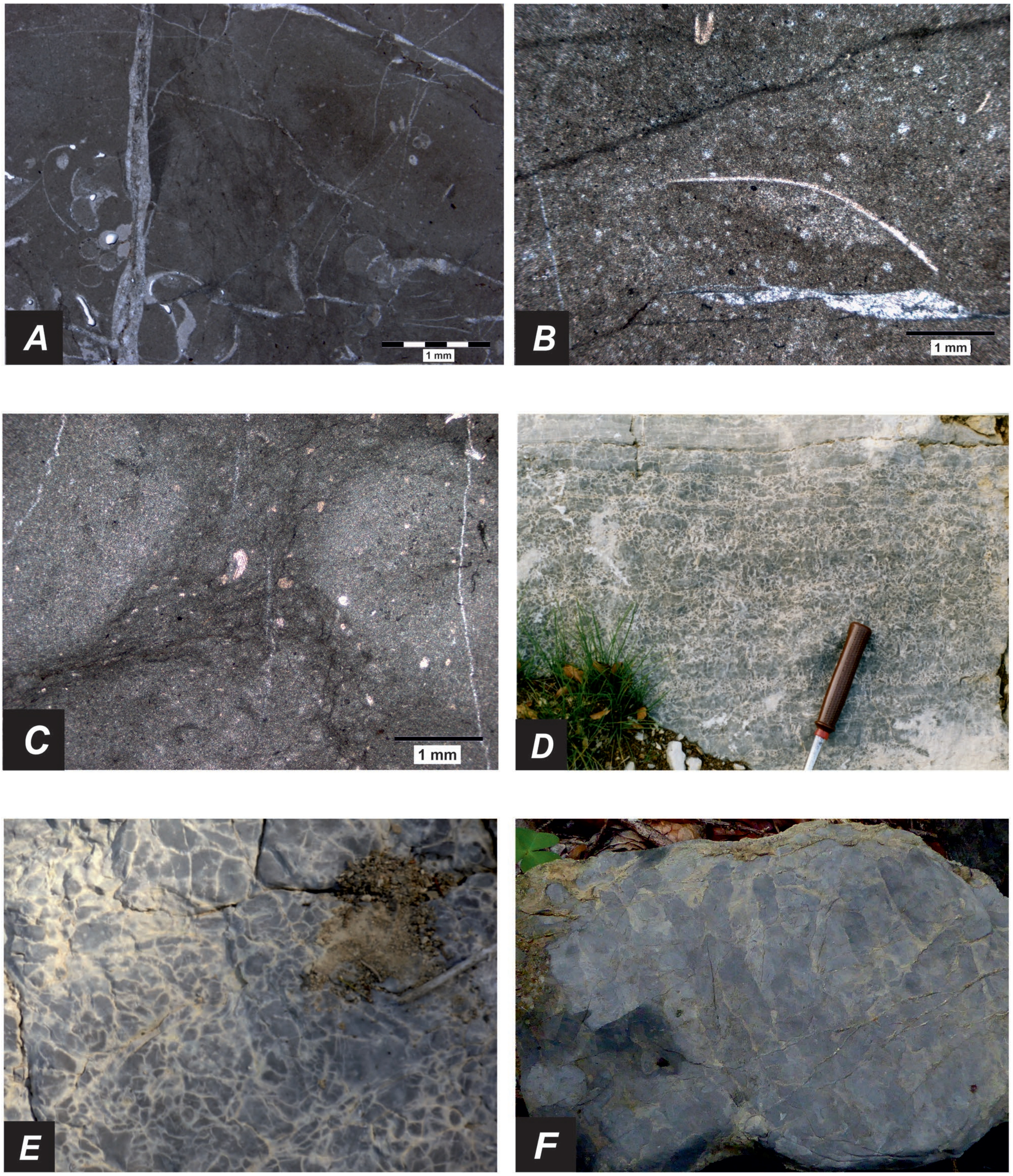

Fig. 10. Characteristic microfacies-types of the Annaberg Formation in thin sections. **A** — Microfacies of the Annaberg Formation at its type-locality 200 meters NW of farm 'Spindelhof' near Annaberg: dark grey biomicrite (wackestone), bearing fine crinoid litter, small bivalves and gastropods. **B** — Microfacies of the Annaberg Formation at the forest road of farm 'Mendlingbauer' up to mount Scheibenberg (1400 m, Lower Austria): Biopelmicrite with fine crinoid litter and thin bivalve shells. **C** — Dark grey mottled micrite with fine crinoid litter (same locality as B). Trace-fossils within the Annaberg Formation. **D** — Dark grey to black colored, thick bedded, disturbed micritic limestone ("Wurstelkalk", vermicular limestone), representing branched burrows of crustaceans (*Thalassinoides*). Location: Excavation at the forest road of farm 'Mendlingbauer' up to mount Scheibenberg (1400 m, Lower Austria). **E** — Dark grey to black colored, thick bedded, disturbed micritic limestone ("Wurstelkalk", vermicular limestone) at mount 'Hochstaff' (1305 m, Gutenstein Alps, Lower Austria). **F** — Dark grey disturbed micritic limestone, showing the trace-fossil *Thalassinoides*, besides little bivalves and gastropods occuring within the Annaberg Formation near the alpine meadow "Ostermaißalm", south of plateau-mountain 'Tennengebirge', Pongau, Salzburg.

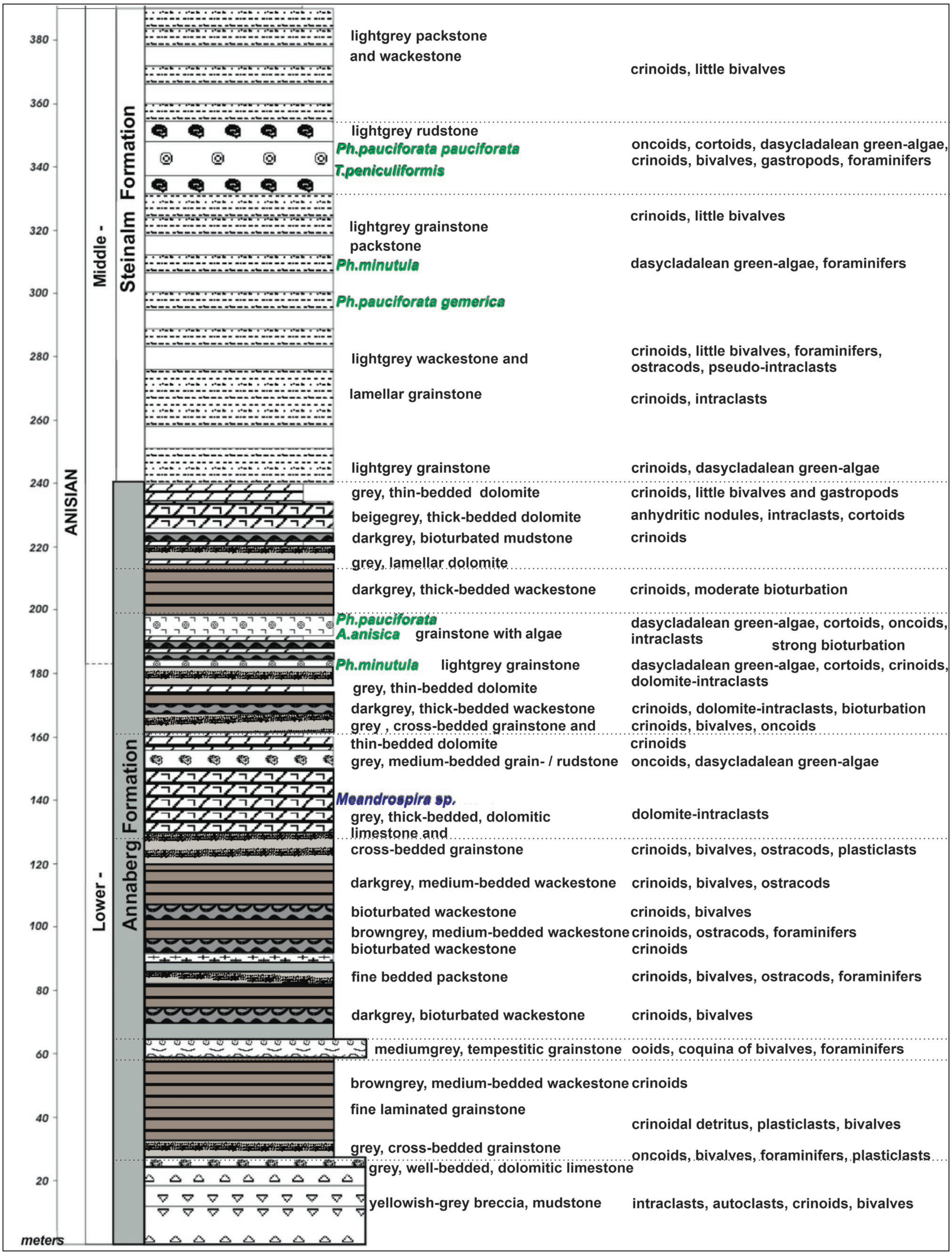

Fig. 11. Idealized columnar section (new reference section) through Annaberg- and Steinalm Formations at mount Scheibenberg, 1400 m (outcrops on forest road of farm 'Mendlingbauer', 800–900 m a.s.l., Lower Austria).

crabs that have lived in shallow water, namely in the deposition area below the fair-weather wave base in about 10 metres water depth. The facies of this special organic-rich, partly dysaerobic and hostile sediment of the Annaberg Formation is in accordance with the habitat of the quoted trace fossils, since these organisms were able to initiate a permanent connection to the overlying oxygen-bearing sea water through tubes and open passages and, additionally, were able to find enough organic material to feed within the sediment. Some layers also can show slump folding, which will confirm a gentle slope on top of the mid and inner carbonate-ramp deposits of the Annaberg Formation. From the microfacies point of view, the Annaberg Formation within the "*Werfen–St. Martin Imbricate-Structure*" may be described as mud-, wacke- and grainstone, showing most of the time fine crinoid ossicles (Fig. 7D). Thin dolomitic layers with less fossil content include dark grey mudstones with thin, dark grey marl layers intercalated between the bedding planes. In contrast, thick dolomitic layers are often developed as coarse-grained biodetritic pack- and grainstones with abundant crinoids, or even small bivalve shells, which were accumulated in tempestitic or tidal layers (Fig. 7E). Occasionally, coated grains can be observed within the (upper parts of) the Annaberg Dolomite, which emphasize the shallow-water character of most of these deposits (Fig. 7G). As a special lithofacies of the Annaberg Formation thick layers of sedimentary breccias (Fig. 7F) can be formed. These consist of matrix-poor intern-breccias, which contain various grey, edge or rounded, poor sorted, millimetre or decimetre-sized dolomite components, between which a fine grained and sandy matrix is developed in the interstices. The lithoclasts within thin breccia layers are formed less coarse than those of thick breccia banks. These occasionally and rarely intercalated breccias together with slump-structures within the Annaberg Formation could be an indication of a local distally steepened ramp configuration (Read 1982), although the homoclinal ramp morphology will be more common developed.

The Annaberg Formation has been described by Moser et al. (1994) from higher tectonic units, such as the Juvavic Mürzalpen Nappe. Here, Moser et al. (1994, p. 481) cite "*90-metres thick alternation of medium bedded, dark grey, Anisian Dolomites and Limestones, which often contain crinoids and bivalves and also show a fine-layered structure*". These rocks quickly change upwards into dasycladalean-bearing limestones of the Steinalm Formation, building up the stratigraphic basement of mount Riegerin (1939 m) and Hochtürnach (1770 m), both mountains placed on the northern edge of the Hochschwab-massif in Styria. Moser et al. (1994) further described pavements of little coquinas, which may have been formed by storm surges or tidal currents. Additionally, coarse sized monomict breccias, composed of dark limestone- and dolomite clasts, can be observed.

In terms of the exact chronostratigraphic age of the Annaberg Formation, its position below the overlying Pelsonian Steinalm Formation is of great importance. A gradual transition from the oxygen-depleted, dysaerobic, shallow marine, only temporarily agitated still-water facies of the Annaberg Formation, poor in fossils, into the up dip following oxygen-rich, higher-energetic, more diverse and fossil-rich, peritidal shallow-water facies of the Steinalm Formation, can be observed in the majority of all middle Anisian profile sections within the NCA. In the same way the Annaberg Formation itself should represent a gradual transitional succession from the anoxic facies of the Gutenstein Formation into the shallow marine inner carbonate ramp deposits of the Steinalm Formation ("*Annaberger Wende*" in Lein et al. 2010, p. 165, or "*carbonate ramp succession*" in Nichols 2009, p.239). Within the area of mount Ruhberg (634 m, near Furth/Triesting, Lower Austria), the overlying light grey coloured, oncoid- and dasycladalean green algae bearing lagoonal limestone facies of the Steinalm Formation occurs exactly on the south-eastern edge of this mountain ridge in the stratigraphic hanging wall of the Annaberg Limestone (not visible on the Geological map ÖK 75 Puchberg/Schneeberg, edited by Summesberger 1991). This position proves the exclusively middle Anisian age of the underlying Annaberg Formation (formerly designated as "Furth Limestone", see above), justified by the Anisian dasycladalean-flora included in the upwards appearing Steinalm Formation. Its fossil assemblage is composed of *Poncetella hexaster* (PIA) GÜVENÇ and the Anisian foraminifer *Endothyranella bicamerata* SALAJ 1967, inclusively. A Ladinian portion, as supposed by Hertweck (1961, p. 13) and Tollmann (1966, p. 121) on basis of an incorrect lithostratigraphic classification of the 'Steinwand'-cliff (4 km SE of Furth/Triesting) as Ladinian "*Wetterstein Limestone*" by Hertweck (1961, p. 16), would no longer be expected here. This misinterpretation was corrected later by Wessely (1984), who was able to describe middle Anisian fossils like *Meandrospira dinarica* KOCHANSKY and PANTIĆ and *Physoporella pauciforata pauciforata* BYSTRICKY from the same location 'Steinwand'-cliff (Hertweck 1961). So, Wessely (1984) was able to correctly attribute the 'Steinwand'-cliff to the Anisian Steinalm Formation exclusively.

The Annaberg Formation on mount Hochstaff (1305 m, Gutenstein Alps, Lower Austria) was first described by Moser (2014). Although an assignment of this tectonic outlier of the Reisalpen Nappe to the "*Muschelkalk*" (Bittner 1893) has been controversial in the past, the main part of mount Hochstaff can be referred as to be composed of the organic-rich, bioturbated vermicular limestone of the Annaberg Formation. Besides that, however, the lithologies of the Annaberg Formation on mount Hochstaff represent a peculiar facies development of (1) dark grey, thin- to medium bedded, vermicular limestone, containing crinoids and little bivalves, (2) middle- to dark grey, fine-grained, phacoidal and vermicular limestone, containing partly silicified trace fossils (e.g. *Thalassinoides*) with ochre-yellowish silt-layers, (3) medium-bedded, grey dolomite, (4) thin- and planar bedded, middle- to dark grey, dolomitic limestone with white calcite-veins, (5) middle- to dark grey, phacoidal limestone with marly and dolomitic layers, (6) thin, slaty, brown, middle- and olive green grey, partly dolomitic marl-layers, (7) thick-bedded and dark grey, coarse-grained crinoid-limestone and (8) dark grey calcareous breccias. Some of these differently developed beds resemble the lithologies of the Virgloria Formation at the western and of the NCA.

Recently, Gawlick et al. (2021) created two new members for the Annaberg Formation: the Sulzkogel- and Rabenkogel Members. Both lithostratigraphic units seem to be related to the Hallstatt Nappe, where a deepening event during the Latest Bithynian and Early Pelsonian led to the deposition of siliceous and cherty limestones and resediments up dip to the Steinalm Formation. These short-term intercalations of deeper-marine limestones at the level of the Annaberg Formation have led Gawlick et al. (2021) to define two members, each of them encompassing the whole Annaberg Formation. In this regard we want to highlight, that within the whole Bajuvaric and Tirolic Nappe System no particularly deep-water intercalation is developed in connection with the Annaberg Formation. Additionally, from our point of view, the Annaberg Formation does not represent a "*dark-grey, hemipelagic, organic-rich limestone*" (Lein et al. 2010, p. 165), so that the Sulzkogel- und Rabenkogel Member (sensu Gawlick et al. 2021) should be assigned (if mappable) to new formations of the Hallstatt Mélange, but not to members of the Annaberg Formation. In a practical way, a member should not comprise the whole range of a formation, but only a part of it (Salvador 2013, p. 34).

Interpretation of the sedimentary environment and sequence stratigraphy

The early and middle Anisian depositions within the NCA can be attributed to the sedimentary environment of a homoclinal carbonate ramp deposit (Lein et al. 2012). According to Tucker & Wright (1990, p. 47) a carbonate ramp can be described as a gently sloping surface with gradients of a few metres per kilometre, on which shallow-water carbonates pass gradually offshore into deeper water and, at last, deep subtidal sediments. The carbonate ramp can be dissected into an inner (back ramp), middle (shallow ramp) and outer (deep ramp) portion (Fig. 12). The distinctive sediments of the inner ramp deposits are carbonate sands, settled down in the agitated shallow subtidal shoreface zone above the fair-weather wave-base. The typical sediments there are lagoonal shoreline carbonate sand bodies. Considering the Steinalm Formation, grainstones (biopelsparites), rich in (dasycladalean) algae, coated grains, oncoids, pellets, bivalves, gastropods, crinoids, ostracods and foraminifers correspond to this shallow-marine environment of inner- and shallow ramp deposits (Fig. 12). Crinoid- (and brachiopod-) rich sand shoals will also occur along the outer edge of the mid-ramp deposits (Fig. 12). Due to the fact, that wave energy is not so intense as at the margin of a carbonate platform, less eroded biopelmicritic sediments will occur locally. These sediments will pass into fine-grained, organic-rich micritic sediments of the outside deep ramp deposits, poor in fossils and in oxygen. Here, slightly above the storm wave-base, organic-rich skeletal packstones and wackestones (with some crinoids and little bivalves) will dominate. Occasionally offshore storm surges will transport sediment and bioclasts into the deeper ramp areas. Hence, distal tempestite-banks, rich in shells of molluscs, sometimes with graded stratification and with erosive basis, can be intercalated. But also transported ooid-sand shoal can be seen, as well as cross-stratified carbonate-sand deposits (pack- and grainstones). The fine lamination, that can often be seen in the limestones of the Annaberg Formation, could be interpreted as fine-grained fair-weather deposits. Following Immenhauser (2009, p. 127), the intercalation of grainstone layers within muddy successions (wackestones), as it can be seen within the Annaberg Formation at its type-locality and other occurrences, points to a depositional environment below the fair-weather base but above the effective base of exceptional storms. After Tucker & Wright (1990, p. 107) the storm wave-base can be estimated to occur at 30–50 metres of water depth. Naturally, because of the complexity of the palaeogeographical and palaeoclimatic situation during the Anisian stage, no provable information exists concerning the depth of the storm wave base at this time and region, so that higher and lower values can also be

Facies model for the Annaberg Formation

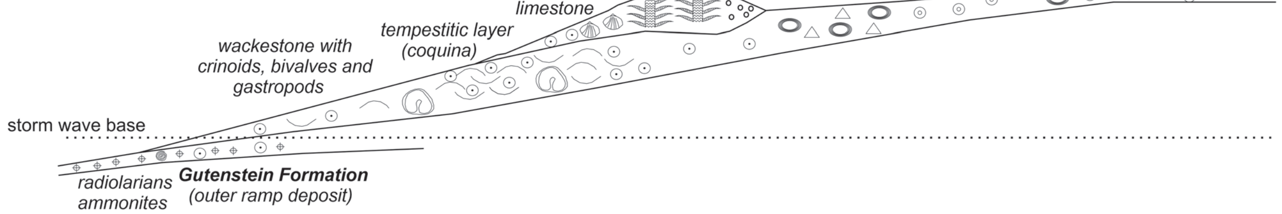

Fig. 12. Environmental transect from the Lower Gutenstein Formation up to the Annaberg and Steinalm Formations.

assumed. Nevertheless, the sedimentary environment of the Annaberg Formation will comprise approximately the water-depth between the littoral and neritic environment. Wright & Burchette (2016, p. 2) propose that storm events can general be regarded as important on mid ramp settings and their development in terms of sand shoals, skeletal and peloidal grainstones (crinoid- and peloid bearing limestones) and mollusc-rich pavements. Also, bioturbation within the mudstone-intervals, deposited between the storm-surges, can be considered typical for mid- and outer ramp deposits (Tucker & Wright 1990, p. 107).

From the sequence-stratigraphic point of view (Rüffer 1995, p. 128, 129), the facies of the late Bithynian/early Pelsonian part of the Gutenstein Formation seems to pass through a falling stage system tract (Haq 2018), which could correspond to the shallowing of the depositional area of the Annaberg Formation, reaching the resulting lowstand system tract during the sedimentation of the Middle Pelsonian peritidal Steinalm Formation. In connection with the environment of the Steinalm Formation, Rüffer (1995, p. 83) cites stromatolites and dasycladalean green algae as constituents of a homoclinal ramp deposit during a lowstand system tract. Rüffer (1995, p. 126–129) has connected this sequence stratigraphic unit with the regressive part of the sequence of third order A3, which should correlate with similar situated sequence-boundaries outside of the Alps (Goggin & Jacquin 1993; Knaust 1998). Recently, Gawlick et al. (2021, p. 439) address the evolution of the Early Pelsonian Annaberg Formation within the Juvavic Hallstatt Nappe to the progradation of the shallow-water carbonate system of the Steinalm carbonate ramp, which quickly filled the accommodation space that had existed since the Late Bithynian. On top, corresponding to the "*Reiflinger Wende*" (Schlager & Schöllnberger 1974), a transgressive trend, starting in the Late Pelsonian, can stated within all profile sections within the NCA.

On the other hand, in the case of the Anisian Muschelkalk formations of Germany, Poland and Spain, the whole lower and middle Anisian "Lower Muschelkalk Sequence" will be coincidentally represented by a transgressive succession of dolomites, evaporites, marly limestones, marls and limestones (Knaust 1998, p. 29), so that we can assume, that, because of these striking differences, the sedimentation within the Alpine sections can be thought more tectonically controlled during the same period.

Discussion

Considerations about the lithostratigraphic units/terms Annaberg Formation, Gutenstein Formation, Virgloria Formation and Steinalm Formation

In the eastern (and middle) sector of the NCA, various lithostratigraphic terms have been used regarding the dark limestones and dolomites of Anisian age. This, without respect to an exact sedimentology or microfacies founded differentiation between them. Thus, for many lithostratigraphic units of the Eastern Alps, the lithostratigraphic term "*Gutenstein Limestone*" and "*Gutenstein Dolomite*" has been used, to nominate all well bedded and dark grey coloured, calcareous or dolomitic rocks of Anisian age. The confusing use of the lithostratigraphic term "*Gutenstein Limestone*", employed in context with other lithologies of Middle Triassic rocks, suffered greatly from the misleading and inadequate first descriptions of this lithostratigraphic unit, also at its type locality, in Gutenstein (Summesberger 1965). On the other hand, the lithostratigraphic generalizing term "*Alpiner Muschelkalk*" (Gümbel 1860) was originally used to nominate all dark grey and massive limestones of probably Anisian age, all cherty and fossil bearing, bedded limestones of Anisian and Ladinian age inclusively. In contrast, with the help of index fossils like conodonts, ammonites, bivalves, dasycladalean green algae and foraminifers within microfacies studies and sequence stratigraphic models we can acquire a much more differentiated picture of all these rock types. In this sense, the lithostratigraphic term "*Gutenstein Limestone*", "*Gutenstein Dolomite*" or Gutenstein Formation (sensu Hauer 1853, p. 716) should be applied only and exclusively with respect to all *thin* and *planar* bedded, mostly fine grained (calcilutitic), sometimes fine laminated and rarely graded bedded, *black* coloured limestones and dolostones, poor in fossils and often showing small, spherical siliceous concretions ("*chert spheres*"). All these lithological parameters represent either a distal slightly steep outer carbonate ramp facies, enclosing predominantly pelagic, but also planktonic, benthonic and nectontic fossils like radiolarians, ammonites, conodontophorids and bivalves (Bechstädt & Mostler 1974, p. 15), or a shallow marine semi-restricted lagoonal deposit (Gawlick et al. 2021, p. 420). Considering the corresponding microfacies types, the limestones of the Gutenstein Formation can easily be distinguished from comparable Anisian rocks like the Virgloria Formation (Richthofen 1859) in the western NCA (Tyrol, Vorarlberg) and from the Annaberg Formation (Tollmann 1966) in the eastern NCA (Lower and Upper Austria). The Gutenstein Formation, as it was defined at its type-locality in Gutenstein, corresponds exclusively to the first 30 metres of the profile section presented in Flügel & Kirchmayer (1963, p. 113). All the other types of sedimentary rocks, described by Flügel & Kirchmayer (1963) in the stratigraphic hanging wall of the Gutenstein Formation *sensu stricto*, should rather be assigned to the shallow marine and algae bearing, peritidal facies of the Anisian (Pelsonian) Steinalm Formation and the upwards following Ladinian Wetterstein Dolomite Formation. In this sense, the rather shallow-marine depositional system of the Annaberg Formation (and Steinalm Formation) can clearly be distinguished from the Gutenstein Formation. The Annaberg Formation, which is characterized by a sublitorial facies of a gently inclined mid and inner carbonate ramp deposit, can be clearly delineated from all of the other Anisian rock formations on the basis of (1) its *thick* beds with varying thicknesses (Fig. 6D), (2) the frequent changes in grain size (mudstones, packstones, grainstones), (3) the mainly dark rock-colour,

(4) the fossil content with *crinoids* (as debris), *bivalves*, *gastropods* and brachiopods (Fig. 10A,B), (5) the lack of dasycladalean green algae and, sometimes, (6) a greater content of sedimentary structures like *fine stratification*, layers of *coquina*, oolites, *tempestites* and breccias (Fig. 7A–H).

Within the western part of the NCA, equivalents of the Annaberg Formation have been described for the first time by Sarnthein (1966, p. 41) under the work term "*Mittlere Serie des Alpinen Muschelkalks*" ("Middle Series of Alpine Muschelkalk") in the area of the mountain chain Nordkette (Karwendel, Tyrol). The herein listed "*crinoid-sands*", "*crinoid-horizons*" and "*crinoid–brachiopod–foraminifer biosparites and -micrites*" are facies counterparts to the sediments of the Annaberg Formation within the eastern part of the NCA (Fig. 7A,B). The biostratigraphic assignment of these bioarenites and biomicrites to the middle Anisian (Pelsonian) was proved by Mostler (1972, p. 7) with the help of conodonts. A detailed description of the "Middle Series of Alpine Muschelkalk" in some sections of the Lechtal- and Inntal Nappe between the rivers Lech and Isar in Tyrol and Bavaria is given by Frisch (1968). His account includes description of these series as bituminous, thick bedded or massive, medium to dark grey coloured, crinoid-, brachiopod- and bivalve-bearing biomicrites and biosparites (encrinites), closely comparable to the bioarenitic limestone-intercalations within the upper part of the Gutenstein Formation on mount Kasberg in Upper Austria (Moser & Moshammer 2018) and, also, to the Annaberg-type limestones in Lower Austria. Next, the Virgloria Formation, a well established lithostratigraphic term within the western NCA, presents some similarities to the lithofacies of the Annaberg Formation in Lower Austria. The term '*Virgloria Formation*' is of widespread use in the local stratigraphic literature of the provinces of Tyrol and Vorarlberg and dates back the first descriptions of Richthofen (1859). At its type-locality (the mountain pass Amatschonjoch and the gorge Virgloriatobel, both locations are situated in the Rätikon-mountains, Vorarlberg, Fig. 4), the Virgloria Formation is usually developed as thin- to medium-bedded, yellowish-ochre grey or dark grey coloured, fine grained, siliceous and argillaceous limestone with dolomitic intercalations, often showing intensive wavy-nodular bedding planes and only a few crinoids, bivalves, brachiopods and scattered plasticlasts as components (Kobel 1969). However, the Virgloria Formation is mainly characterized by its intensively disturbed and bioturbated intercalations of *vermicular limestones*, mostly ingested by *Thalassinoides* ("*Wurstelbänke*", firstly mentioned by Rothpletz 1888, p. 19, "*Wurstelkalke*" or "*Flaserkalke*", in Brandner 1972), as well as by its intercalations of bioarenitic horizons, ooidal limestones, oncoidal limestones, evaporitic "knife-cavity"-limestones ("*Messerstichkalke*"), stromatolitic limestones and massive, beige grey coloured, peritidal dolomites, showing LF-fabrics (Kobel 1969, p. 36, 37; Bechstädt & Mostler 1974, p. 18). Gruber (2016, p. 305) claims that "*Virgloria and Annaberg Formations can be subsumed together almost into one stratigraphic unit*" by calling calcarenites and crinoidal limestone beds as to be typical for the Annaberg Formation also within the area of the Nordkette-mountain chain (Karwendel, Tyrol, western NCA). Despite these similarities, we assume that some lithological and microfacies differences between the Annaberg and Virgloria Formations will still exist. Additionally, Bechstädt & Mostler (1974, p. 17, 18) noted that within the western NCA of the provinces of Tyrol and Vorarlberg the facies of the Gutenstein Formation of early and middle Anisian age should not be developed, since the thin bedded black limestones of the Gutenstein Formation, which often bear some radiolarians, sponge-needles, ammonites and conodontophorids do not occur within the western portion of the NCA. Instead of it, the thick- and intensive wavy bedded limestones of the Virgloria Formation occur, which occasionally contain some biota like crinoids, gastropods, brachiopods, dasycladalean green algae and foraminifers. Hence, all the Anisian lithotypes, described by Nittel (2006, p. 97*f*) from the Nordkette mountain-chain north of Innsbruck (Karwendel), encompass the entire range of lithological variability of the shallow marine Steinalm, Virgloria and Annaberg Formations as described above. That the Anisian depositional area becomes shallower to the west would be consistent with the position of the western NCA closer to the hinterland (e.g. siliciclastic influence from the Vindelicic continent in the early Anisian). Following Kobel (1969, p. 47), we can characterize the thin- to medium bedded limestones of the Virgloria Formation as a "*deposition of a shallow sea, positioned within the tidal range*", similar to the depositional environment of the Annaberg Formation. However, some lithological characteristics of the Virgloria Formation, as described by Kobel (1969, p. 49), differ from that of the Annaberg Formation in terms of its predominantly *bulky-nodular* and *wavy* bedding planes, its thin *clay* and *marl-coatings*, its *siliceous* character and its dominant composition of vermicular limestones ("Wurstelkalke", grade of bioturbation 4, after Nichols 2009, p. 176). Hence the lithostratigraphic term 'Virgloria Formation', as it was erected by Richthofen (1859), can just be opposed to the lithostratigraphic term 'Annaberg Formation' as defined here. The term Virgloria Formation is also listed in the "Stratigraphic Table of Austria" (Piller et al. 2004), but is restricted there to the Bajuvaric Nappe System, the western part of NCA and the Drauzug region in Carinthia. On the other hand, the lithostratigraphic term Annaberg Formation can be used within all three nappe systems of the eastern NCA (Bajuvaric, Tirolic and Juvavic Nappe System). Both, the Annaberg Formation and Virgloria Formation, as defined herein, can clearly be differentiated microfacially and chronostratigraphically from the Gutenstein Formation, the Steinalm Formation and Reifling Formation. The Annaberg Formation can be distinguished from the Virgloria Formation due to its on average *larger bank* thicknesses, its mainly *planar* bedding planes *without clay* coatings on the bedding planes and its lower content in bioturbation (grade of bioturbation 2, after Nichols 2009, p. 176). These differences may indicate slightly greater depth of deposition in the sedimentary environment of the Virgloria Formation. The wide lithofacies similarity of the Virgloria

Formation to the Upper Gutenstein Formation within the Kasberg area (Moser & Moshammer 2018, p. 44), showing thin and thick beds with wavy-nodular bedding-planes and thin clay and marl coatings, is also noticeable. In turn, the microfacies, biofacies, lithology and chronology of the Annaberg Formation is believed to be more related to the sedimentary environment of the Steinalm Formation and, thus, comes to be deposited in some more shallow marine, nearly peritidal depositional environment.

In any case, the Annaberg Formation, with its total thicknesses of 100–200 metres, seems to be large enough to represent it in all scales as a clearly mappable lithostratigraphic unit. The Annaberg Formation may also be easy to distinguish from the stratiform underlying thin bedded Gutenstein Formation and, also from the upwards following light grey coloured and algae-bearing Steinalm Formation. Similar arguments for the definition of the Annaberg Formation can be found in Lein et al. (2012, p. 476–477). The following lithological and facial characteristics enable us to clearly distinguish the Steinalm Formation from the Annaberg Formation: the Steinalm Formation shows for the most part a *light grey* rock-colour, is recognizable by a multitude of fossils like *different algae* (dasycladalean algae, cyanobacteria in stromatolites, loferites and oncoids), molluscs (bivalves and gastropods) and foraminifers (particularly of the genus *Meandrospira* sp., *Endothyranella* sp., *Glomospirella* sp.) with increasing diversity. Additionally, the Steinalm Formation shows a higher content of coated grains (oncoids) and bears a somewhat better out-washed matrix.

Exactly the same microfacies elements of the Steinalm Formation have been described by Piros (2002) within the Inner Western Carpathians and, therefore, are valid beyond the Alpine region. The depositional area of the Steinalm Formation can be placed within an inner ramp sector, where the activity of algae and bacteria (like calcareous algae, epi- and endolithic algae, bacteria and sponges), mostly bound to photosynthesis, allow a maximal depositional depth of up to 20 metres. The transition from the underlying Annaberg Formation to the upward following Steinalm Formation can observed at many locations within the NCA, but also within the Western Carpathians (Mahel 1979, p. 18; Piros 2002, p. 125; Hips 2007, p. 100). The descriptions of Hips (2007, p. 100) confirm, that equivalents to the alpine Annaberg Formation will exist also in the Inner Western Carpathians. The lithological descriptions as well as the fossil-content of "*thin bivalve shells, micro-gastropods, echinoderm-fragments, ostracods and worms*" mentioned by her, correspond entirely to our descriptions above. The microfacies descriptions of "*burrow-mottled mudstones*", "*bivalve coquina layers*", "*slump structures*", "*evaporite crystal molds*" and "*detrital carbonate silt*" given by her, correspond very well to our observations within the Eastern Alps. In a similar way we will assume, that the microfacies descriptions of the Vysoká Formation (Malé Karpaty), given by Michalík et al. (1992) and Michalík (1997), which encompass tempestitic shallow marine inner ramp deposits, will correspond in its main part rather to the microfacies of the middle Anisian Annaberg and Steinalm Formations then to those of the lower Anisian Gutenstein Formation, as proposed by Andrusov (1959) before. In addition, we suggest, that the "Gutenstein Formation" (sensu Roth 1939) within the area of the Aggtelek-mountains in Northern Hungary, will correspond in the same way to the alpine Annaberg Formation, because of its medium bedding (10–50 cm), dark grey rock-colour and its low-energetic, shallow-marine, restricted lagoonal depositional environment (Piros 2002, p. 124).

Finally, it seems to be remarkable, that the biogenic and clastic content of the storm-influenced limestones of 'Muschelkalk carbonates' in the Betic Cordillera of Southern Spain (Pérez-López & Pérez-Valera 2012, p. 654) corresponds entirely to that of the Annaberg Formation in Lower Austria.

Conclusion

Formal definition of the Annaberg Formation

1966: Annaberger Kalk, Tollmann (1966)
1966: Annaberger Dolomit, Tollmann (1966)
1966: Further Kalk, Tollmann (1966)

Type area: Türnitz Alps, between Türnitz (Lower Austria) and Mariazell (Styria); ÖK 50/sheet 73 Türnitz and 50/sheet 72 Mariazell; UTM 4205 St. Aegyd am Neuwalde and UTM 4204 Gaming.

Type-section: Creek and forest road approx. 200 metres NW of the farm Spindelhof (3 km west of Annaberg, Lower Austria).

Reference section: Outcrops along the road on both sides of the 'Lassing gorge', E of 'Innere Schmelz' (1.5 km south of Annaberg, Lower Austria).

New reference section: Outcrops along the forest road of the farm 'Mendlingbauer' up to mount Scheibenberg, 1.3 km south-west of Lassing, Lower Austria.

Coordinates: Type-section Spindelhof: BMN M 34: 6 75 534/ 3 04 633 or WGS 84: 47°52'33"/15°20'12".

Reference section 'Innere Schmelz': BMN M 34: 6 78 293/ 3 02 580 or WGS 84: 47°51'28"/15°22'26"

New reference section 'Mendlingbauer'-forest road: BMN M 34: 6 40 803/2 90 061 or WGS 84: 47°44'24"/14°52'34".

Name: The village of Annaberg in Lower Austria, district Lilienfeld.

Synonyms: Annaberger Kalk (Tollmann 1966, p. 118), Annaberger Dolomit (Tollmann 1966, p. 114), Further Kalk (Tollmann 1966, p. 120), Alpiner Muschelkalk (Stur 1871, p. 215), Muschelkalk (Hauer 1853, p. 722), Anisische Kalke und Dolomite (Plöchinger 1955, p. 96), dunkelgrauer Massendolomit und Massenkalk (Rossner 1972, p. 11), Mittlere Gesteinsserie des Alpinen Muschelkalkes (Sarnthein 1966, p. 41).

Lithology: Medium to thick-bedded, sometimes thin-bedded, dark grey to brownish grey, rarely medium grey, mostly bituminous, fine grained, often also fine bedded and planar bedded limestone, which occasionally can bear some crinoids and small bivalves. Subordinately developed are bioclastic limestones, rich in crinoids and brachiopods, tempestitic limestones with accumulations of small bivalves and gastropods, oolitic limestones, bioturbated limestones (vermicular limestone, containing *Thalassionoides*), crinoid-brachiopod limestones and monomictic breccias.

Lithostratigraphic superunit: "Alpiner Muschelkalk-Gruppe".

Lithostratigraphic subdivision: –

Chronostratigraphy: Early to middle Anisian (Bithynian–Pelsonian).

Biostratigraphy: *Dadocrinus gracilis* Buch, *Rhynchonella decurtata* Gir., *Coenothyris vulgaris* Schlotheim, *Mentzelia mentzeli* Buch, *Spirigera trigonella* Schlotheim, *Anisoporella anisica* Ott, *Physoporella pauciforata pauciforata* Bystrický, *Meandrospira dinarica* Kochansky-Devidé, *Meandrospira deformata* Salaj, *Glomospira densa* Pantić, *Pilaminella grandis* Salaj.

Facies: Restricted shallow-marine middle and inner carbonate ramp succession of the lower sublittoral up to the subtidal with limited water circulation, but occasionally with intercalations of storm-generated shell deposits (tempestites), crinoidal bioclastic limestones (encrinites), rarely sandbars like ooidal sand shoals and dolomitic limestones with coated grains and "knife-cavity-limestones". Depositional depth: 50–5 metres.

Thickness: 100–200 metres.

Underlying unit: Gutenstein Formation, Virgloria Formation, Reichenhall Formation.

Lower boundary: With the first appearance of medium- to thick bedded, dark grey, planar bedded limestones or bioclastic limestones, crinoidal limestones.

Overlying unit: Steinalm Formation, Reifling Formation.

Upper boundary: Gradual transition (with facies recurrences, interbedding) into the upward following Steinalm Formation, which is characterized by light grey, algae and oncoid bearing beds; frequently observed within the transitional beds between Annaberg and Steinalm Formations are "knife-cavity-limestones" ("Messerstichkalke"), cortoids, dolomitic intraclasts and dolomitized oncoidal limestones.

Regional distribution: Characteristically, the Annaberg Formation is regularly developed on the bottom side of the Steinalm Formation, as a transitional facies ranging from the outer ramp deposits of the Gutenstein or Virgloria Formation until the peritidal and lagoonal inner ramp deposit of the Steinalm Formation; the Annaberg Formation is found in all tectonic units of the NCA, but its characteristic features particularly bind it to the Bajuvaric Nappe-System.

Laterally bordering units: Gutenstein Formation, Virgloria Formation, Steinalm Formation, which can also interlock with the Annaberg Formation.

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