AGE AND CORRELATION OF THE MIDDLE ORDOVICIAN BENTONITES ON BORNHOLM

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A restudy of fossils from the lowermost part of the *Dicellograptus* Shale on Bornholm shows that they provide no reliable evidence that the lowermost part of the bentonite-bearing succession in that unit, including the thickest bentonite bed, belongs in the *Nemagraptus gracilis* Zone. Comparison with Scanian successions in the Fågelsång area and at Tommarp indicates that this portion of the *Dicellograptus* Shale on Bornholm is more probably coeval with a part of the *Diplograptus multidens* Zone. Regional comparisons between the bentonite-bed successions of the Fågelsång area, Kinnekulle, and the Sinsen section in Norway suggest that at least some bentonite beds can be traced over very long distances in southern Baltoscandia.

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The presence of light-coloured clays in the Middle Ordovician part of the *Dicellograptus* Shale on the Island of Bornholm has been known since at least the later part of the 19th century (Tullberg, 1882), but these beds attracted little, if any, interest until their bentonitic nature was recognised some 60 years later (Thorslund, 1945). During the 1940's the geology and mineralogy of these strata were the subject of several studies and some debate (Bøgvad, 1947a, 1947b; Thorslund, 1947a, 1947b; Gry, 1948), but since Gry's (1948) detailed description, virtually no new data on these deposits have been published.

It is reasonable to assume that an individual bentonite bed was deposited during a relatively short period of volcanic activity and, accordingly, if such a bed can be traced with a satisfactory degree of certainty from section to section, it should theoretically provide an ideal reference level for precise stratigraphic correlations. A considerable amount of work has been done on the use of bentonite beds as index horizons in stratigraphy, especially in the Middle Ordovician (see, for instance, Kay, 1935; Rosenkrans, 1936; Fox and Grant, 1944; Miller and Fuller, 1954; Templeton and Willman, 1963; Thompson, 1963; Mossler and Hayes, 1966; and Drahovzal and Neathery, 1971) and Devonian (see, for instance, Dennison and Textoris, 1968; and Dennison, 1969) of eastern and central North America, and it has proved possible to trace some bentonite beds over very large areas.

Also in Baltoscandia, the discovery of the bentonitic nature of a large number of clay beds in the Middle Ordovician stimulated investigations of their potential value for local and regional correlations (Thorslund, 1948, 1958; Jaanusson & Martna, 1948; Hagemann and Spjeldnaes, 1955; Skoglund, 1963; Jaanusson, 1964; Männil, 1966, etc.). Although attempts were made to trace individual bentonite beds some 300 km from the Oslo region in Norway to Kinnekulle in southwestern Sweden (Hagemann & Spjeldnaes, 1955), many geologists have remained somewhat skeptical about the possibility of recognising and safely identifying especially the thin bentonite beds over large distances in Baltoscandia. This may be due at least partially to the fact that practically all of the Baltoscandic Middle Ordovician bentonite beds are less than 0.2 m thick and more or less impersistent in their occurrence in sections of dominantly calcareous rocks. However, one bentonite bed in the bentonite-bed complex tends to be much thicker than the others (up to 1.8 metres) and to be present regularly at the expected stratigraphic level from section to section. This bed, the so-called "Big Bentonite Bed", has been used to some extent for correlation within Sweden (Jaanusson, 1964; Skoglund, 1963; Thorslund, 1948, 1958) and a presumably equivalent bentonite bed is widely distributed also in the East Baltic area (see, for instance, Männil, 1966).

Recent work in the Fågelsång area in Scania has proved that the portion of the Middle Ordovician bentonite-bed complex that includes the "Big Bentonite Bed" occupies a stratigraphic position well up in the *Diplograptus multidens* Zone (Nilsson, in preparation). The Middle Ordovician bentonite-bed complex on Bornholm has until now been considered to be within the *Nemagraptus gracilis* Zone (Gry, 1948), also in the most recent detailed review of the Ordovician of that island (V. Poulsen, 1966). In order to clarify, if possible, this apparent age anomaly we have re-examined the evidence for the biostratigraphic age of the Middle Ordovician bentonite-bed complex on Bornholm and the relations between that complex and the ones in some other parts of Baltoscandia. We also nursed the hope that such a study might contribute data of importance for the evaluation of the regional chronostratigraphic significance of individual bentonite beds in the Middle Ordovician succession of this part of northwestern Europe.

Stratigraphic setting of the Ordovician bentonites on Bornholm

In his detailed paper on the Middle Ordovician bentonites on Bornholm, Gry (1948) described bentonite beds in the *Dicellograptus* Shale from four borings and two surface sections, all on the southern part of the island. In all, Gry (1948) reported 12 separate bentonite beds, the most prominent of which – 0.75 m thick – is in the basal two metres of the *Dicellograptus* Shale. No determinable fossils were listed from the borings and Gry (1948, fig. 1) based his stratigraphic classification of the drilled sections on lithologic comparisons with the available surface sections, especially that along the rivulet Læså near Vasagård. There, as well as in the borings, the

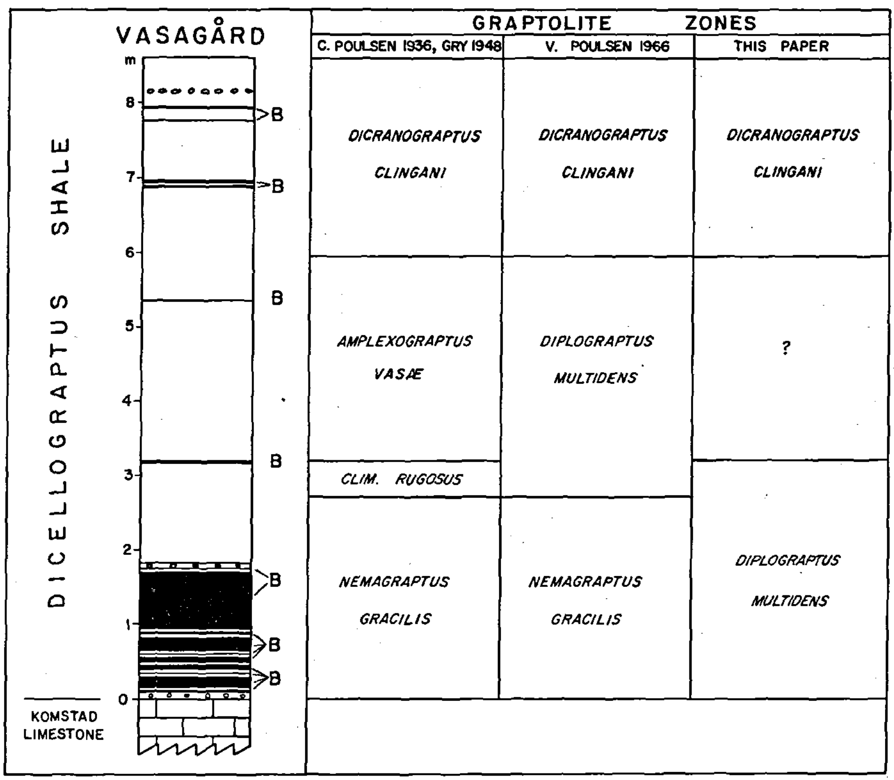


Fig. 1. The bentonite-bearing *Dicellograptus* Shale sequence near Vasagård on southern Bornholm according to Funkquist (1919) and Gry (1948) and a comparison of three interpretations of the local succession of graptolite zones. The stratigraphic interval previously recognized as the *Amplexograptus vasae* Zone has so far yielded no graptolites useful for evaluation of its precise age in terms of standard graptolite zones but bentonite bed correlations (see fig. 3 below) suggest that at least part of that interval is equivalent to strata of the *Dicranograptus clingani* Zone in the Fågelsång area. B denotes bed of bentonitic rock.

bentonite beds occur in a very condensed sequence of dark to grey shales without limestone intercalations, which is separated from the subjacent Lower Ordovician limestone succession by a thin phosphoritic conglomerate. The bentonite-bearing section at Læså is illustrated diagrammatically in fig. 1.

Fossils are not very abundant in the *Dicellograptus* Shale on Bornholm although graptolites and inarticulate brachiopods are relatively common in some intervals in its upper part (Hadding, 1915a; C. Poulsen, 1936). The lowermost few meters of the shale sequence, which includes the critical part of the bentonite bed complex, have yielded few megafossils, which may be partly due to poor exposures. However, the fossils found are important because they are the basis for referring this portion of the *Dicellograptus* Shale to the *Nemagraptus gracilis* Zone (C. Poulsen, 1936; V. Poulsen, 1966). Through the courtesy of the authorities at the Mineralogisk Museum in Copenhagen, we have had the opportunity to study the available specimens and to make some preparations that have revealed diagnostic characters which were previously more or less covered by the shale matrix. The identification of these specimens has also been greatly facilitated by direct comparisons with specimens in very large collections of especially graptolites made by Hadding and Nilsson from the *Nemagraptus gracilis* and *Diplograptus multidens* Zones in the Fågelsång area. On the basis of our re-examination of the fossil collection available, we feel that the following megafossil species are represented in the lowermost *Dicellograptus* Shale on Bornholm:

Orthograptus truncatus aff. *intermedius* Elles and Wood

Collected from »Læsaa S. f. Hullegaard. Lok. B« by C. Poulsen 1924. Some preparation of the specimens previously listed as *Diplograptus toernquisti* Hadding (C. Poulsen, 1936) revealed details indicating that these specimens do not represent Hadding's species but rather a form close to, if not identical with, *O. truncatus intermedius.*

Climacograptus cf. *brevis* Elles and Wood

Collected from the same locality as the above. These specimens have previously been listed as *Climacograptus* cf. *putillus* (Hall) (C. Poulsen, 1936).

Pseudoclimacograptus scharenbergi (Lapworth)

Some specimens collected from the same locality as above; also four collections from »Soldatergaard« marked 1871–1036. All these specimens were previously listed as *Climacograptus scharenbergi* (C. Poulsen, 1936).

»*Lingula*« *magna* Hadding

Collected from »Læsaa S. f. Hullegaard. Lok, B« by C. Poulsen 1924. This form was previously listed as *Lingula dicellograptorum* Hadding (C. Poulsen, 1936).

Onniella sp.

Collected at »Soldatergaards Brud«; several specimens numbered 1871–1035 and 1869–1473. These specimens were previously listed as *Orthis argentea* Hisinger (C. Poulsen, 1936).

In all previous discussions about the age of the lowermost part of the *Dicellograptus* Shale on Bornholm, the occurrence of the specimens identified as *Diplograptus toernquisti* has, with justification, been taken to indicate that this part of the Bornholm shale succession belongs in the *Nemagraptus gracilis* Zone (see, for instance, C. Poulsen, 1936). The fact that the specimens previously referred to *D. toernquisti* should be grouped with *O. truncatus* removes the principal evidence for the presence of the *Nemagraptus gracilis* Zone in the very lowermost part of the *Dicellograptus* Shale on Bornholm. Unfortunately, none of the species listed above is very diagnostic of a particular graptolite zone although it should be noted that such species assemblages are a good deal more common in the *Diplograptus multidens* Zone than in other strata in the Fågelsång area in Scania. Indeed, representatives of *O. truncatus intermedius,* as well as of other *O. truncatus* forms, are unknown in *Nemagraptus gracilis* Zone strata in the Fågelsång succession (Nilsson, 1960) or in Great Britain (Elles & Wood, 1901–18, table A).

Through the friendly cooperation of Dr. Sven Laufeld, Lund University, a small sample of one of the slabs with *Climacograptus* cf. *brevis* was dissolved for chitinozoans. According to Laufeld (written communication 1972), who plans to describe the material in a future publication, the sample proved to contain specimens of, among others, *Desmochitina juglandiformis* Laufeld, *D. lata* Schallreuter, and *Spinachitina multiradiata* (Eisenack). This chitinozoan assemblage is quite characteristic of the Skagen Limestone (see Laufeld, 1967, fig. 6), that is, strata immediately above the "Big Bentonite Bed" in Sweden. The lithology of the shale sample studied is rather unusual but fits the description of the major portion of unit 7 of Funkquist's (1919, p. 30) section, more specifically strata 0.2 to 0.8 m above the "Big Bentonite Bed". The graptolite zone equivalent of the Skagen Limestone (including the Scanian *Lonchodomas rostratus* Zone) has been uncertain up to now but the chitinozoan and graptolite data from Bornholm indicate that at least a part of this unit is coeval with the *Diplograptus multidens* Zone. The chitinozoan evidence that the beds right above the "Big Bentonite Bed" at Vasagård are of the same age as strata above the "Big Bentonite Bed" in sections in south-central Sweden, and evidently are no older than the uppermost portion of the *Diplograptus multidens* Zone, clearly supports the idea that the lowermost part of the Dicellograptus Shale in Bornholm belongs to this graptolite zone in its entirety. This is also indicated by the occurrence of specimens of *Conochitina suecica* Laufeld and *Desmochitina rugosa* Eisenack in a sample from beds 2–3 in Funkquist's well section at Vasagård (Funkquist, 1919, p. 31). This sample, which was collected by Funkquist himself and is preserved at the Palaeontological Institute at Lund University along with Funkquist's other Vasagård samples, originates from the very lowermost part of the *Dicellograptus* Shale immediately above the basal phosphorite conglomerate. Although not restricted to a very thin stratigraphic interval, both the chitinozoan species just mentioned are characteristic of the middle and upper part of the Dalby Limestone (Laufeld, 1967, fig. 6), that is, an interval generally correlated with a portion of the *D. multidens* Zone (see, for instance, Bergström, 1971, figs. 4–5). Hence as far as both the megafossils and microfossils are concerned, we may conclude that there is currently no diagnostic evidence that the lowermost part of the *Dicellograptus* Shale on Bornholm represents the *Nemagraptus gracilis* Zone; the available faunal evidence strongly suggests that it rather belongs in the *Diplograptus multidens* Zone.

Comparison with the succession in Scania

Some 50 to 150 km northwest of Vasagård, strata equivalent to the Bornholm *Dicellograptus* Shale are present in several areas in Scania. At the present time, this stratigraphic interval is best exposed at Fågelsång and Röstånga in the west-central part of the province where it is referred to as the *Dicellograptus* Shale. The *Dicellograptus* Shale at Röstånga has not been the subject of the modern investigations it deserves, and the classical reports by Olin (1906) and Hadding (1913, 1915b), although still useful, are now more than 50 years old. By contrast, the Fågelsång succession has received a considerable amount of study during recent decades (Hede, 1951; Lindström, 1953; Nilsson, 1953, 1960; Glimberg, 1952, 1961) and it is now by far the best known section through the *Dicellograptus* Shale in Scania.

The Middle Ordovician portion of the *Dicellograptus* Shale in the Fågelsång area, which attains a thickness of 49.8 m, is developed dominantly as shales and mudstones, and the few beds and nodules of limestone present in some parts of the unit are of insignificant thickness. Many of the shales, especially the dark fissile ones in the *Glyptograptus teretiusculus* and *Nemagraptus gracilis* Zones, contain few fossils other than graptolites, chitinozoans, conodonts, and inarticulate brachiopods (Hadding, 1913; Hede, 1951; Nilsson, 1960) but some of the more light-coloured shales and mudstones, particularly those in the upper half of the *Diplograptus multidens* Zone, have yielded a variety of shelly fossils (Lindström, 1953; Nilsson, in preparation). The very detailed work carried out on graptolites from the *Dicellograptus* Shale has made the unit one of the best known Middle Ordovician graptolite successions in the world. Accordingly, it seems most appropriate to regard this sequence as a reference standard for the Middle Ordovician graptolite zonal succession not only in Scania but in the whole Baltoscandic area.

Most surface exposures in the Fågelsång area are relatively small but virtually all of the *Glyptograptus teretiusculus* and *Nemagraptus gracilis* Zones are well exposed (fig. 2). Only minor portions of the *Diplograptus multidens* and the *Dicranograptus clingani* Zones are currently available for study in surface sections, and the exact mutual relations between some of these sections are still in doubt because there are faults in the area. Fortunately, two overlapping drilling cores – the Fågelsång core and the Koängen core – provide a complete section through the *Dicellograptus* Shale. These and other Fågelsång sections, with ranges of faunal zones according to Hede (1951) and Nilsson (1960, and in preparation), are illustrated diagrammatically in fig. 2.

One of the more interesting results of the examination of the Koängen core was the discovery of numerous bentonite beds through practically all of the *Dicellograptus* Shale (table 1). A few bentonite beds were previously known from surface exposures of strata of the *Nemagraptus gracilis, Diplograptus multidens,* and *Dicranograptus clingani* Zones (see, for instance, Lindström, 1953 and Regnéll, 1960) but the general distribution of bentonites through the *Dicellograptus* Shale was unknown prior to study of the Koängen core (Nilsson, 1960, and in preparation). This recent study has shown that the *Dicellograptus* Shale of the Fågelsång area contains more bentonite beds than any other currently known upper Middle Ordovician section in Europe, if not in the world. A partial explanation of this may be that the striking colour difference between the greyish bentonite beds and the dominantly dark shales makes it easy to identify even very thin bentonite beds. However, of even greater significance is probably that these deposits were apparently laid down in an environment with little, if any, water turbulence that elsewhere may have prevented the preservation of a reasonably complete record of the local ash falls. As long as the geographic location of the source volcanoes remains unknown, it cannot, of course, be entirely ruled out that the abundance of bentonite beds in the Fågelsång area also reflects a greater proximity to the source area compared to bentonite-bearing successions in other regions of Baltoscandia; however, this idea is difficult to harmonize with the generally postulated (but still unproved) location of a source area somewhere in the Caledonian geosyncline (Thorslund, 1947; Hagemann and Spjeldnaes, 1955) or in the area of the present North Sea (Thorslund, 1948).

When making a general comparison between the sequence of bentonite beds in the Fågelsång area and on Bornholm, one is struck immediately by the general similarity between the thick beds between 37.08 and 38.47 m in the *Diplograptus multidens* Zone of the Koängen core and the 0.75 m thick bed at Vasagård. In the Koängen core, no older bentonite bed except that one between 40.82 and 41.76 m, which is also well up in the

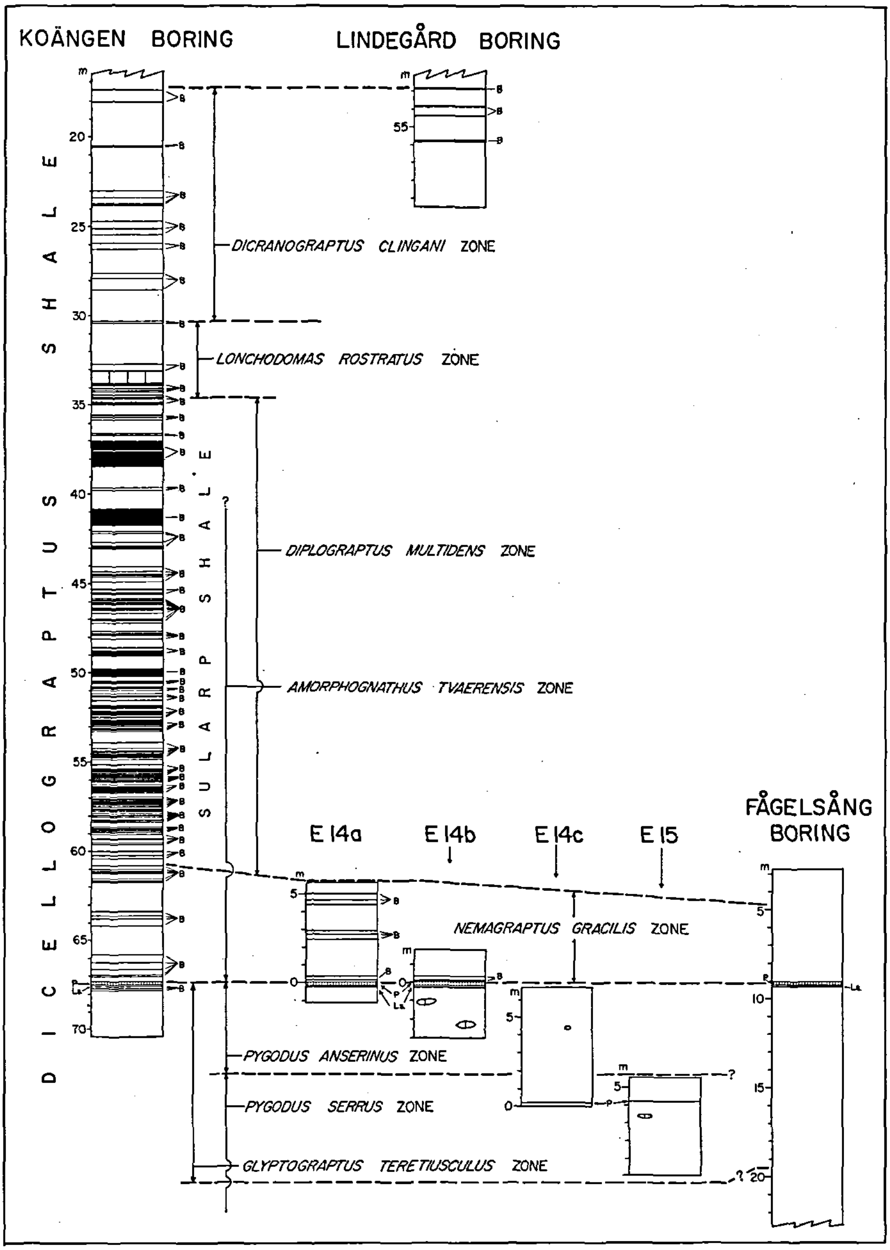


Fig. 2. Bentonite beds in the *Dicellograptus* Shale of some cores and surface exposures in the Fågelsång area. Core lithologies and range of megafossil zones after Nilsson (1960, and in preparation), Hede (1951), and Glimberg (1961). Conodont zones and correlation of sections after Bergström (1971, and in preparation). Surface section designations follow Moberg (1896). P denotes bed of phosphorite, Ls. bed of limestone, B bed of bentonitic rock. For further explanation, see fig. 3.

TABLE 1. Distribution of bentonite beds in the Middle Ordovician part of the Koängen core. For intervals of fossil zones, see fig. 2. cl denotes core loss.

Depth below surface (m)	Bentonite bed thickness (cm)		Depth below surface (m)	Bentonite bed thickness (cm)		Depth below surface (m)	Bentonite bed thickness (cm)	
20.53–20.54	1.5	cl	44.825–44.830	0.5		53.90–53.905	0.5	
20.68–20.71	0.1	cl	45.34?–45.38	3.0	cl	54.28–54.31	0.3	cl
23.050–23.051	0.1		45.540–45.555	1.5		54.40–54.41	1.0	
23.395–23.3955	0.05		45.94	<0.1		54.58	0.2	
23.79	0.1	cl	45.965–46.000	3.5		54.60	3.5	
23.845–23.860	1.5		46.03	<0.1		54.62–54.74	12.0	
24.72–24.724	0.4		46.08	<0.1		54.84	<0.1	
25.135–25.150	1.5		46.14–46.15	1.0		55.15	0.5	
25.37–25.38	0.2	cl	46.37–46.39	0.2		55.46–55.54	5.5	cl
25.96	<0.1	cl	46.43–46.44	1.0		55.60	<0.1	
26.28–26.32	0.15	cl	46.47	0.2		55.64	<0.1	
27.700–27.7015	0.15		46.73	0.5		55.68–55.69	1.0	
27.91–27.92	0.2	cl	47.01–47.06	5.0		55.71	<0.1	
28.62–28.622	0.2		47.24	0.2		55.73–55.82	9.0	
30.29–30.30	0.3	cl	47.71	<0.1	cl	55.85–55.86	1.0	
30.40–30.41	0.1	cl	47.87–47.89	2.0		56.05	<0.1	
32.82–32.83	1.0		47.92	<0.1		56.07	<0.1	
33.18–33.19	0.1	cl	48.16–48.18	2.0		56.09	<0.1	
33.82–34.00	5.0	cl	48.63–48.65	2.0		56.17	0.5	
34.13–34.155	2.5		48.80–49.11	31.00		56.33–56.34	0.5	cl
34.26–34.28	1.5		49.81–50.27	46.00		56.46–56.50	4.0	
34.33–34.34	<0.1		50.43	<0.1		56.50–56.65	15.0	
34.46–34.475	1.5		50.46	<0.1		56.68	<0.1	
34.58–34.64	6.0		50.478	0.2		57.04	<0.1	
34.90–35.00	10.0		50.77	0.5		57.09–57.12	3.0	
35.53–35.54	1.0		50.815–50.880	6.5		57.16	<0.1	
35.60–	<0.1	cl	50.92?	<0.1		57.17	<0.1	
35.85–35.89	<0.1	cl	51.23	<0.1		57.21–57.40	19.0	
36.60–36.65	<0.1	cl	51.35?	0.4		57.45	0.2	
36.70–36.75	<0.1	cl	51.37–51.39	2.0		57.49–57.53	4.0	
37.08–37.53	45.0		51.57–51.64	7.0		57.55	0.6	
37.66–38.47	81.0		51.92–51.93	1.0		57.64–57.68	4.0	
39.720–39.725	0.5		51.95–52.00	5.0		57.73	0.2	
39.830–39.835	0.5		52.12	<0.1		57.76	<0.1	
40.82–41.76	94.0		52.23–52.34	11.0		57.80–57.97	0.1	cl
42.1085–42.110	0.15		52.375–52.410	0.035		57.99–58.00	0.1	
42.195–42.200	0.05		52.51–52.53	2.0		58.05–58.051	0.1	
42.70?–42.81	<0.1	cl	52.54	0.1		58.142	<0.1	
42.95–43.035	8.05		52.58	0.1		58.198–58.200	0.2	
44.072–44.075	0.3		52.69–52.98	29.0		58.285–58.287	0.2	
44.339–44.340	0.1		53.00–53.02	2.00		58.351–58.355	0.4	
44.42–44.46	4.0		53.16–53.26	10.0		58.642–58.643	0.1	
44.56	<0.1		53.28–53.31	0.3		58.680–58.705	2.5	

(cont. p. 38)

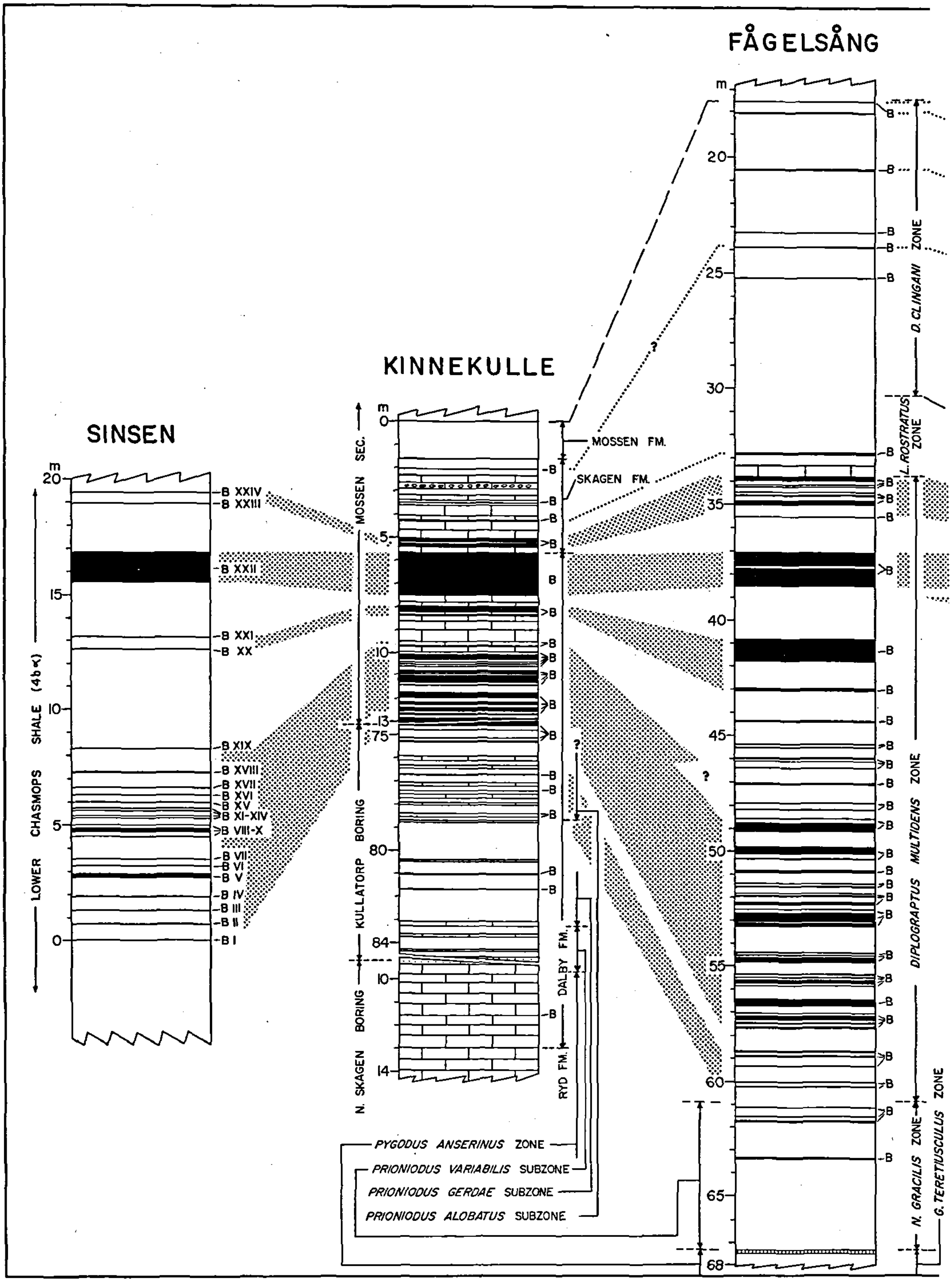
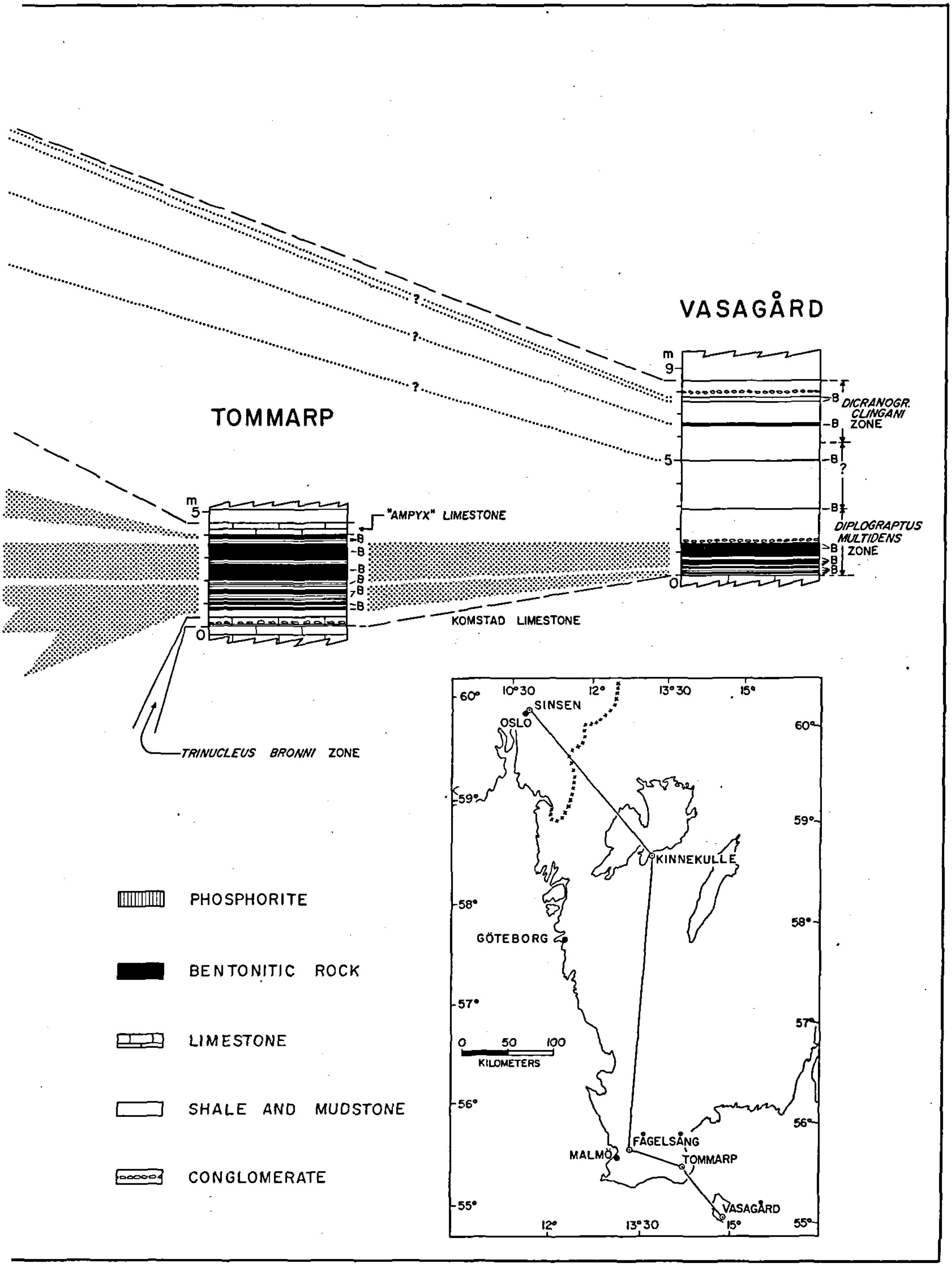


Fig. 3. Comparison between some bentonite-bearing successions in southern Balto-scandia. Megafossil zones in the Koängen core according to Nilsson (1960, and in preparation). The *Lonchodomas rostratus* Zone cannot be interpreted in terms of standard graptolite zones by means of graptolites at present due to the lack of zonal graptolites in that unit. Conodont zones according to Bergström (1971, and in preparation). Only bentonite beds thicker than 2.5 cm have been illustrated in the



Koängen core columnar section. Dotted lines and areas denote proposed tentative correlations based on bentonite beds, broken lines correlations based on fossils. The correlation between the section at Sinsen and Kinnekulle follows Hagemann & Spjeldnaes (1955). Note that the lowermost part of the Vasagård shale succession apparently corresponds to a portion of the *Diplograptus multidens* Zone in the Koängen core.

Table 1. *(cont.)*

Depth below surface (m)	Bentonite bed thickness (cm)		Depth below surface (m)	Bentonite bed thickness (cm)		Depth below surface (m)	Bentonite bed thickness (cm)	
58.845–58.900	1.5		61.010–61.055	<0.1	cl	65.800–65.805	0.5	
58.705–58.970	0.1	cl	61.110–61.125	1.5		66.345–66.350	0.5	
59.170–59.174	0.4		61.145–61.150	0.5		66.680–66.840	0.1	cl
59.310–59.335	2.5		61.530–61.540	1.0		67.050–67.060	<0.1	cl
59.528–59.530	0.2		61.705–71.740	3.5		67.125–67.127	0.2	
59.599–59.600	0.1		63.345–63.370	2.5		67.510–67.512	0.2	
60.000–60.100	1.0		63.600–63.602	0.2		67.600–67.620	0.2	
60.210–60.225	1.5		63.875–63.877	0.2		67.685–67.690	0.5	
60.379–60.380	0.1		64.310–64.320	0.1		67.725–67.730	0.1	
60.760–60.770	0.7							

Diplograptus multidens Zone, attains a comparable thickness and the bentonite beds in the *Nemagraptus gracilis* Zone all have an individual thickness of less than 0.04 m (Nilsson, 1960). Considering this, it seems highly unlikely that the thick bed on Bornholm is equivalent to any of the beds in the *Nemagraptus gracilis* Zone in the Fågelsång area, especially as Bornholm was probably located farther from the source area than was west-central Scania. It would seem much more probable that the thick bed is equivalent to the thick beds in the *Diplograptus multidens* Zone in Scania, which is in full agreement with the fossil data from Bornholm reported above.

Additional indications in the same direction are provided by a comparison with a section between Fågelsång and Bornholm, namely the one at Tommarp in southeastern Scania. No surface section of the bentonite-bearing Middle Ordovician succession in that area is currently available for study but the detailed description by Funkquist (1919) of an excavated section and his extensive suite of rock samples from that locality, which are preserved at the Palaeontological Institute at the Lund University, give enough information for an evaluation of the sequence of bentonite beds through this succession (fig. 3). As might be expected, the bentonite-bed sequence in the Tommarp section shows similarities to that of the Fågelsång area as well as to the one at Vasagård. Hence we feel there is little doubt that the two thick beds at Tommarp correspond to the thick beds between 37.08 and 38.47 m in the Koängen core and to the thick bed at Vasagård. This supports the idea that the unusually thick bentonite bed(s) in this region, as well as elsewhere in Baltoscandia, is located in strata equivalent to a portion of the *Diplograptus multidens* Zone.

Comparison with successions outside Scania

It is a well-known fact that the detailed correlation of individual bentonite beds, especially if they are thin, in many cases involves great difficulties over even very short distances. However, this should not discourage attempts to compare details in different bentonite-bed successions, particularly if there is reason to believe that these successions may represent an unusually complete record of the local ash falls in a particular area during a particular time interval. We believe the latter to be the case with the Middle Ordovician portion of the Fågelsång succession and a comparison with bentonite-bearing sequences outside Scania is therefore in order.

The most extensive bentonite-bed complex previously known from the Middle Ordovician of Baltoscandia is that on Kinnekulle in the Province of Västergötland in southwestern Sweden (Thorslund, 1948; Byström, 1956; Skoglund, 1963; Jaanusson, 1964). Only a part of this complex is, or has been, exposed but two boring cores – the Norra Skagen core and the Kullatorp core – provide much additional data and make it possible to piece together a complete section (fig. 3). Our correlation between various parts of this composite section is based on characteristic key beds and we consider its reliability beyond question. Because of the well-known difficulties involved in getting good core recovery in bentonite-bearing successions, especially of thin bentonite beds, we believe this composite section to be more representative as far as the local bentonite-bed succession is concerned than the Kullatorp core, which otherwise includes the whole bentonite-bearing interval (Thorslund, 1948; Jaanusson, 1964).

Apart from the Mossen Formation, dark shales are virtually absent in that part of the Middle Ordovician of Kinnekulle that concerns us here and the succession is dominantly grey limestones and calcareous mudstones, which are referred to the Ryd, Dalby, and Skagen Formations, respectively (Jaanusson, 1964), and which are about 27 m in total thickness. Surprisingly, this figure is considerably smaller than that of the presumably coeval portion of the *Dicellograptus* Shale in the Fågelsång area, which is estimated to be more than 40 m thick.

Although it appears clear that at least the major portion of the bentonite-bearing succession on Kinnekulle was deposited in a low-energy environment (Jaanusson, 1964), there seems to be little doubt that this environment of deposition was, by and large, characterised by considerably more water turbulence than that of the Fågelsång area during deposition of the major part of the *Dicellograptus* Shale. It is true that portions of the upper part of the *Diplograptus multidens* Zone in the Fågelsång area consist of mudstones not greatly different from those in the upper member of the Dalby Limestone on Kinnekulle, but also in that stratigraphical interval in the Fågelsång succession, there are intercalations of dark shales which were apparently formed in an environment with very little water turbulence. On Kinnekulle, it is therefore to be expected that, particularly in the case of minor ash falls, much of the material was not deposited or was winnowed away and hence never became part of the local rock record (cf. Rosenkrans, 1936). If this is correct, it is clear that in any comparison between the Kinnekulle and Fågelsång bentonite successions, particular attention should be directed toward bentonite beds that are at least several cm thick whereas thinner beds should be regarded as of only secondary, or no, importance for correlation. Following this principle, we have worked out a comparison between the two bentonite-bed successions just mentioned (fig. 3). A number of important details in this correlation are briefly commented on below.

1. Because of the comparatively extreme thickness of the beds involved, we feel there is good reason to believe that the bipartite bentonite bed between 37.08 and 38.47 m in the Koängen core corresponds to the "Big Bentonite Bed" on Kinnekulle, that is, the bed between 5.6 and 7.4 m in the Mossen section. We have considered the possibility that the thick bed between 40.84 and 41.76 m in the Koängen core might be coeval with the "Big Bentonite Bed" but we believe it is more likely that the former corresponds to the uppermost of the two beds immediately below the "Big Bentonite Bed" on Kinnekulle.

2. The complex of relatively thick beds between about 10 and 13 m in the Mossen section exhibits great similarity to the complex of thick beds between (?47.01) 48.16 and 57.21 m in the Koängen core; indeed, the number and mutual positions of the thick beds are almost the same in the two sections.

3. The four beds between 76.71 and 78.61 m in the Kullatorp core appear to have their counterparts in beds between 56.68 and 60.225 m in the Koängen core.

4. With the exception of the two beds between 81.00 and 81.72 m in the Kullatorp core and the single thin bed at 11.54 m in the Norra Skagen core, beds equivalent to the numerous thin bentonite beds in the *Nemagraptus gracilis* Zone and the lowermost *Diplograptus multidens* Zone in the Koängen core are evidently not preserved in the Kullatorp and Norra Skagen cores. This is hardly surprising in view of the fact that this stratigraphic interval consists mainly of limestone and mudstone on Kinnekulle but of shale in the Koängen core.

5. Some of the beds in the uppermost part of the *Dicellograptus* Shale in the Koängen core appear to have their counterparts in beds in the Skagen Formation in the Mossen section. However, we regard our correlations in this interval as particularly tentative because the beds involved are

mostly thin and the Skagen Formation was probably deposited under conditions not very favourable for the preservation of thin bentonite beds.

A check of the reliability of the suggested bentonite bed correlations between the Fågelsång and Kinnekulle successions is made difficult by the fact that the fossils known from the two sections are largely different and of little assistance for precise biostratigraphic correlations. Hence the graptolites collected from the Dalby and Skagen Formations on Kinnekulle (Thorslund, 1948; Jaanusson, 1960, 1964; Jaanusson and Skoglund, 1963) are rather indifferent stratigraphically and hardly characteristic of a particular part of the *Diplograptus multidens* Zone. The megafossils, as well as the conodonts, of the Skagen Formation are quite similar to those in the calcareous beds between about 30 and 34 m of the Koängen core (the *Lonchodomas rostratus* Zone or the "Ampyx" Limestone of previous authors; the Skagen Limestone of Bergström and others, 1968) and these units are apparently equivalent. Further, the Mossen Formation contains graptolites of the *Dicranograptus clingani* Zone (Skoglund, 1963) which are similar to those in the *Dicranograptus clingani* Zone of the Koängen core. Support for some of the suggested correlations is also provided by other conodont evidence; for instance, the boundary between the *Prioniodus variabilis* and *P. gerdae* Subzones of the *Amorphognathus tvaerensis* Zone (Bergström, 1971) is at about 9.5 m in the Norra Skagen core and apparently very near the top of the *Nemagraptus gracilis* Zone in the Koängen core.

As was noted above, Hagemann & Spjeldnaes (1955) attempted a long-distance bed-by-bed correlation between the bentonite-bed complexes on Kinnekulle and at Sinsen in the Oslo area, Norway. The Sinsen bentonite succession exhibits considerable similarity, including thickness of the interval, to the one in the Fågelsång area (fig. 3); indeed, it appears to be easier to correlate between that section and the Koängen core than between the latter and Kinnekulle. The following tentative correlations between these successions may be suggested:

1. Beds XXIII and XXIV of the Sinsen section appear to correspond to beds between 33.82 and 35.00 m in the Koängen core.
2. Bed XXII ("The Big Bentonite Bed") is the same as the bipartite bed between 37.08 and 38.47 m.
3. Beds XXI and XX may correspond to beds between 40.82 and 43.035 m.
4. Bed XIX should be equivalent to a bed between 45.34 and 48.80 m, probably that between 47.01 and 47.06 m.
5. Beds XVIII to X are evidently the same as beds between 48.80 and 52.58 m.
6. Beds IX and VIII appear to be equivalent to beds between 52.69 and 52.98 m and 53.16 and 53.26 m, respectively.

7. The correlation of Sinsen beds VII and VI is uncertain but bed V may well correspond to the one between 54.62 and 54.74 m in the Koängen core.
8. Beds IV to I appear to correspond to beds between 55.46 and 57.68 m.

It should be stressed again that the above correlations are only tentative. However, a close comparison between the bentonite-bed successions at Sinsen and in the Koängen core reveals so many similarities in details that we feel it is justified to believe that our correlation between these successions is reasonably correct. Interestingly, it appears that correlation between these sections would come out in the same general way regardless if one compares the Sinsen section directly with the Fågelsång one, or if one correlates via the Kinnekulle succession as has been done in fig. 3. These data provide considerable support for the idea that at least some isochronous surfaces may be traced all the way from the Oslo region to west-central Scania, and also to Bornholm, by means of distinctive bentonite beds and thereby provide a basis for correlations far more precise than may currently be achieved by use of fossils or other means.

Deposition and source area of Middle Ordovician volcanic ash

In a recent paper Vingisaar (1972) reviews the distribution of the "Big Bentonite Bed" in Scandinavia and of what he regards as the corresponding bed in Estonia (see Männil, 1966). Vingisaar also discusses factors affecting the distribution of bentonite beds and concludes that the source area of the Baltoscandic Middle Ordovician volcanic ash deposits was located between the eastern part of the present North Sea and North Wales. The data presented in the present paper change drastically the distributional picture envisioned by Vingisaar and we feel some of his conclusions are now untenable in the light of our current knowledge about Middle Ordovician bentonites in Baltoscandia. Although several questions dealt with in Vingisaar's interesting paper merit discussion, we will here give brief remarks on only two of these problems, namely the influence of environmental parameters on the deposition of bentonite beds and the location of the source area of the Middle Ordovician bentonites in Baltoscandia.

According to Vingisaar (1972, p. 70) "the sole factor conditioning that distribution [that is, the horizontal distribution of volcanic ash] is considered to be the wind; the effect of agents acting in the basin itself may be neglected". We believe, however, that the bentonite bed succession in the *Dicellograptus* Shale in the Koängen area, which is by far the most extensive one known in the Ordovician anywhere, provides a very striking illustration of the fact that conditions in the environment of deposition were, contrary to the opinion of Vingisaar, of crucial importance for the deposition and preservation, and hence the horizontal distribution, of, in particular, thin bentonite beds. Abundant evidence in the same direction has been known for years in the literature on Middle Ordovician bentonites in North America (for a recent summary, see Fetzer, 1973). Indeed, an inspection of Vingisaar's own isopach map (Vingisaar, 1972, fig. 1) of the bentonite bed "d" in Estonia shows that the thickness of this bed may vary from 5 to 45 cm at localities less than 20 km apart. We feel it is most likely that such local differences were caused by special conditions in the environment of deposition rather than by the wind. As indicated above, our conclusion is that in the environments in which much of the carbonate units of the Baltoscandian bentonite-bearing intervals were deposited, the water turbulence was such that only the heaviest ash falls are likely to have left a depositional record whereas minor ash falls in most cases have been preserved only in low-energy type of sediments such as those present in the Koängen *Dicellograptus* Shale.

As far as the source area of the volcanic ash is concerned, we believe that the currently available evidence hardly warrants Vingisaar's conclusion that the source area of the ashes that form the Ordovician bentonite beds in Baltoscandia is between the eastern part of the present North Sea and Wales. Especially in view of the uncertainties associated with the calculation of the location of the source area on the basis of regional thickness variations of key beds without proper regard to regional differences in the sedimentary environment, we think the only reasonable conclusion that may be drawn at the present time is that the source area must have been at a longitude west of the present Estonia. Hence we feel that the search for a source area should not be restricted to the region between Scandinavia and Wales but should also include parts of the European continent; indeed, the source area may even have been now subducted volcanic islands in the contracting Proto-Atlantic Ocean. It is appropriate in this connection to note that Middle Ordovician bentonite beds are quite widespread in the eastern and central United States (see, for instance, Kay, 1935; Templeton and Willman, 1963). Although it can be proved that at least locally, for instance in the well-known Tumbling Run section near Strasburg, Virginia (Cooper and Cooper, 1946; Bergström, 1971), the bentonite beds occur in the same Middle Ordovician conodont subzone(s) as in southern Sweden, it is as yet premature to make any trans-Atlantic comparisons even if similarities do exist between these bentonite-bed successions.

Summary and Concluding remarks

The principal results of the present study may be summarized as follows.

1. A restudy of the fossils previously reported from the lowermost part of the bentonite-bearing Middle Ordovician succession on Bornholm shows that there is no indisputable evidence that this portion of the *Dicellograptus* Shale is coeval with the *Nemagraptus gracilis* Zone. Rather, the available fossils suggest that the succession belongs in the upper part of the *Diplograptus multidens* Zone.

2. Studies of the Koängen core from the Fågelsång area in Scania have disclosed the presence of no less than 157 bentonite beds in the *Glyptograptus teretiusculus, Nemagraptus gracilis, Diplograptus multidens,* and *Dicranograptus clingani* Zones in the Middle Ordovician portion of the *Dicellograptus* Shale. Obviously the idea, cited sometimes in the literature, that the number and thickness of the Middle Ordovician bentonite beds decrease southward in southern Sweden is not correct.

3. The unusually thick bentonite beds in the Koängen core are all located well up in the *Diplograptus multidens* Zone. A comparison between the Bornholm and the Fågelsång successions suggests that the thick bentonite bed on Bornholm is identical with the "Big Bentonite Bed" of the *Diplograptus multidens* Zone of the Fågelsång area. This is supported also by a comparison with the bentonite-bed succession in a section at Tommarp in southeastern Scania, which is situated between Fågelsång and Bornholm geographically.

4. The extensive complex of bentonite beds in the Koängen core shows considerable similarity in details to that of the Dalby, Skagen, and Mossen Formations on Kinnekulle, and it appears feasible to correlate some of the more distinctive beds in these successions.

5. If the bentonite-bed correlations between Kinnekulle and Fågelsång are reasonably correct, the base of the *Diplograptus multidens* Zone should correspond to a level 4–7 m above the base of the Dalby Formation on Kinnekulle. Evidence from the Bornholm succession indicates that the top of the same graptolite zone corresponds to a level within the Skagen Formation, although its precise location is uncertain due mainly to the fact that in the Koängen core, the interval evidently corresponding to the lowermost part of the Skagen Formation on Kinnekulle lacks biostratigraphically diagnostic graptolites. There are some indications from bentonite-bed correlations, however, that the uppermost part of the Skagen Formation on Kinnekulle may be equivalent to a portion of the *Dicranograptus clingani* Zone (fig. 3) in the Fågelsång area. Hence it may well be that the base of this graptolite zone is comparable to the level of the conglomerate at 2.8–2.9 m in the Mossen section (Thorslund, 1948, pl. XXII, fig. 3) and

at 64.81–64.90 m in the Kullatorp core (Thorslund, 1958; Hagemann & Spjeldnaes, 1955; Jaanusson, 1964). This conglomerate has been interpreted to mark a considerable gap in the sequence (Hagemann & Spjeldnaes, 1955; however cf. also Jaanusson, 1964) and another, possibly greater, hiatus has been postulated to be present at the base of the Mossen Formation (Jaanusson, 1960; 1964). If the related bentonite-bed correlations proposed herein are correct, it is obvious that at least the latter hiatus should correspond to a portion of the *Dicranograptus clingani* Zone although the data available do not permit a precise calculation of its magnitude.

In the past, it has frequently been claimed, and we feel with justification, that the individual thickness of, and mutual relations between, bentonite beds may have been controlled to such an extent by parameters of the local environment of deposition that most individual bentonite beds cannot be traced with confidence from one section to another. This is no doubt correct also in many cases in Baltoscandia. Nevertheless, we feel that it is very difficult to escape the conclusion that under favourable circumstances, as exhibited in the cases presented above, individual bentonite beds can indeed be traced over very long distances and be of great value for precise correlations.

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Dansk sammendrag

Fornyede studier af faunaen fra den nederste del af den bentonit-førende serie i den bornholmske *Dicellograptus* skifer har vist, at der ikke er nogen grund til at henføre denne del af serien, som indeholder det tykkeste bentonitlag, til *Nemagraptus gracilis* zonen. Sammenligning med tilsvarende lagfølger i Fågelsång området og ved Tommarp i Skåne synes at vise, at den undersøgte del af *Dicellograptus* skiferen på Bornholm måske snarere tilhører *Diplograptus multidens* zonen. Regionale sammenligninger mellem de bentonitførende serier i Skåne, Kinnekulle og Sinsen profilet i Norge, antyder at enkelte af bentonitlagene kan følges over meget lange afstande.

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