

Vila Maria Formation (Silurian, Paraná Basin, Brazil): integrated radiometric and palynological age determinations

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Abstract – Fresh shale samples taken from a well-known outcrop section of the Silurian Vila Maria Formation, located on the northeastern margin of the Paraná Basin (Três Barras Farm, Goiás State, central-western Brazil), have been analysed for both palynological and radiometric age determinations. The rocks yielded a fairly diverse, age-definitive cryptospore assemblage, and the same samples proved suitable for Rb–Sr analysis, despite Silurian sedimentary rocks being rarely suited to radiometric dating techniques. This study thus introduces an alternative, independent method for estimating the minimum depositional age of the Vila Maria Formation. The Rb–Sr age value has been calculated via an isochron diagram that yields 435.9 ± 7.8 Ma. Accordingly, the latter value is interpreted as the minimum depositional age of the analysed Vila Maria strata, implying their deposition during Llandovery times. This concurs with the palynological results, which indicate an age no older than Early Silurian and, more particularly, favour an Early to Middle Llandovery (Rhuddanian–Early Aeronian) attribution.

Keywords: Silurian, absolute age, palynology, biostratigraphy, Parana Basin.

1. Introduction and material

The Ordovician–Silurian sedimentary sequence of the vast Paraná Basin of South America includes a number of siliciclastic rock units that are developed extensively in the subsurface (Milani *et al.* 1995; Pereira, Bergamaschi & Rodrigues, 1998; Moreira & Borghi, 1999; Assine, 2001, and references therein). Fossiliferous strata of this sequence are best exposed in eastern Paraguay, on the west flank of the basin, where the Itacurubí Group (particularly the Vargas Peña Formation) contains fairly rich marine invertebrate faunas and palynomorph assemblages of Early Silurian age (Harrington, 1950, 1972; Wolfart, 1961; Ciguel, Rösler & Clérice, 1987; Ciguel, 1988; Wood *et al.* 1989; Babcock *et al.* 1990; Melo & Boucot, 1990; Gray, 1991; Boucot *et al.* 1991; Wood & Miller, 1991; Gray *et al.* 1992; Milani & Daemon, unpub. report, 1992; Milani *et al.* 1995; Y. Grahn, unpub. report, 1998; Grahn, Pereira & Bergamaschi, 2000). Towards the east, in south and central-western Brazil, fossiliferous Silurian strata are less well developed and mostly restricted to the Vila Maria Formation, both in the subsurface and in discontinuous outcrops along the northwestern and northeastern margins of the basin (Burjack & Popp, 1981; Popp, Burjack & Esteves, 1981; Faria, 1982; Gray *et al.* 1985; Boucot *et al.* 1986;

Grahn, 1992; Y. Grahn, unpub. report, 1997; Milani & Daemon, unpub. report, 1993; Milani *et al.* 1995; Moreira & Borghi, 1999; Grahn, Pereira & Bergamaschi, 2000; Assine, 2001).

The palynological part of our study involves a biostratigraphic reassessment of the Vila Maria Formation at its well-known Três Barras Farm outcrop section in Goiás State, on the northeastern margin of the Paraná Basin in central-western Brazil (Fig. 1). That section was also investigated by Gray *et al.* (1985), who first documented the occurrence of palynomorphs. The location of this fossil site, as well as the regional stratigraphy and lithological characterization of the Vila Maria Formation in the study area, has already been described in sufficient detail by those authors and also by Faria (1982). Our six samples, collected by A. J. Boucot, A. Faria and PETROBRAS (Brazilian state-owned oil company) geologists in 1986, are well representative of a 3.5 m thick section within Faria's (1982) 'middle sequence' (Fig. 2), that is, the dark shale interval that has also yielded all of the palynomorphs recorded by Gray *et al.* (1985).

The samples from the Vila Maria Formation have been utilized concurrently for radiometric Rb–Sr analyses. The purpose of this was to provide an alternative, independent basis for estimating the minimum depositional age of the formation and to compare this with palynological data obtained from the same samples.

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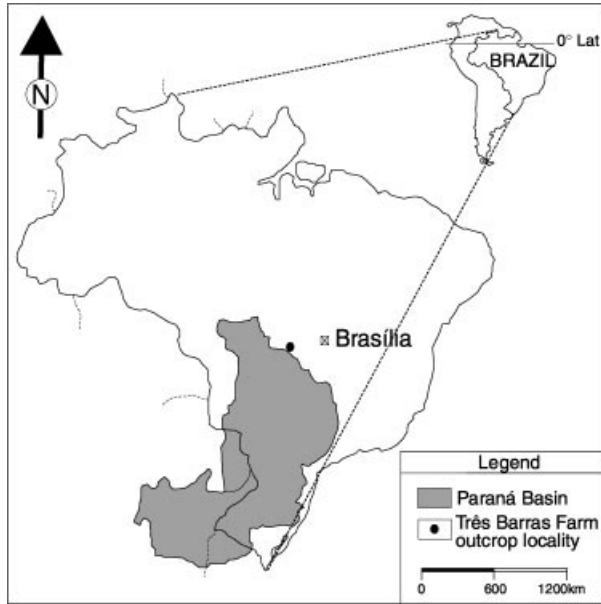


Figure 1. Location of Três Barras Farm outcrop locality, Vila Maria Formation, central-western Brazil.

2. Palynological results

Miospores from a single sample of the Vila Maria Formation at the Três Barras Farm section were investigated by Gray *et al.* (1985), who described only unenclosed tetrads and dyads associated with rare possibly trilete spores (probably dissociated from tetrads). One of the six samples analysed herein (our Sample I, from the base of a waterfall) was collected from that same horizon, and the others (Samples II–IV, VI and VIII) are from somewhat higher stratigraphic levels. They contain a much richer miospore assemblage than was selectively reported by Gray *et al.* (1985). They also include abundant microphytoplankton (mainly leiospheres, with less common acritarchs), a few scolecodonts, and rare, doubtful graptolite remains (that are so poorly preserved and comminuted as to be unidentifiable). Chitinozoans were not observed in any of the samples. The palynomorphs are, in general, poorly preserved, moderately carbonized, brown to dark brown, and often pyrite-impregnated. In

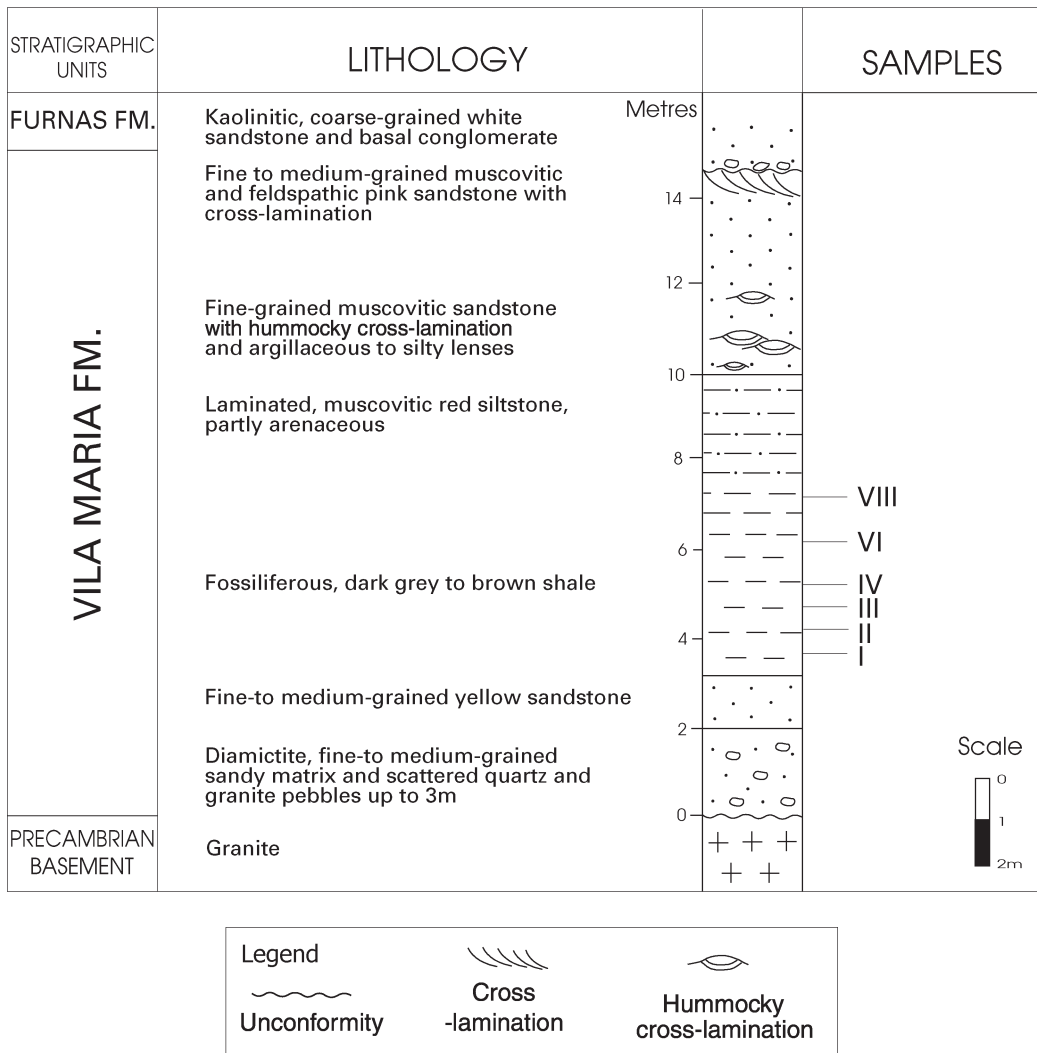


Figure 2. Lithological column of the Vila Maria Formation at Três Barras Farm section and location of analysed samples (modified after Gray *et al.* 1985).

addition, unstructured films and clumps of amorphous organic matter make up a considerable proportion of the total organic residue in these samples.

Our biostratigraphic analysis of the palynoflora concerns the miospore components only. The associated microphytoplankton include no age-diagnostic forms. They constitute a very low-diversity acritarch–prasinophyte assemblage dominated by leiospheres and *Diexallophasis* sp.; minor constituents include *Eupoikilofusa* sp. (one fragment found), *Multiplicisphaeridium?* sp., indeterminate acanthomorphs, and very rare *Dictyotidium?* sp. and *Pterospermella?* sp. This taxonomically restricted association, together with the overwhelming representation of leiospheres and presumably land-derived miospores, and the apparent absence of chitinozoans, indicates a very shallow marine, near-shore depositional environment for the Vila Maria Formation in the study area, as suggested by previous palynological studies (Gray *et al.* 1985; J. Melo, unpub. report, 1997; Laranjeira, Melo & Pereira, 1997). Moreover, this inferred setting is also consistent with the occurrence of *Arthropycus alleghaniensis* in nearby outcrops (Burjack & Popp, 1981) and, more particularly, with the low diversity molluscan fauna reported from the same level as Sample I at the Três Barras Farm section (Popp, Burjack & Esteves, 1981; Faria, 1982; Boucot *et al.* 1986).

The miospore assemblage is similar in all six samples and consists of cryptospores only. These include rare monads and much more abundant dyads and tetrads which are either unenclosed or envelope-enclosed. Envelopes are smooth or variably ornamented with a reticulate pattern, small convolute ridges, or rarely small granae. No true trilete spores have been observed. The few specimens that bear an incipient trilete mark are artifacts and belong to the cryptospore genus *Imperfectotriletes* (Stemans, 2000; Stemans, Higgs & Wellman, 2000). These probably correspond to the 'possible trilete spores' recorded by Gray *et al.* (1985, p. 523).

The following species have been identified in the samples of this study: *Abditusdyadus laevigatus* Wellman & Richardson, 1996; *Dyadospora murusattenuata* Strother & Traverse, 1979; *D. murusdensa* Strother & Traverse, 1979; *Imperfectotriletes patinatus* Stemans, Higgs & Wellman, 2000; *I. vavrdovae* (Richardson) Stemans, Higgs & Wellman, 2000; *Laevolancis divellomedia* (Chibrikova) Burgess & Richardson, 1991; *Nodospora rugosa* sensu Richardson, 1988; *Pseudodyadospora laevigata* Johnson, 1985; *P. petasus* Wellman & Richardson, 1993; *Rimosotetras problematica* Burgess, 1991; *Segestrespora membranifera* (Johnson) Burgess, 1991; *S. rugosa* (Johnson) Burgess, 1991; *S. laevigata* Burgess, 1991; *Sphaerasaccus glabellus* Stemans, Higgs & Wellman, 2000; *Tetrahedraletes medinensis* Strother & Traverse, 1979; *Velatitetras anatoliensis* Stemans, LeHérissé &

Bozdogan, 1996; *V. retimembrana* (Miller & Eames) Stemans, LeHérissé & Bozdogan, 1996; *V. rugosa* Stemans, LeHérissé & Bozdogan, 1996; and *V. laevigata* Burgess, 1991 (Figs 3, 4).

The Três Barras Farm cryptospore assemblage is typical of palynofloras of Caradoc–Llandovery age that are known virtually worldwide. In South America such assemblages are known from Lower Silurian rocks of the Paraná Basin in Brazil and Paraguay (J. Melo, unpub. report, 1997; Laranjeira, Melo & Pereira, 1997; Stemans & Pereira, 2000) as well as from the Amazon and Parnaíba basins of northern Brazil (J. Melo & P. Stemans, unpub. report, 1997; P. Stemans, unpub. report, 2000). Furthermore, similar palynofloras have been reported from numerous other regions, such as Belgium (Stemans, 2001), Bulgaria (Lakova, Gocev & Yanev, 1992), China (Wang, Li & Wang, 1997), the Czech Republic (Vavrdová, 1984, 1988, 1989), Libya (Richardson, 1988), Saudi Arabia (Stemans, Higgs & Wellman, 2000; Wellman, Higgs & Stemans, 2000), Turkey (Stemans, LeHérissé & Bozdogan, 1996), United Kingdom (Burgess, 1991; Wellman, 1996), and North America (Strother & Traverse, 1979; Miller & Eames, 1982; Duffield, 1985; Johnson, 1985). A more complete list of such early miospore occurrences is given in Edwards & Wellman (2001).

There is only very limited palynostratigraphic evidence to distinguish Late Ordovician from earliest Silurian miospore assemblages. The main criteria include the first occurrence of *L. divellomedia*, the appearance and proliferation of true trilete spores (*Ambitisporites avitus* morphon *sensu* Stemans, LeHérissé & Bozdogan, 1996), and the progressive decline of cryptospores featuring a membranous envelope. A provisional biostratigraphic scheme based on these features has been formulated by Stemans, Higgs & Wellman (2000). The Vila Maria miospore assemblage documented herein contains rare *L. divellomedia*, abundant membrane-bearing cryptospores, and some specimens of *Imperfectotriletes*, but no true trilete spores. Accordingly this assemblage can be attributed to Sub-zone α of the *L. divellomedia* Interval Biozone (Stemans, Higgs & Wellman, 2000). The possible age for this biozone ranges from Rhuddanian to Early Aeronian (cryptospores bearing an outer membrane become scarcer in the Upper Aeronian according to Stemans, Higgs & Wellman, 2000). Moreover, the stratigraphic inception of *Ambitisporites* seems to occur at a somewhat higher level in South America (upper Aeronian: see Stemans & Pereira, 2000) than elsewhere. However, the above-mentioned criterion, based on the absence or presence of trilete spores, must be accepted with caution. Indeed, there are few reported occurrences of pre-middle Aeronian trilete spores. Moreover, first occurrences of trilete spores appear to be diachronous (Stemans & Pereira, 2000).

In light of the above, and perhaps also because of

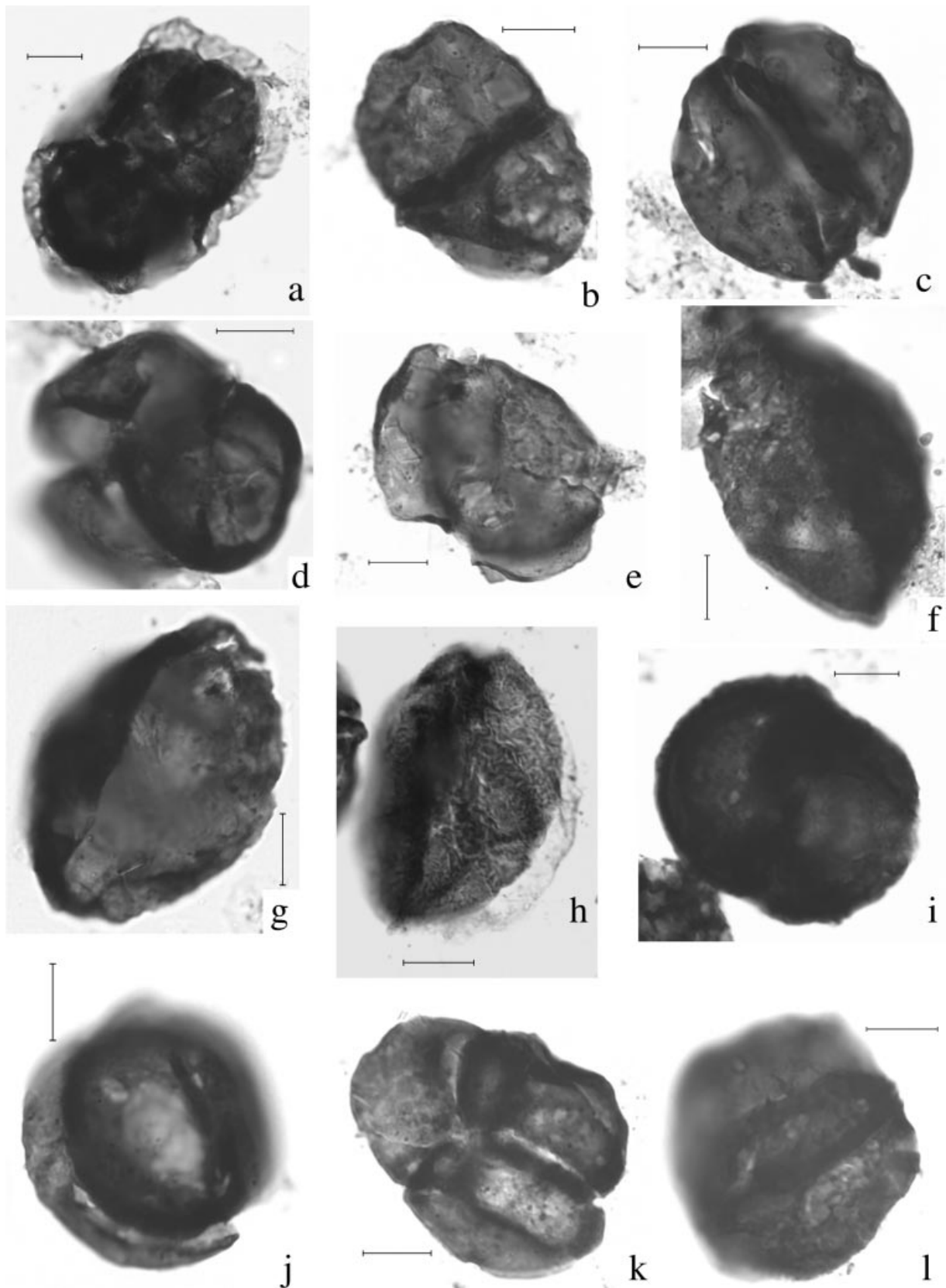


Figure 3. Cryptospores from the Silurian Vila Maria Formation at Três Barras Farm section, Goiás State, central-western Brazil. All palynological slides are from the collection of Management of Applied Biostratigraphy and Paleoecology at PETROBRAS R & D Centre (CENPES/PDEP/BPA, Rio de Janeiro, Brazil). Each palynomorph name is followed by indications of the source sample, preparation number, and England Finder coordinate. Scale bar = 10 μ m. (a) *Abditusdyadus laevigatus*, dyad enclosed within a smooth envelope, Sample VIII, 2002978, F16/0. (b) *Dyadospora murusattenuata*, smooth dyad with thin wall, Sample VIII, 2002978, F21/3. (c) *Dyadospora murusdensa*, smooth dyad with thick wall, Sample VIII, 2002978, J20/4. (d)

the restricted sampling available to this study (restricted to the 'middle sequence' of the Vila Maria Formation), we were unable to confirm the younger Llandovery (later Aeronian to Telychian) sedimentation proposed by Grahn, Pereira & Bergamaschi (2000, fig. 11) for higher parts of the formation. In fact, our palynological dating is in agreement with the Early to Middle Llandovery age span proposed by Grahn (1992) on the basis of chitinozoan evidence from the Paraná Basin subsurface. In particular, our data support Gray *et al.*'s (1985) Early Llandovery age determination based on the size range and mean size of tetrads. However, the cryptospore size criterion is of dubious chronostratigraphic value. Indeed, the coalification of organic matter causes a decrease in palynomorph size as do laboratory oxidation techniques (Johnson, 1985). Sedimentary processes also tend to produce pre-depositional sorting of palynomorphs. According to Gray *et al.* (1985), Llandovery-age tetrads of *T. medinensis* from the Três Barras Farm section display a 18–43 µm size range (mean 29 µm), from 150 measured specimens. Virtually identical values were recorded by Wellman (1996) for appreciably older (Late Ordovician, Caradoc) representatives of the same species from southern Britain, that is, 19–43 µm (mean 28 µm), based on 100 specimens. This confirms that tetrad size is unreliable biostratigraphically.

3. Rb–Sr radiometric dating of the Vila Maria Formation

The Rb–Sr isochron method has been employed in dating Palaeozoic and Early Mesozoic pelitic rocks of Brazilian sedimentary basins (A. Thomaz-Filho, unpub. Ph.D thesis, Univ. Estado de São Paulo, 1976; Cordani, Kawashita & Thomaz-Filho, 1978; Cordani *et al.* 1985; Mizusaki, Alves & Pedrão, 1999). In all cases the Rb–Sr results have geological significance and can be associated with the depositional age proposed for the varied formations.

Cordani, Kawashita & Thomaz-Filho (1978) and Cordani *et al.* (1985), using whole rock samples from argillaceous sedimentary formations, have presented radiometric Rb–Sr ages compatible with the sedimentation processes. According to these authors, the fundamental condition that must be satisfied is the isotopic homogenization of the initial ratio $^{87}\text{Sr}/^{86}\text{Sr}$. We prefer to use the alternative expression 'isotopic uniformizing' when describing the characteristics of

these sedimentary rocks (A. M. Mizusaki, unpub. Ph.D. thesis, Univ. Estado de São Paulo, 1992).

Several other authors (A. Thomaz-Filho, unpub. Ph.D thesis, Univ. Estado de São Paulo, 1976; Bonhomme, 1982; J. Morton, unpub. Ph.D thesis, Univ. Texas, 1983; Morton, 1985) have enumerated the essential conditions for the application of the Rb–Sr methodology to pelitic rocks and consequently to the homogenization process of initial values of the ratio $^{87}\text{Sr}/^{86}\text{Sr}$. We believe that the isotopic homogenization in cogenetic sedimentary rock samples is a process that must occur during or immediately after sedimentation. In order to verify this hypothesis, Mizusaki, Kawashita & Thomaz-Filho (1998), working with Recent sediments, described the conditions necessary for the homogenization process to occur in sedimentary rocks, and consequently for the calculated isochron age to be considered representative of the depositional time. These conditions include: closely spaced samples, control of the associated detrital material, clay fraction enriched in expansible minerals, and deposition preferably in saline (but not necessarily marine) waters. Accordingly, the Vila Maria Formation samples have been carefully examined in order to verify whether or not they were suitable for application of the methodology proposed by Mizusaki, Kawashita & Thomaz-Filho (1998).

Initially, all six samples were described macroscopically, highlighting such parameters as colour, biogenic textural patterns, presence of salts, carbonates, feldspars, micas, oxidation products and organic matter. The samples were found to be pelitic, argillaceous, homogeneous, grey to brown, and to show some features probably associated with biogenic textural patterns. Locally minor open fractures and rare millimetric veins of white calcite were observed. The samples include small amounts of potassium feldspar and micas, and show little evidence of oxidation. The opposite condition would be regarded as problematic because potassium minerals usually contain some Rb that could adversely affect the analytical results.

Thereafter, clay minerals present in the fine fractions of the samples were identified. All samples were analysed with X-ray diffraction techniques (XRD) in whole rock and fine fraction (<2 µm) preparations. They were found to be very similar and homogeneous in whole rock mineralogy: quartz, micas (rare), iron oxides and clay fraction. The latter (<2 µm) includes interstratified illite–smectite, illite and rare kaolinite.

Imperfectotriletes patinatus, thick-walled monad with a pseudo-trilete mark and attached tetrad remains, Sample VIII, 2002978, O20/3. (e) *Imperfectotriletes vavrdovae*, thin-walled monad with a pseudo-trilete mark, Sample VIII, 2002978, P19/3. (f, g) *Laevolancis divellomedium*, smooth monads, Sample VIII, 2002978; (f) N52/3; (g) X22/0. (h) *Nodospora rugosa sensu* Richardson 1988, tetrad ornamented with convolute muri, enclosed within a smooth envelope, Sample VIII, 2002978, K28/0. (i) *Pseudodyadospora laevigata*, smooth pseudo-dyad, Sample VIII, 2002978, P19/3. (j) *Pseudodyadospora petasus*, smooth pseudo-dyad, Sample VIII, 2002978, U22/1. (k) *Rimosotetras problematica*, smooth tetrad with loosely attached spore-like cells, Sample VIII, 2002978, D40/0. (l) *Segestrespora membranifera*, smooth dyad enclosed within an envelope ornamented with a reticulate pattern.

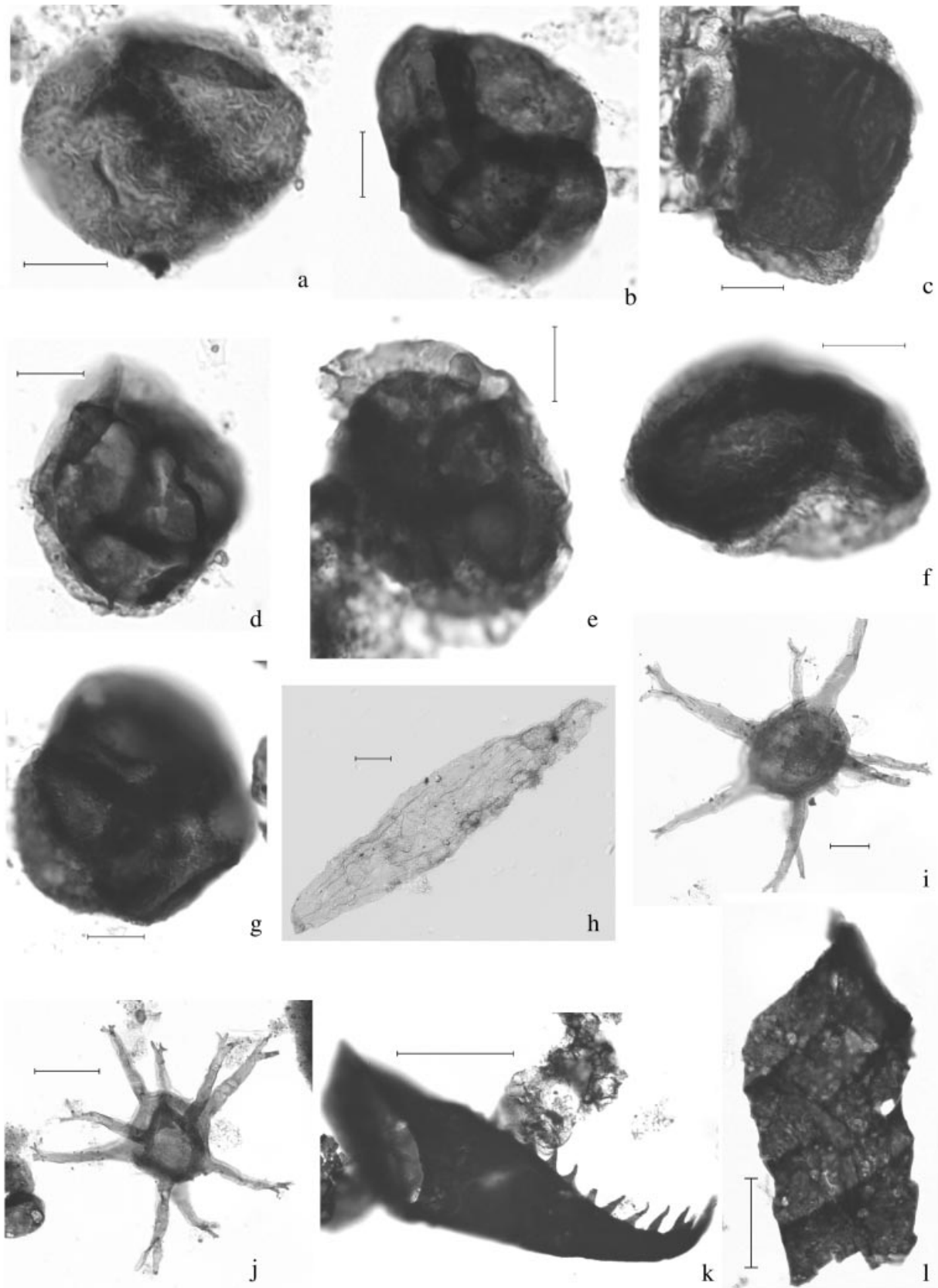


Figure 4. Cryptospores and other organic-walled microfossils from the Silurian Vila Maria Formation at Três Barras Farm section, Goiás State, central-western Brazil. All palynological slides are from the collection of Management of Applied Biostratigraphy and Paleocology at PETROBRAS R & D Centre (CENPES/PDEP/BPA, Rio de Janeiro, Brazil). Each palynomorph name is followed by indications of the source sample, preparation number, and England Finder coordinate. Scale bar in (a–j) is 10 μ m. Scale bar in (k, l) is 50 μ m. Items (a–g) are cryptospores; (h–j) are acritarchs; (k, l) are other marine

Table 1. Rb (ppm), Sr (ppm), $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios in pelitic samples of the Vila Maria Formation, Paraná Basin, Brazil

| Sample | Rb (ppm) | Sr (ppm) | $^{87}\text{Sr}/^{86}\text{Sr}$ | Error | $^{87}\text{Rb}/^{86}\text{Sr}$ | Error |
|--------|----------|----------|---------------------------------|---------|---------------------------------|--------|
| I | 13.15 | 483.81 | 0.71433 | 0.00012 | 0.079 | 0.001 |
| II | 186.50 | 151.60 | 0.73593 | 0.00011 | 3.570 | 0.101 |
| III | 186.70 | 156.20 | 0.73549 | 0.00012 | 3.464 | 0.098 |
| IV | 187.50 | 129.30 | 0.73900 | 0.00015 | 4.210 | 0.119 |
| VI | 184.20 | 156.20 | 0.73503 | 0.00007 | 3.422 | 0.097 |
| VIII | 14.93 | 440.63 | 0.71463 | 0.00007 | 0.098 | 0.0008 |

Regarding the depositional environment, the palynological analysis suggests shallow marine settings with likely significant input of continental organic debris. These mineralogical and paleoenvironmental circumstances are appropriate for the application of Rb–Sr methodology.

The isotopic analysis enables determination of the Rb and Sr contents and the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios. The appropriate procedures, as adopted by K. Kawashita (unpub. Ph.D thesis, Univ. Estado de São Paulo, 1972) and A. M. Mizusaki (unpub. Ph.D thesis, Univ. Estado de São Paulo, 1992), were performed at the Geochronology and Isotope Geology Research Centre of the Geosciences Institute of São Paulo University (USP). First, whole rock samples were dried in a special oven with controlled temperature not exceeding 70 °C, thus preventing thermal disturbances in the clay mineral structure, and carbonates were removed with HCl (0.1 N).

Following brief treatment with H_2O_2 (to remove possible organic matter), specific isotopic analyses were conducted. These included: semi-quantitative and qualitative determination of Rb and Sr (using X-ray fluorescence); chemical digestion ($\text{HF} + \text{HClO}_4$); separation of the Sr by exchange with cationic resin (AG-50; W-X8; Biorad 200 to 400 mesh) and determination of the Sr isotopic compositions by means of a mass spectrometer VG-354 with simple collector.

These determinations were made during the year 1999 when (according to the international standard NBS-987) the average value obtained with 34 determinations was 0.71025 ± 0.00002 (1σ). The calculated average error with $^{87}\text{Sr}/^{86}\text{Sr}$ is 0.0131%. The values obtained from isotopic analyses of the six samples are presented in Table 1. Initially we made a selection of the available isotopic results as the samples have similar values (Table 1). We chose four points that present

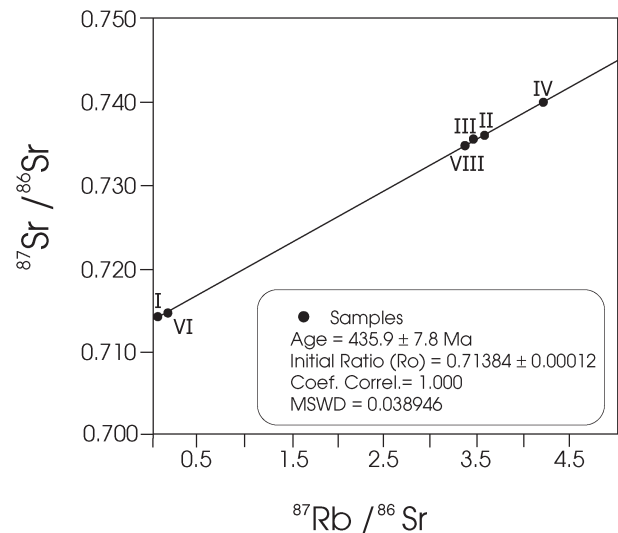


Figure 5. Rb/Sr isochron diagram for pelitic samples representative of the Vila Maria Formation, Paraná Basin, Brazil (modified after Williamson, 1968)

a good dispersion of isotopic ratio $^{87}\text{Rb}/^{86}\text{Sr}$ (calculated by X-ray fluorescence technique) and are considered representative of the sampled interval of Vila Maria Formation. These points (samples I, II, III and IV) were plotted on an isochron diagram (Fig. 5) using a regression program (modified from Williamson, 1968). The result obtained is 435.9 ± 7.8 Ma, with correlation 1.00 and initial ratio $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ of 0.71384 ± 0.00012 .

4. Discussion of results

The isochron age obtained from pelitic samples of the Vila Maria Formation (435.9 ± 7.8 Ma) is considered representative of the depositional age because

palynomorphs. (a) *Segestrespora rugosa*, smooth dyad enclosed within an envelope ornamented with convolute muri, Sample VIII, 2002978, N35/3. (b) *Tetrahedraletes medinensis*, smooth tetrad, Sample VIII, 2002978, U17/3. (c) *Velatitetras anatoliensis*, smooth tetrad enclosed within an envelope ornamented with grana, Sample VI, 20029780, U14/4. (d, e) *Velatitetras laevigata*, smooth tetrads enclosed within a smooth envelope, Sample VIII, 2002978; (d) U17/1; (e) H20/3. (f, g) *Velatitetras rugosa*, smooth tetrads enclosed within an envelope ornamented with convolute muri, Sample VIII, 2002978; (f) P20/1; (g) U22/0. (h) *Eupoikilofusa* sp., Sample II, 2002977, H48/0. (i, j) *Diexallophasis* sp., Sample III, 2002978; (i) U55/0; (j) U55/3. (k) Scolecodont, Sample VI, 2002980, R47/0. (l) Graptolite fragment, Sample VI, 2002980, F40/0.

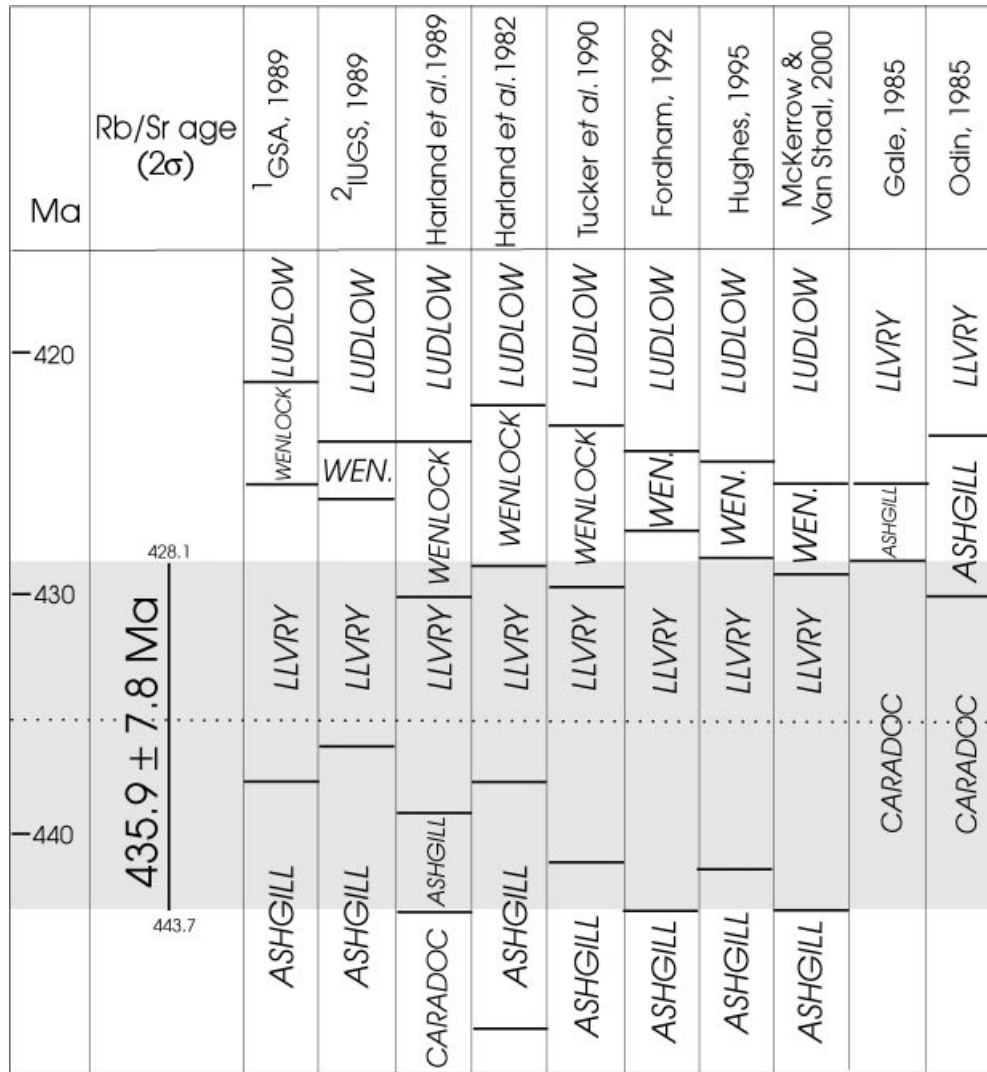


Figure 6. Graphical representation of the Rb–Sr isochron age and referenced time-scales (modified after Tucker *et al.* 1990), (1) GSA, Geological Society of America, 1989; (2) IUGS, International Union of Geological Sciences, 1989.

the Sr isotopic homogenization was evidently penecontemporaneous with sedimentation. The reduced statistical error (1.7%) recorded for the analysed samples is coherent with the application of the Rb/Sr method to sedimentary rocks (A. M. Mizusaki, unpub. Ph.D thesis, Univ. Estado de São Paulo, 1992). The lack of significant diagenetic alteration of the original mineralogy adds to the reliability of our dating.

Comparison of the present result with some numerical values in published geological time-scales (International Union of Geological Sciences, 1989; Geological Society of America, 1989; Harland *et al.* 1982, 1989) indicates Early Silurian (Llandovery) as the possible minimum age for the investigated Vila Maria interval. However, taking into account the statistical error (± 7.8 Ma), the value ranges from 428.1 to 443.7 Ma, and is consistent with any dating within the Caradoc–Llandovery age span (Gale, 1985; Odín, 1985).

Several papers have been published recently that present Early Silurian isotopic ages, derived from many geological sources and based on a variety of isotopic systems, especially U/Pb in zircons (Harland *et al.* 1989; Hughes, 1995; Fordham, 1992; McKerrow & Van Staal, 2000). Unfortunately, as discussed by Hughes (1995), there is considerable variation in numerical values given in the literature.

Johnson & McKerrow (1991) used 430 Ma for a ‘mid Aeronian’ position and 432 and 435 Ma for the top and base of the Rhuddanian, respectively. On the other hand, these values would appear too young for such authors as Tucker *et al.* (1990) and Fordham (1992), who placed the base of Rhuddanian respectively at 441 and 443 Ma.

McKerrow & Van Staal (2000) have proposed a revised time-scale based on a compilation of U/Pb ages on zircons from tuffs interbedded or associated with zonal fossils, and, to a lesser extent, based also on more precise palaeontological correlations. These

authors settle an absolute age of 443 Ma for the base of Silurian. This value is consistent with our Rb/Sr lower age (443.7 Ma), if one takes into account the 2σ error.

In order better to visualize this problem, the interval of the Rb–Sr isochronic age (428.1 to 443.7 Ma) and the average age obtained from pelitic samples of the Vila Maria Formation are plotted graphically against some published time-scales (Fig. 6). The ages do not conform completely to any single time-scale although they do agree with parts of each of them when the uncertainty (2σ) is considered. Our radiometric Rb–Sr isochron age indicates Llandovery (columns 1 to 8 in Fig. 6) as the main Vila Maria depositional interval. However, the radiometric age is most compatible with that presented by McKerrow & Van Staal (2000) (see Fig. 6). These authors proposed 443 Ma as the Llandovery base, thus conforming with our older Rb–Sr age limit and with our palynological data. A significant finding of our study is that the palynological dating indicates Early to Middle Llandovery, excluding pre-Silurian ages or ages younger than Aeronian.

Current understanding of the applicability of the Rb–Sr isochron method to sedimentary rocks is insufficient for precise interpretation of the radiometric data. However, when such data can be associated with palynology it is clear that meaningful results are obtainable.

5. Conclusions

(1) Pelitic samples from the Silurian Vila Maria Formation (Paraná Basin, Brazil) present a special case because they are suitable to both palynological analysis and the Rb–Sr methodology. This is the first time that radiometric dating techniques have been successfully applied to Silurian sedimentary rocks and integrated with biostratigraphic age determinations in the Paraná Basin. Results obtained from both methodologies (Radiometry and Palynology) show excellent coherence.

(2) The Rb–Sr isochron age obtained from the shale samples (435.9 ± 7.8 Ma) is considered as the depositional age of the Vila Maria strata. Comparison of the Rb–Sr data with numerical values in the literature indicates Early Silurian (Llandovery) as the possible minimum age for the investigated interval.

(3) Considering the statistical error of our Rb–Sr dating, the value ranges from 428.1 to 443.7 Ma, which is consistent with the proposition of McKerrow & Van Staal (2000) for the Llandovery base (443 Ma). This is also in agreement with the Early to Middle Llandovery palynological dating of the Vila Maria samples. This information restricts the Rb–Sr age span and suggests that the most reliable results are obtained when different methodologies are combined.

(4) The shaly interval investigated herein (the

'middle sequence' of the Vila Maria Formation) documents the maximum Early Silurian marine transgression over the Brazilian part of the Paraná Basin, encroaching upon diamictites and dropstones related to a glacial episode near the Ordovician/Silurian boundary (Grahn & Caputo, 1992; Assine & Soares, 1993; Assine, 2001).

(5) At least three such transgressional peaks are recorded on a global scale during Llandovery time. They can be recognized over much of Gondwana (Johnson & McKerrow, 1991; Johnson, Rong & Yang, 1984), and are also notable in Baltica (Johnson *et al.* 1991) and Laurentia (Johnson, 1987). These Llandovery floodings alternated with, and were probably controlled by, four short-lived successive glacial events in northwest Gondwana. The latter are dated: early latest Ashgill to earliest Rhuddanian; Early Aeronian (*gregarius* graptolite Zone); latest Aeronian to Early Telychian, and latest Telychian to earliest Wenlock (Grahn & Caputo, 1992; Caputo, 1998).

(6) Based on our radiometric dating (435.9 ± 7.8 Ma) and the postulated attribution of the Vila Maria samples to Sub-zone α of the *L. divellomedia* Interval Biozone (Rhuddanian to Early Aeronian age, after Steemans, Higgs & Wellman, 2000), a correlation of the Vila Maria 'middle sequence' shales with the oldest of the three global Llandovery marine transgressions seems most likely, as proposed in some previous works (Grahn & Caputo, 1992; Caputo, 1998).

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