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STRATIGRAPHIC EVIDENCE FOR DEVONIAN TECTONISM ON LINEAMENTS AT ALLEGHENY FRONT, WEST VIRGINIA--SUPPORTING MATERIAL

By

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This report is preliminary and has not been reviewed for conformity with the U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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ABSTRACT

At the Allegheny Front in northeastern West Virginia, five large structural lineaments trend northwesterly to westerly across the structural grain. This paper concludes that two and perhaps three of them separated structures that were active in Devonian time.

Along strike over about 200 km of the Front, J. M. Dennison and coworkers recognized and mapped numerous, mostly thin, shale, siltstone, sandstone, and limestone units in 18 measured sections between the Early Devonian Oriskany Sandstone and the Late Devonian Hampshire Formation. Many of these units terminate in intervals between measured sections. Nonparametric statistical analysis reveals that significant numbers of stratigraphic terminations occur in and between intervals in which three of the five lineaments intersect the Front.

The Petersburg and Fairmont-Rowlesburg and perhaps the Bartow lineaments were loci of structural control over topography, bathymetry, or both, and of structural influence on patterns of influx and dispersal of clastic sediment. It is not clear whether this pre-Alleghany activity reflects intermittent motion (1) on a strike-transverse basement fault, as occurred under similar lineaments in Pennsylvania and Alabama, or (2) between Paleozoic thrust masses advancing somewhat independently of each other. However, if the Petersburg lineament formed over a basement fault, it cannot still overlie it because the rocks containing the lineament have been detached and transported too far to the northwest. Of the five lineaments considered, the one most likely to have formed over and to still overlie a basement fault is the Parsons lineament, especially in its northwestern portion in the eastern Plateau province.

INTRODUCTION

This report contains diverse statistical, structural, and stratigraphic material that is pertinent to the arguments and conclusions of Wheeler (1984) and should be available to interested readers, but which is neither crucial enough to be included in that already long paper, nor important enough to justify separate publication in a refereed journal.

The abstract of Wheeler (1984) is repeated above, in order to provide the context of this open-file report and a link between the two papers. Tables of this report are taken from Wheeler (1984), and retain the numbering of that paper to make it easier to read both. The rest of this report covers four topics: (1) a critique of a suggestion that detached anticlines in the Plateau province of Pennsylvania were growing in Devonian time, and a suggested outline of a statistical investigation that could provide a rigorous evaluation of the suggestion; (2) a short summary of the stratigraphic sequence that was sampled by the measured sections of J. M. Dennison, for readers not familiar with the longer and more complex published descriptions and with the gross field aspects and regional relations of the units; (3) general geological and statistical considerations that influenced the design of the statistical investigation that forms the basis of this report and Wheeler (1984), and a summary of results of the analysis; and (4) principal facts of the individual statistical tests that were performed during the analysis, including references to textbooks that describe the tests and their prerequisites.

I provide the following material in the hope that it may furnish useful examples, suggestions, or guidelines to other geologists who may contemplate investigations similar to this one. More generally, both this report and Wheeler (1984) illustrate the value of appropriate statistical analysis in the investigation of small samples of standard geological data. No statistical test can ever wholly remove uncertainty. However it can remove much of the subjectivity that too often characterizes geological investigation of small samples. Also, when used properly statistical tools can change an argument about whether or not a particular perceived pattern is real into a dispute about whether we are willing to accept it as real if there is, say, one chance in twenty (or ten, or one hundred) that we would be wrong. In my experience the first sort of argument can rarely be resolved. The second sort at least provides a refreshing change, and it tells us the odds of being wrong. Such a change is an improvement worth seeking.

DEVONIAN TECTONISM IN THE PLATEAU PROVINCE OF WESTERN PENNSYLVANIA?

Harper and Piotrowski (1978, p. 313) and Piotrowski and Harper (1979, p. 22 and 23) mapped structure contours atop the Middle Devonian Onondaga Group in the Plateau province of Pennsylvania. For the same region they also mapped net feet of radioactive shale as calculated from well logs of the overlying Middle Devonian Marcellus Shale of the Hamilton Group. They note that contour lines of net thickness of radioactive shale form closed shapes that are elongate in directions parallel to trends of detached structures of the underlying Onondaga Group.

However their map of net thickness of radioactive shale is contoured by hand. By visually comparing the map distribution of their data points with the shapes of the shale isopachs, it appears that they used a subjective contouring method. That method is standard in analyses of detached terrains, and involves elongating contour patterns in directions parallel to trends of surrounding detached structures. Thus structure contours and contours of values of other variables that are known independently to vary with structure, such as bed dip or thickness of a unit that was deposited while the structures were growing, can be drawn with confidence through areas of few or no data. However for variables that are not already known to vary with structure, such as net thickness of radioactive shale, that contouring method may force the isopach patterns into an apparent but artificial similarity to the structure contours. Thus it is difficult to evaluate Harper's and Piotrowski's claim of parallel trends without an objectively contoured map of the net thickness data, probably produced by computer.

Both papers also suggest that areas with at least 125 net ft (38 net m) of radioactive shale in the Marcellus Shale coincide with structural highs at the Onondaga level. This relationship appears to the eye when plates 4 and 5 of Piotrowski and Harper (1979) are compared. The authors interpret the relationship in terms of detached structures that moved and grew during Marcellus time to produce bathymetric patterns that influenced dispersal of clays and of organic material that contains the radioactive matter. Coarse facies equivalents of the dark shales would have accumulated in synclines. However their plate 4 shows 17 areas with at least 125 net ft (38 net m) of radioactive shale. Of these, 8 areas coincide with structural highs at Onondaga level, 5 with structural lows, and 4 with intermediate areas. The suggested relationship is not completely enough stated to allow a statistical test. The sample is so small that without such a test it seems difficult to determine whether the suggested relationship is other than a chance association. Later in this paper I suggest further work that could clarify and evaluate the suggested association of thick shale with structural highs.

Finally, even if radioactive shale can be demonstrated to be thicker atop anticlines than in synclines, it is possible that the shale flowed into anticlinal cores during Pennsylvanian deformation, rather than having been preferentially deposited atop growing anticlines during Devonian time. That possibility arises from consideration of the documented structural behavior of the radioactive shales and their lithologic and stratigraphic equivalents. In the Devonian clastic rocks of the central Appalachians, relatively radioactive intervals have been found to contain dark, fissile, organic-rich shales that produce gas from extensive fracture systems (Martin and Nuckols, 1976; Patchen, 1977; Piotrowski and Harper, 1979). Those dark Devonian shales were also mechanically weak during detached deformation. They are observed to be intensely and chaotically deformed in many exposures and wells, and to be rocks in which detachments commonly ride (Wheeler, 1978). Thus the radioactive shales may have been tectonically thickened in cores of detached anticlines that grew above relatively flat, undetached strata. Elevation of the anticlinal crest would have created the space problem typical of disharmonic folds. That space problem could have been solved if the dark shales either flowed ductilely into the anticlinal core, or were structurally duplicated there by stacking of fault-bounded slices. Perry (1980) infers the existence of an example of such structural thickening of the dark shales, using subsurface data from the Mann Mountain anticline of southern West Virginia. Wheeler (1978) infers the existence of another example from folds and related structures in dark shales exposed on the Browns Mountain anticline in southeastern West Virginia.

There are two ways in which to test a structural explanation of thick, radioactive, organic-rich shales on structural highs. If the present thicknesses of radioactive shales reflect Devonian depositional patterns of organic-rich and organic-poor facies, and if coarser, organic-poor sediment accumulated in synclines, then rocks of the relatively stiffer organic-poor facies should be thicker in synclines and thinner or absent on anticlines. On the other hand, if present thicknesses reflect Pennsylvanian movement of shale into cores of growing anticlines, then stiffer units above the organic-rich shales should be no thinner on anticlines than in synclines. Those two possibilities are not mutually exclusive, but examination of subsurface thicknesses determined from gamma ray logs might be productive.

Also, Wheeler (1978) described abundant small folds, faults, and other fractures in exposed dark Devonian shales that have been penetratively deformed during detached deformation. He also described nearby exposures of the same rocks that have not been penetratively deformed. Presence or absence of that structural imprint on the shales should be recognizable in well logs. Several types of logs, tools, cameras, and cores can record the presence or probable absence of abundant fractures, contorted and disrupted bedding, and abundant slickensides. If such indicators appear to be absent in the radioactive shales in a given well, then the present thickness of the shales is probably of depositional rather than structural origin.

The rest of this section suggests statistical work that could test the Harper-Piotrowski hypothesis that radioactive shale is thicker on structural highs than in structural lows under the Plateau province of Pennsylvania.

The hypothesized association is a positive one, between net feet of radioactive shale penetrated in a well drilled through the Marcellus Shale of the Devonian Hamilton Group, and structural elevation of the base of the Marcellus Shale, that is, the top of the underlying Onondaga Group. The appropriate test would be of Pearson's correlation coefficient. If it is feared or found that the assumptions of that test are not met by the data, then a test of Spearman's rank correlation coefficient would suffice. Each sample would consist of a pair of values of net radioactive thickness and of structural elevation from one well. Net thickness values can be read directly from the map of Plate 4 of Piotrowski and Harper (1979).

Values of structural elevation can be calculated from the subsea elevations recorded on Plate 5 of Piotrowski and Harper (1979). The subsea elevations are not themselves the desired structural elevations because the subsea elevations generally deepen to the southeast. The structural elevations needed are those which created the inferred bathymetric highs during Marcellus time. Those elevations are the differences between the subsea elevations of the Onondaga tops now (as recorded on Plate 5), and their elevations at the start of the deposition of Marcellus sediments in Middle Devonian time. The present elevations of the Onondaga tops for each well can be read from the map of Plate 5 of Piotrowski and Harper, which shows structure contours atop the Onondaga Group. The Middle Devonian elevations are those from which the detached anticlines rose to reach their present heights. Any uplift, subsidence, tilting or warping since that time will drop out at each well when Middle Devonian elevation is subtracted from present elevation.

Thus the problem is that of estimating the Middle Devonian elevations. Here a suggestion of Gwinn (1964) is useful. He noted that in cross section many Appalachian synclines have trough lines whose elevations fall on straight lines sloping gently to the southeast. He suggested that the synclines were passive structures, containing rocks that remained at their pre-detachment structural levels, and that the anticlines were active structures, which rose above the level of the synclinal troughs. Thus the Middle Devonian elevations for each well should be approximately the elevations of a trend surface fit to elevations on Onondaga tops in or near troughs of todays synclines. If such wells are sparse they could be supplemented by values estimated from cross sections drawn through appropriate portions of the structure-conton map of Plate 5 of Piotrowski and Harper (1979).

The trend surface should probably be of a second degree polynomial in order to approximate the expected shape, which is a broad trough plunging gently to the southeast. If that form is unsuitable, a machine-contoured and -smoothed map of trough elevations may suggest a more appropriate form, or could suffice instead of a trend surface.

Such an analysis may seem needlessly elaborate, but the following simpler approach failed to detect the suggested association. One hundred and seventy-six wells in the southeastern half of the area mapped by Piotrowski and Harper were classified as lying on anticlinal crests, in synclinal troughs, or in unclear structural positions. Structural position for each well was determined from plate 5 of Piotrowski and Harper, but only for areas where the structure depicted on that map was consistent with structure shown on the more detailed map of Cate (1961). Cate drew structure contours on the Oriskany Sandstone, which immediately underlies the Onondaga Group and deforms with it as part of the same stiff structural unit. Assignment of structural position was purposely conservative. Consequently the crestal and troughal categories each contained one sixth or fewer of the 176 wells.

Then nonparametric statistical tests were used to investigate whether net thicknesses of radioactive shale greater than 125 feet (138 meters) are associated with crestal wells in preference to troughal wells. No significant association was found, either by the Chi-squared test using the Yates correction for a 2 by 2 table (Siegel, 1956, p. 107-190), by the Fisher exact probability test, which is more suitable than the Chi-squared test for small sample sizes (Siegel, 1956, p. 96-104), or by the Kruskal-Wallis test, which uses more of the information contained in the data than do the Chi-squared or Fisher tests (Siegel, 1956, p. 184-193).

In fact, thicknesses are very slightly greater in troughal than crestal wells. However that difference is far from significant. Thus a carefully designed statistical analysis, informed by stratigraphic and structural knowledge of the rocks involved, appears to be necessary in order to evaluate the suggested association between structural position and net thickness of radioactive shale.

If the suggested association proves to be statistically significant, then several further investigations are possible. First, regression analysis may enable prediction of net shale thickness to be expected in areas not yet drilled. That could produce useful results because in the Marcellus Shale net radioactive thickness is linked to gas content through organic content.

Second, additional growth of the anticlines in Pennsylvanian time may not have occurred everywhere. If so, then scatter plots and maps of regression residuals may locate individual anticlines or areas in which Pennsylvanian growth accentuated Devonian anticlines.

Third, Plate 5 of Piotrowski and Harper (1979) can be interpreted to suggest that structural elevation, net thickness of radioactive shale, or both decrease to the northeast, across the approximate position of the Tyrone - Mount Union lineament. The lineament is a cross-strike structural discontinuity (CSD: Wheeler, 1980) trending northwest across central Pennsylvania, and is one of the CSD's that is most likely to have formed over and to still overlie a long-active basement fault (Diment and others, 1972; Diment and others, 1980; see especially numerous papers by authors associated with The Pennsylvania State University and listed by Wheeler and others, 1979, and Chaffin, 1981). To test the visual impression of an association of structural elevation and net thickness of radioactive shale with the lineament, the data of Piotrowski and Harper could be divided at the lineament into two portions, and the portions analyzed separately. If the suggested difference is significant, then the lineament separated two detached blocks that deformed partly or entirely independently in Middle Devonian and perhaps Pennsylvanian time.

Finally, it is possible that depositional patterns of the radioactive shale and related rocks were influenced by syndepositional tectonism, but that the growing structures were not caused by Devonian detachment, but instead were reactivated basement faults. Such basement faults would be most likely to trend northeasterly through the area studied by Harper and Piotrowski, and to have formed in early Paleozoic time as normal faults. Those normal faults would have developed in the rifting episode that gave birth to the Rome trough and to the Iapetus Ocean with its passive continental margin (see reviews in Bollinger and Wheeler, 1982, and Chaffin, 1981). Most such faults dip to the southeast (Wagner, 1976; Chaffin, 1981) but some dip to the northwest (Berg, 1980). An additional complication is the likelihood of northwest-striking faults in the basement, which may have experienced several tens of kilometers of strike slip in Precambrian or early Paleozoic time (Chaffin, 1981). How one would evaluate the possibility of basement influence on shale deposition probably cannot be decided until results are known for some of the analyses described in preceding paragraphs.

MEASURED STRATIGRAPHIC SECTIONS

Along the Allegheny Front in Maryland, West Virginia and Virginia, John Dennison and coworkers have measured and interpreted 18 stratigraphic sections along about 200 km of strike belt, in exposures of the Middle and Upper Devonian clastic wedge (Dennison, 1970; McGhee and Dennison, 1976 and 1980; Dennison and Hasson, 1974, 1976 and 1977; Hasson and Dennison, 1977; Avary and Dennison, 1980). The sections are distributed along the southeast-facing hillslopes and adjacent northeast-trending valley, on the southeast side of the topographic scarp of the Allegheny Front. The papers give lithostratigraphic and biostratigraphic descriptions, field appearances and locations, chronostratigraphic and biostratigraphic ages, local and regional correlations, and formal and informal names.

In general the sequence examined by those authors and considered in this paper is that of the Catskill delta as expressed in the central Appalachians. The lower portion of the sequence comprises mostly thin marine dark shales and siltstones with some limestones. The rocks become coarser-grained and lighter in color upward. Many of the siltstone beds are turbidites. The upper portion comprises mostly thicker sandstones and siltstones, with common reddish and brownish beds. The sequence is bounded below by the Lower Devonian Oriskany Sandstone, and above by the red beds of the upper Upper Devonian Hampshire Formation. The Oriskany and Hampshire are omitted from the measured sections and from the discussion of this paper.

Dennison and coworkers found many named and unnamed units that are typically from about 10 to several hundred meters thick, and can be recognized and correlated along the entire strike belt, in measured sections typically separated by about 10 km. In particular the disappearance of a unit from one section to the next can be recognized. These terminations of stratigraphic units in the intervals between measured sections form the data that were analyzed statistically for this paper and Wheeler (1984).

The terminations are shown schematically in Tables 1, 2 and 3. The statistical analysis to follow will seek significant patterns and anomalies in the way the terminations are distributed among the intervals between measured sections, as recorded in Tables 1, 2 and 3.

STATISTICAL ANALYSIS: GENERAL CONSIDERATIONS

The data subjected to statistical analysis are the numbers of terminations in the various intervals, as recorded in Tables 1, 2 and 3.

Effect of small samples

Tables 1 and 2 respectively contain only 12 and 18 terminations. These numbers are so small that some readers may question whether statistical analysis is justified at all. Indeed many of the most widely familiar statistical methods are invalid or of limited usefullness for such small samples.

However a class of methods known as nonparametric contains many tests suitable for small sample sizes, as well as for other situations in which more familiar methods break down. The most widely known nonparametric test is the Chi-squared, but even that breaks down by becoming overly sensitive for samples as small as those analyzed here. The nonparametric tests used in this paper are named in the next section ("....Principal facts") together with citations of textbooks containing clear and well-illustrated instructions and precautions for their use. In numerous investigations in the past decade colleagues and I have found these and other nonparametric tests to be flexible, easily calculated, and powerful tools in the exploration of many types of standard geological data, and in the evaluation of subtle patterns and anomalies that we have found or think we have found in such data. Such sturdy and dependable statistical aids are particularly useful in analyses of small samples, because it is in just such cases that a pattern or anomaly that may be visually striking could have a high probability of arising by chance alone. In fact it can be argued that statistical tests become most needed when sample sizes are small, because then visual impressions can be most misleading. A later discussion of some analytical results begins with an example of just that pitfall.

Effects of sea-level changes

The observed distributions of terminations among the intervals can be affected by local, regional, and global changes of sea level (Dennison and Head, 1975; McGhee and Dennison, 1980; Dennison, 1980). Local sea level changes are likely to record just the anomalies that this analysis seeks, so their occurrence will not distort the results reported and interpreted below. Regional and global sea level changes are also not a problem here, for two reasons. First, widespread changes that occur during deposition of a particular thin unit, such as changes that are glacially induced, are likely to move the termination of the unit from one interval to another in a manner that would be hard to distinguish from a random change. That is, such widespread changes are more likely to destroy or blur patterns or anomalies in the distribution of terminations than to accentuate real anomalies or create false ones. Protection against the potentially misleading effects of randomness is one of the purposes of a statistical test. Second, widespread sea level changes that operate over the times of deposition of many successive units, like basin subsidence, will tend to shift the entire package of terminations to the northeast or southwest, rather than to disrupt the relative positions of the individual terminations within the package.

Effect of an oblique shoreline

The Allegheny Front is not parallel to Devonian shorelines and depositional trends, which trended more northerly, both for individual units and for the entire sequence (Kepferle and others, 1977; sheets 1 and 2 of de Witt and others, 1975; Lundegard and others, 1980; Potter and others, 1980; Clausen and McGhee, 1981). However the Front may still be regarded as a randomly located section through the stratigraphic sequence. Then the observed terminations constitute a random sample and are acceptable for statistical analysis. The Front is a randomly located section with respect to the Devonian depositional systems because the Front is localized and oriented by the Wills Mountain anticline and adjacent structures, whose positions cut across and therefore are not affected by the depositional patterns of Devonian rocks.

Independence of terminations

The individual terminations must be independent of each other, in the sense that the probability of a termination is the same whether any other termination is given or not (Kendall and Buckland, 1971, p. 70). Here that means that the occurrence or nonoccurrence of any particular termination in an interval does not affect the probability that any other termination will occur in the same interval.

There are two ways in which such independence might fail. One is if a succession of terminations all had the same local cause. For instance, a succession of siltstones might all be dammed by continual growth of the same anticline, and so would all occur in the same interval. If such dependence occurred, then Tables 1, 2 and 3 would record it because each dependent termination would occur in or close to the interval containing the next older termination. Perusal of the Tables indicates that such dependent terminations are rare or absent, with one exception. That is the group of 5 southwestern terminations of successive siltstones and silty shales, from the lower tongue of the Mahantango Formation up to the Clearville Member (Table 1). However such a concentration of terminations is just the sort of anomalous pattern that this paper attempts to find and interpret. It is not the sort of dependence that would invalidate the statistical analysis.

The second way in which independence might fail could occur if units are genetically linked. For example, consider a facies change by which a siltstone with shales above and below is replaced laterally by an equivalent limestone bounded by the same two shales. The terminations of the siltstone and the limestone are not independent of each other, because each localizes the other. Another example involves the Pokejoy Member (Hasson and Dennison, 1974), a fossiliferous limestone whose fauna are suggested to have grown on the firm silty substrate of the underlying Clearville Member. The Pokejoy termination is not independent of the Clearville termination.

In each of the two examples just cited the solution is to count one termination, not two. Such genetic dependencies have been avoided in identifying terminations in Tables 1, 2, and 3. However Table 3 was constructed to record all terminations, including those of units mapped but not discussed or named by Dennison and coworkers. It is possible that some of the broadly intertonguing units, whose terminations are collectively distributed over several adjacent intervals, are weakly dependent. Thus conclusions drawn from analysis of Table 3 may be less reliable than those drawn from Tables 1 and 2.

Significance level

The statistical analysis involves numerous individual tests. That affects the choice of significance level. The more tests and significance values one calculates, the greater is the chance that one or more results will be significant by chance alone. (That is the statisticians Type I error: false rejection of a true null hypothesis.) Thus the habitual level of 0.05 is too high. This problem is formalized by the Bonferroni inequality (Miller, 1966, p. 8; see Wheeler and Holland, 1981, and Jones-Cecil and others, 1981, p. 14-18 and 85-94, for geological applications).

I know of no general guidelines to aid in determining how much smaller than 0.05 the significance level should be. Choice of too small a significance level could lead to a Type II error: failure to detect and reject a false null hypothesis, that is, failure to detect a real anomaly or pattern in the distribution of terminations. Often a preference for a Type I error rather than a Type II error, or vice versa, is influenced by consideration of the practical consequences of each type of error. For example, in a speculative geological investigation, the consequences of an error would be different than in, say, a pre-marketing toxicity test of a new drug.

Nineteen individual tests were calculated for the analysis summarized here. Strictly conservative application of the Bonferroni inequality would dictate choice of a significance level of 0.05/19, or about 0.003. That would be too small to be useful. However, the 19 actual significance values (P-values, or associated probabilities: Gibbons, 1976, p. 11-15) are grouped. 8 are roughly evenly distributed between 0.004 and 0.03, one is 0.05 or greater, and the remaining eleven exceed 0.2. It seems reasonable to choose a significance level of 0.03. That gives 8 of the 19 results in which the null hypothesis is rejected.

Use of nonparametric tests

This paper uses only nonparametric tests, for two reasons. First, the distributions of the populations from which the samples of terminations were drawn are wholly unknown. There seems no reason to assume normal or other specified distributions. Second, the sample sizes are small. For instance, in no case was a sample large enough to allow use of the Chi-squared test. In several cases even Fisher's exact probability test (Siegel, 1956, p. 96-104) lacked useful resolving power for such small samples, though the test remained valid. For such small samples the extra computational effort usually associated with a nonparametric test is not a deterrent to its use.

Effect of incomplete measured sections

Some of the measured sections are incomplete. For the most part this occurs in the southwestern three sections. There, stratigraphic work concentrated mostly on the Back Creek Siltstone Member of the Brallier Formation (Table 1; Avary and Dennison, 1980). However incompleteness of those sections is probably not a serious problem. All units of Table 1 except the Back Creek Siltstone Member terminate before reaching those southwestern sections, and so are not affected by the incompleteness. It is possible that new units exist in the southwest, in the upper portion of the sequence that was not measured there. That is unlikely, because mappable units other than dark shales disappear southwestward along the line of sections. In the northeast, the dark shales are distinguishable in part because they are bounded by distinct units of other lithologies. Southwestward, the dark shales converge and merge as the other units disappear, so that it seems unlikely that units other than the dark shales exist to the southwest, undetected.

Table 2 and the analyses based on it do not extend as far southwest as those incomplete sections, and so are not affected by them. Table 3 would be affected, because it includes those sections. The effect of undetected terminations of unknown units would be to increase the P-values of some of the central intervals with numerous terminations in Table 3, and to decrease the liklihood of a Type I error. However considerations of independence have already led to conclusions based on Table 3 being identified as perhaps less reliable than those based on Tables 1 and 2.

For all these reasons it seems permissible to assume that incomplete sections are unlikely to invalidate seriously the conclusions of this paper.

Results of the statistical analysis

In the following paragraphs, reference is given parenthetically to specific test results that are reported in the following section (......"principal facts"), for instance "(test 1)".

Despite visual impressions created by Tables 1, 2, and 3, there is no evidence for any broad exceptions to the statement that the terminations are scattered more or less evenly among the intervals. In particular, there is no evidence for systematic increases to the northeast or southwest in frequency of terminations per interval (tests 1, 6 and 12), or for terminations to cluster progressively toward the center of any particular portion of the string of intervals (tests 2, 7 and 13). That conclusion shows how misleading is the strong visual impression created by Tables 1 and 3, of a peak in the number of terminations in the several intervals northeast of Mouth of Seneca or Moyer Run. Similarly, the visual impression of a northeastward increase in termination frequency is misleading. The reason for such a contradiction between visual impressions and statistical results is that the sample size of Table 1 is too small and the clustering of Table 3 too subtle to be distinguishable with confidence from clustering or other patterns that could arise by chance alone.

However several individual intervals contain significantly large numbers of terminations in particular portions of the stratigraphic sequence. In the lower portion of the sequence that is true for the interval containing the Petersburg lineament (Table 1, test 3), but not for the interval containing the Parsons lineament. The interval containing the eastward projection to the Allegheny Front of the Fairmont-Rowlesburg lineament contains as many terminations as does that containing the Petersburg lineament (Table 1). That is evidence that the Fairmont-Rowlesburg lineament extends at least as far east as the Front, and has a length of at least about 120 km. On the other hand the Morgantown-Sang Run and Bartow lineaments project eastward into intervals that do not contain significantly large numbers of terminations. Thus those lineaments either do not extend to the Front, or did not affect deposition of the lower portion of the sequence, or both.

In the upper portion of the sequence, none of the five lineaments occurs in intervals with significantly large numbers of terminations (Table 2, test 8).

In the sequence taken as a whole only the Fairmont-Rowlesburg lineament is associated with a significant number of terminations (Table 3, tests 14 and 15). The interval containing the Parsons and Petersburg lineaments is significant only if combined with that containing the Fairmont-Rowlesburg lineament (test 16). The significant effect of the Fairmont-Rowlesburg lineament in the sequence as a whole arises from terminations of three unnamed brownish gray, grayish red, and olive gray units in the Foreknobs Formation of the upper portion of the sequence, from one termination of an unnamed unit without sandstones at the top of the Scherr Formation, and from terminations of two unnamed tongues of dark shale in the middle of the Millboro Shale Formation in the lower portion of the sequence (compare Table 3 with Tables 1 and 2). As already mentioned, such terminations may be less accurately located than those of units that are named, discussed, or both by Dennison and coworkers in their various papers cited above. Thus the effect of the Fairmont-Rowlesburg lineament on the upper portion of the sequence may be less certain than its effect on the lower portion.

Whether clastic sources for particular portions of the sequence lay more to the northeast or more to the southwest can be inferred from the proportions of southwestern and northwestern terminations. In the lower portion of the sequence southwestern terminations dominate (test 4). Most of the terminated units are siltstones, silty shales, sandy units, or limestones containing fauna that are inferred to have grown on silty substrates. Thus the clastic source lay somewhere to the southeast, but more to the northeast than to the southwest. That is consistent with thickness and facies patterns for the whole Devonian clastic sequence (Colton, 1970, p. 35-36; de Witt and others, 1975, sheet 1).

Terminations in the Brallier Formation do not indicate a northeastern source (Tables 1, 2 and 3). However that exception is consistent with the depositional model suggested for Brallier turbidites by Lundegard and others (1980). They concluded that the turbidites that dominate the Formation flowed northwestward from numerous local point sources distributed for more than 350 miles (560 km) along strike of the paleoslope, rather than from a few major sources in the northeast.

Neither is there evidence for a preferred source direction in the upper portion of the sequence, or in the sequence as a whole (tests 9 and 17). That is consistent with the depositional mechanism suggested by McGhee and Dennison (1980, p. 282) for the reddish and brownish units whose terminations dominate the upper portion of the sequence. They suggest that oxidized nonmarine sediment was swept offshore to the northwest nearly simultaneously from many local delta lobes to form each of the individual brownish and reddish units. That could occur as lobes prograded when regional sea level dropped (McGhee and Dennison, 1980, p. 282), or as delta fronts became oversteepened when regional sea level rose (Dennison, 1980). Then on the scale of the string of measured sections southwestern terminations should be as likely as northeastern ones.

In the lower portion of the sequence terminations are significantly concentrated in the intervals between Moyer Run and Route 50 or Pinto (Table 1, test 5). The terminations in those intervals are mostly southwestern ends of silty units. Thus apparently during times of deposition of most units of Table 1, bathymetric highs between Moyer Run and Route 50 or Pinto dammed southwesterly or southerly transport of clastic sediment from the northeasterly source.

In the upper portion of the sequence, terminations of brownish-gray units are significantly abundant in the intervals between Hopeville Gap and Route 642 (Table 2, test 10). There is no evidence for a preferred source direction for the clastic sediment (test 11). If one or both of the depositional models of McGhee and Dennison (1980, p. 282) and Dennison (1980) are correct, then those intervals may have contained an unusually large number of discrete delta lobes or other bathymetric or topographic highs or northwestward projections, which shed oxidized sediment to the northwest as sea level changed.

The three intervals between Mouth of Seneca and Route 50 contain the Petersburg and Fairmont-Rowlesburg lineaments. For the sequence as a whole those intervals also contain a significantly high proportion of the terminations of Table 3 (test 18), though without a preferred source direction (test 19). In light of the probable northeastern component of sources for the lower portion of the sequence, and of the depositional models cited above for the turbidites of the Brallier Formation and the brownish and reddish beds of that and younger formations, the concentrations of terminations in those three intervals allows the inference that throughout deposition of the sequence, the terrain between and containing the Petersburg and Fairmont-Rowlesburg lineaments localized bathymetric or topographic highs that affected dispersal patterns of clastic sediment.

STATISTICAL ANALYSIS: PRINCIPAL FACTS

Lower portion of sequence

The following test results apply to the upper Middle Devonian to lower Upper Devonian sandstones, siltstones, and limestones between the Purcell Member and the Scherr Formation (Table 1).

(1) The first two tests are designed to select the distribution of the null hypothesis, from which significant departures can then be sought.

TEST 1 tests the visual impression that Table 1 records a systematic northeastward increase in the number of terminations per interval, across the 17 intervals. The appropriate test is that of Spearman's rank correlation coefficient (Siegel, 1956, p. 202-213). The alternative hypothesis is the one-sided one of a northeastward positive association between the number of terminations per interval and the number of the interval. The P-value after correction for ties exceeds 0.250, so the conclusion is that there is no evidence for such a northeastward increase in the frequency of terminations.

TEST 2 considers whether there is any non-random pattern in the distribution of terminations among the 17 intervals of Table 1. In particular, is there either a non-random alternation of intervals with many terminations and intervals with few, or as seems more likely, is there a cluster of intervals near the northeast end of Table 1, in which terminations are unusually frequent? The appropriate test is that of runs up and down (Davis, 1973, p. 184-191; Gibbons, 1976, p. 363-378). The alternative hypothesis is the one-sided A- of Gibbons (p. 372-373), that there is an unusually small number of runs. That would reflect the suspected clustering of terminations between Moyer Run and Route 50. There are several ties, or adjacent intervals with the same number of terminations, so the runs test requires calculation or estimation of P-values for all possible assignments of ties to runs up and to runs down. Except for the most extreme such assignments, all P-values exceed 0.500, so the conclusion is that there is no evidence for a clustering of terminations between Moyer Run and Route 50.

Therefore the null hypothesis from which significant departures are to be sought is that the 12 terminations are drawn from a population that is uniformly distributed among the 17 intervals.

(2) The next test is designed to determine the significance of the observation that the Petersburg lineament is associated with 3 terminations. That is, the lineament intersects the Allegheny Front in an interval that contains 3 terminations.

TEST 3: the appropriate test is the binomial. The alternative hypothesis is the one-sided one that the probability of any given termination falling in the interval containing the lineament exceeds 1/17. Note that we are not concerned here with how the other terminations fall into the other intervals. In particular, the hypothesis is phrased so that it is irrelevant that one other interval also contains 3 terminations. If the null and alternative hypotheses were worded to include that other interval, the resulting P-value would double and preclude significance at 0.03. In fact the P-value of the stated hypothesis is just 0.03, so the conclusion is that the Petersburg lineament is associated with an unusually large number of terminations.

(3) The next two tests are designed to evaluate the observation that most units in Table 1 terminate to the southwest, and also the observation that the terminations appear to concentrate in the intervals between Moyer Run and either Route 50 or Pinto.

TEST 4 considers whether southwestern terminations are significantly more common in Table 1 than are northeastern terminations. The appropriate test is the sign test (Gibbons, 1976, p. 94-106; Siegel, 1956, p. 68-75). The Back Creek Siltstone and Pokejoy Members each have both terminations within the strike section sampled, and so cannot be used. However all 8 of the remaining terminations are southwestern ones. Thus this test is also one of whether a sample size of 8 is large enough to achieve significance. The alternative hypothesis is the one-sided one that the probability of a southwestern termination rather than a northeastern one exceeds 0.5. The P-value is 0.004, so the conclusion is that southwestern terminations are preferred for the rocks and geographic area represented by Table 1.

TEST 5 considers whether terminations in Table 1 are unusually concentrated in the 4 (or 6) intervals northeast of Moyer Run. The appropriate test is the randomization test (Conover, 1971, p. 357-364; same as the permutation test of Mosteller and Rourke, 1973, p. 12-19). The test is based on the sum of the numbers of terminations in any 4 (or 6) of the 17 intervals. The alternative hypothesis is the one-sided one that there is a preference for terminations to fall in the 4 (or 6) intervals immediately northeast of Moyer Run. The P-values are 0.029 for the 4 intervals northeast of Moyer Run, and 0.016 for 6 intervals. The conclusion is that those 4 to 6 intervals do contain anomalously many terminations.

Upper portion of sequence

The following test results apply to the Upper Devonian grownish-gray interbeds of the Brallier, Scherr, and Foreknobs Formations (Table 2). Questions to be answered, statistical tests used, null and alternative hypotheses, and other details are modeled after those just described for the lower portion of the sequence and Table 1, so discussions here will be brief.

(1) TEST 6: Spearman's test finds no evidence that the number of terminations per interval decreases systematically to the northeast (P-value exceeds 0.250).

TEST 7: the runs up and down test finds no evidence of general non-randomness in the distribution of terminations among the intervals (P-value exceeds 0.500).

Thus again the null hypothesis is that the 18 terminations are drawn from a population that is uniformly distributed among the 11 intervals.

(2) TEST 8: the binomial test finds no evidence that the interval containing the Parsons and Petersburg lineaments has an unusually large number of terminations (P-value = 0.221).

(3) TEST 9: the sign test finds no evidence that there is a preference for southwestern terminations over northeastern ones, or vice versa (P-value = 0.500).

TEST 10: the randomization test, based on the sum of the numbers of terminations in any 4 of the 11 intervals, finds that terminations of the brownish-gray interbeds are significantly concentrated in the 4 intervals south of the Parsons lineament (P-value = 0.012).

TEST 11: however, within those southwestern intervals, the sign test finds no evidence for southwestern terminations being preferred over northeastern ones, or vice versa (P-value = 0.500).

Entire sequence

The following test results apply to the combination of the terminations of Tables 1 and 2 with those of other, less well defined, mostly unnamed units in the Middle and Upper Devonian rocks between the Oriskany Sandstone and the Hampshire Formation (Table 3). Again, analysis was similar to that already described.

(1)TEST 12: Spearman's test finds no evidence that the number of terminations per interval increases systematically to either the northeast or the southwest (P-value exceeds 0.250).

TEST 13: the runs up and down test finds no evidence for general non-randomness in the distribution of terminations among the intervals (P-value = 0.384).

Thus again the null hypothesis is that the 63 terminations are drawn from a population that is evenly distributed among the 11 intervals.

(2) TEST 14: the binomial test finds no evidence that the interval containing the Parsons and Petersburg lineaments has an unusually large number of terminations (8 of the 63 terminations; P-value = 0.210).

TEST 15: however, the binomial test does find that the interval between Scherr and Route 50 contains a significantly large number of terminations (11 of the 63; P-value = 0.024).

TEST 16: furthermore the randomization test, based on the sum of the numbers of terminations in any 2 of the 11 intervals, finds that a significant number of terminations fall in those 2 intervals (P-value = 0.018). That is, the interval between Scherr and Route 50 and that containing the Parsons and Petersburg lineaments together contain a significant number of terminations.

(3) TEST 17: the sign test finds no evidence of a preference for southwestern terminations over northeastern ones, or vice versa (P-value = 0.435).

TEST 18: the randomization test, based on the sum of the numbers of terminations in any 3 of the 11 intervals, finds that terminations fall preferentially in the 3 intervals between Mouth of Seneca and Route 50 (26 of the 63 terminations; P-value = 0.012).

TEST 19: however, within those 3 intervals the sign test finds no evidence for preference of southwestern terminations over northeastern ones, or vice versa (P-value = 0.402).

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TABLE CAPTIONS

Table 1.--Terminations from the lower portion of the sequence. Vertical lines show relative positions of all 18 measured sections are named at the top of the table; they do not indicate completeness of exposure. Horizontal lines show lateral spans of named stratigraphic units, with terminations shown by x's. Sources indicated: D, Dennison (1970); AD, Avary and Dennison (1980); DH, Dennison and Hasson (1977). At the bottom of the table are numbers of terminations in each interval, the interval numbers, and the intervals in which a lineament or its eastward extension intersects the Allegheny Front: Bartow (B), Parsons (PA), Petersburg (PE), Fairmont-Rowlesburg (FR), and Morgantown-Sang Run (MS).

Map symbols for Tables 1-3 are as follows: Df is Foreknobs Formation, Ds is Scherr Formation, Db is Brallier Formation, Dh is Harrell Shale, Dmt is Mahantango Formation, Dm is Marcellus Shale, and Dn is Needmore Shale.

Table 2.--Terminations of brownish gray interbeds in the upper portion of the sequence. Notations are as for Table 1, with these differences: (1) only 12 sections are measured through this portion of the sequence; (2) the Briery Gap Run section of this table lies between the Judy Gap and Ketterman Knob sections of Table 1; and (3) source is McGhee and Dennison (1976).

Table 3.--Highly schematic depiction of all terminations from entire sequence. Notations are as for Table 1, with these differences: (1) x's represent terminations shown in Tables 1 and 2, except for the omission of the southwestern termination of the Back Creek Siltstone Member of Table 1 in order to merge Tables 1 and 2; (2) o's represent terminations of other units not shown in Tables 1 and 2, but obtained as described by Wheeler (1982); and (3) the Briery Gap Run section of Table 2 is equated with the Judy Gap and Ketterman Knob sections of Table 1.

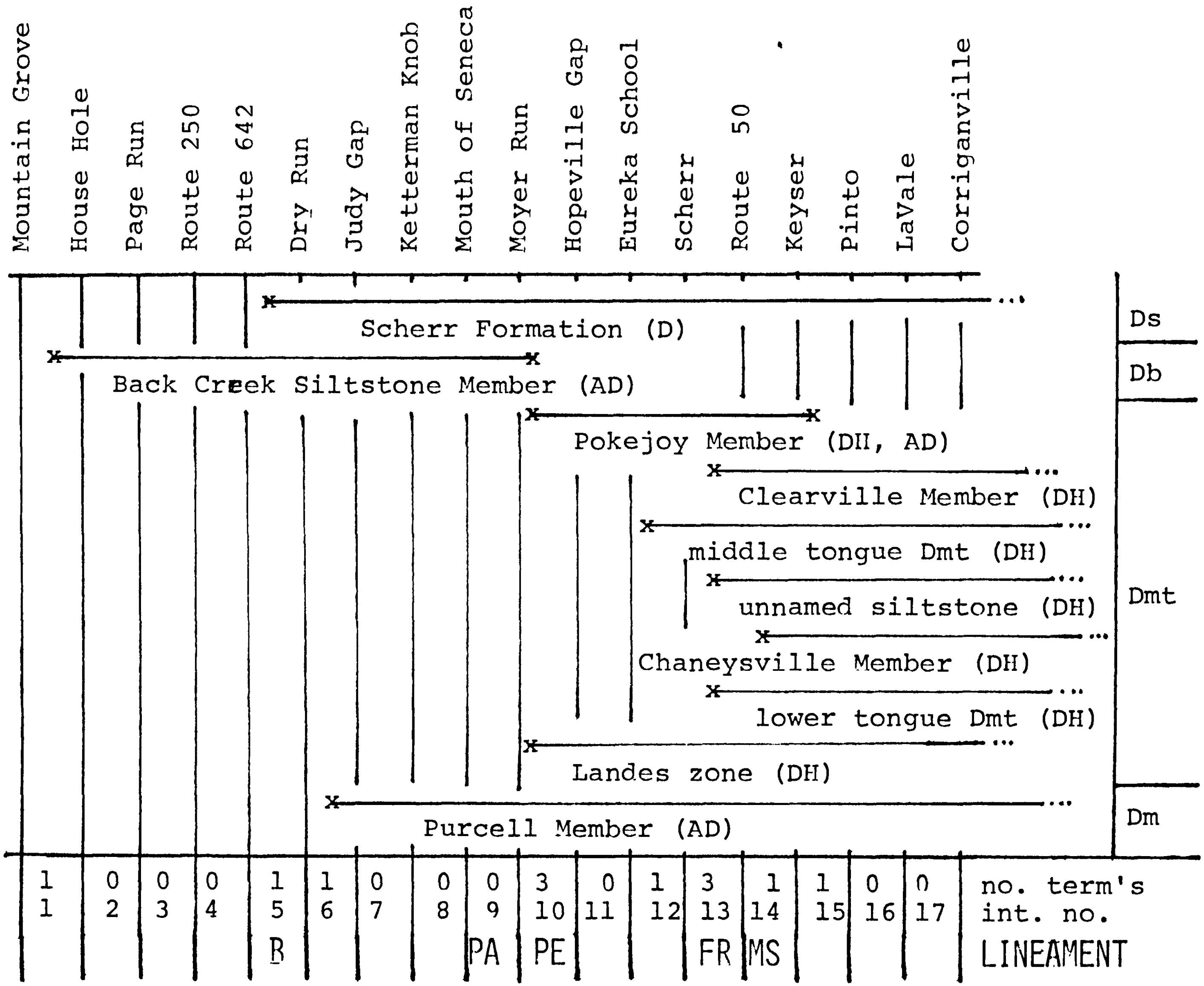

Table 1. Terminations from the lower portion of the sequence.

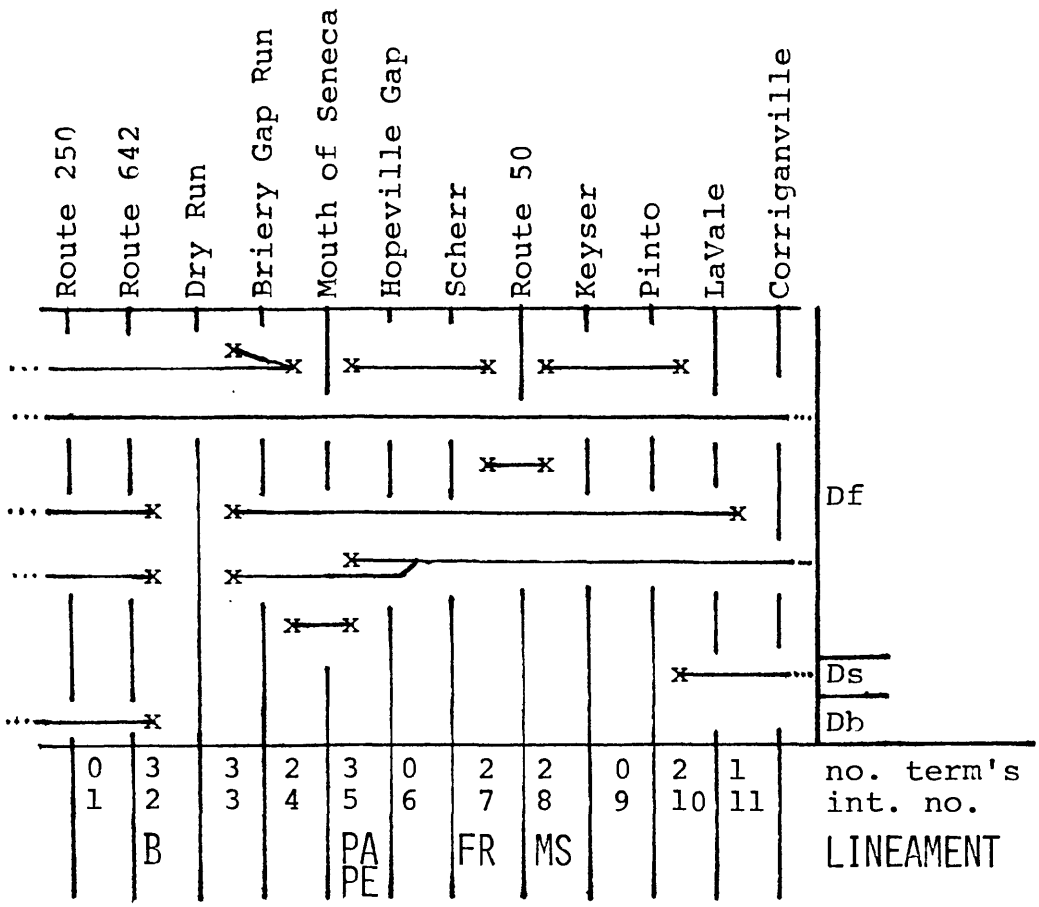

Table 2. Terminations of brownish gray interbeds in the upper portion of the sequence.

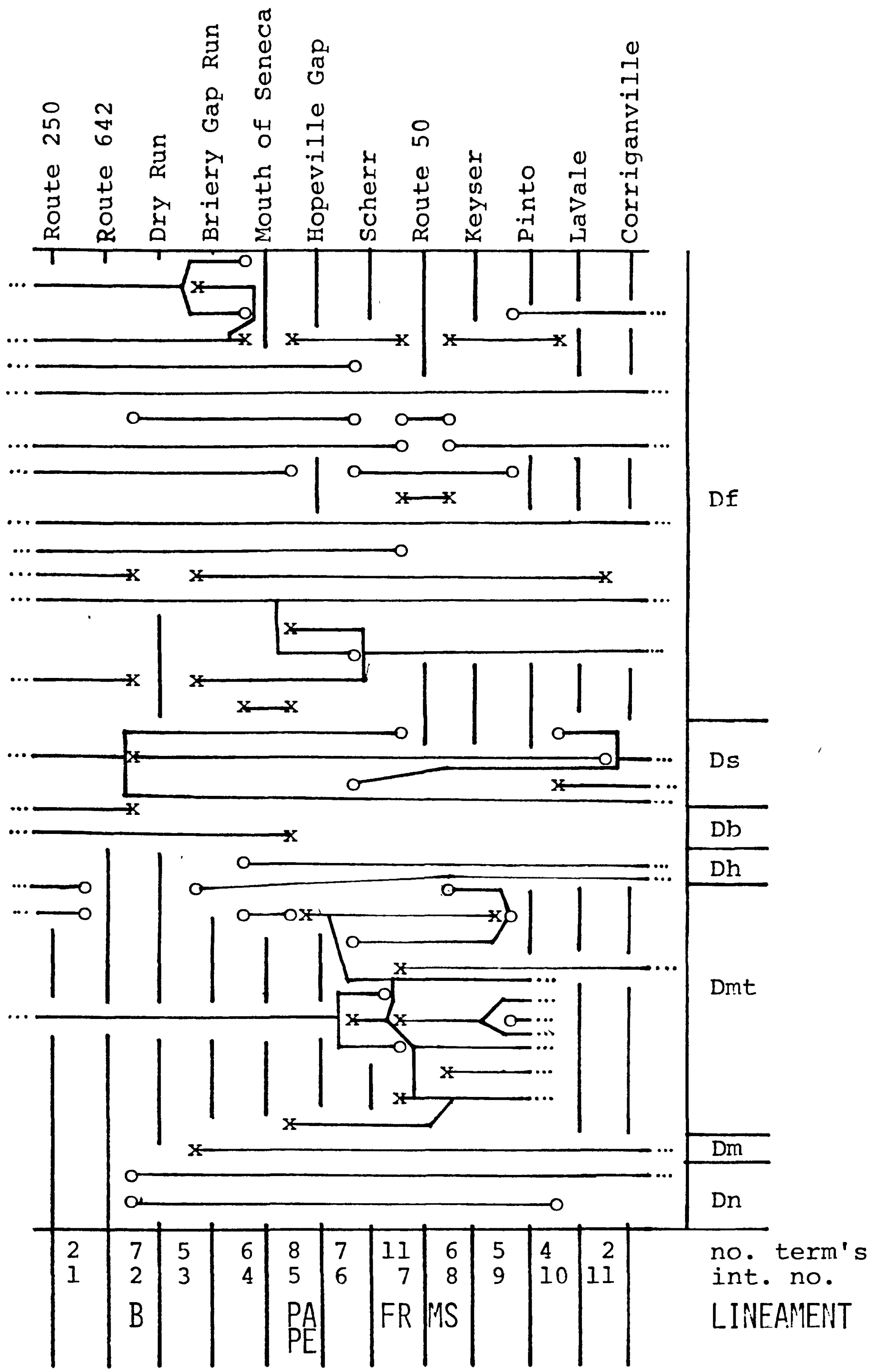

Table 3. Highly schematic depiction of all terminations from entire sequence.