Rather, the facies sequence of PACs in the Upper Tonoloway at Tyrone more closely resembles the Tonoloway PACs below PAC 1 at localities to the south.

Although lacking confirming evidence, this correlation is offered as a conservative solution to the regional correlation problem. The lack of correlation of the uppermost Tonoloway PAC at Tyrone with PACs 1-5 to the south suggests that this PAC must correlate lower in the Tonoloway Formation. This correlation is conservative because correlation lower in the Tonoloway Formation increases the amount of section missing at Tyrone and lengthens the depositional hiatus that occurred there. An interpretation of the dynamics which produced this disconformity based on stratigraphic and structural information is provided in more detail in the the Basin Dynamics section of this thesis.

In conclusion, the correlations presented in this study (Plate 1) are the result of three methods of PAC correlation. In particular, five groups of facies related PACs, separated by major punctuation events are observed in the interval at all sections and can be correlated throughout the study area. Also, PAC boundaries which are produced by major deepening events at PACs 8, 13, and 16 have been used as primary correlation surfaces, and several PACs containing unique facies have been recognized at all sections. The position of surfaces produced by major deepening events in sequence and relative to PACs with unique facies remains constant, as does the number of PACs in a sequence and between major deepening events.

Previous workers have constructed correlations in this interval based on biostratigraphic techniques using range zones [Reeside, 1917], assemblage zones [Bowen 1967, Head, 1969] and based on occurrence of lithologic facies changes in the interval at the member and formational scale [Head, 1969]. While these correlations have seemed useful assuming a model of gradual accumulation, a small-scale approach to this interval from an episodic perspective reveals correlations on a finer scale than previously determined. This detailed time-stratigraphic framework can now be used to determine the paleoenvironmental and paleogeographic relationships of these PACs and the basin dynamics which produced the interval.

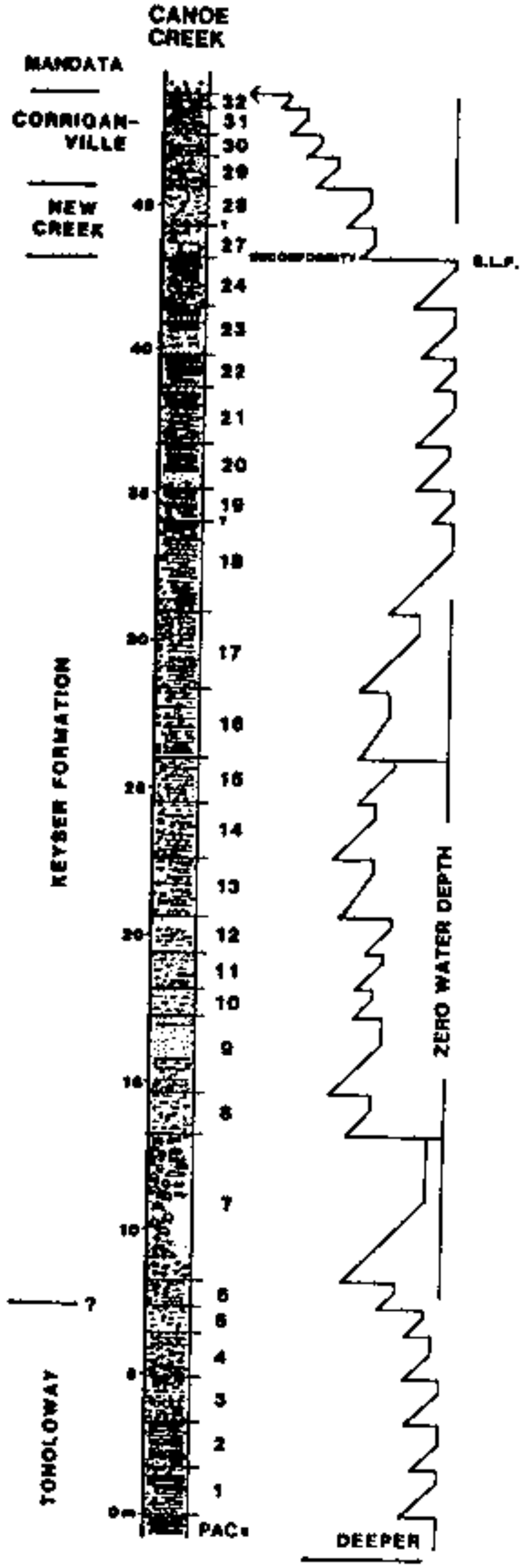
PALEOENVIRONMENTS and PALEOGEOGRAPHY

Pac boundaries provide the time-stratigraphic framework necessary to complete a detailed "paleogeographic reconstruction of individual PACs based on the occurrence of facies and therefore, the depositional environments that occur within a PAC prior to each punctuation event" [Saraka, 1985 p. 43]. By classifying facies into four environments: shelf, subtidal, intertidal and supratidal, it is possible to simplify the depositional history of a PAC and construct a cross-sectional view of an individual PAC.

Groups of PACs of similar facies are described for their vertical and lateral facies variation and a single PAC , 'typical' of this group is used for paleotopographic reconstruction. The cross-section of each 'typical' PAC is constructed utilizing the upper PAC boundary as the surface of topographic expression relative to sea-level, and the lower PAC surface as the lower limit of that specific PAC based on the interpretation of the topography inherited from the PAC below. No correction for thickness has been incorporated to account for gradual subsidence or compaction, opposing factors which tend to neutralize each other as contributors to thickness.

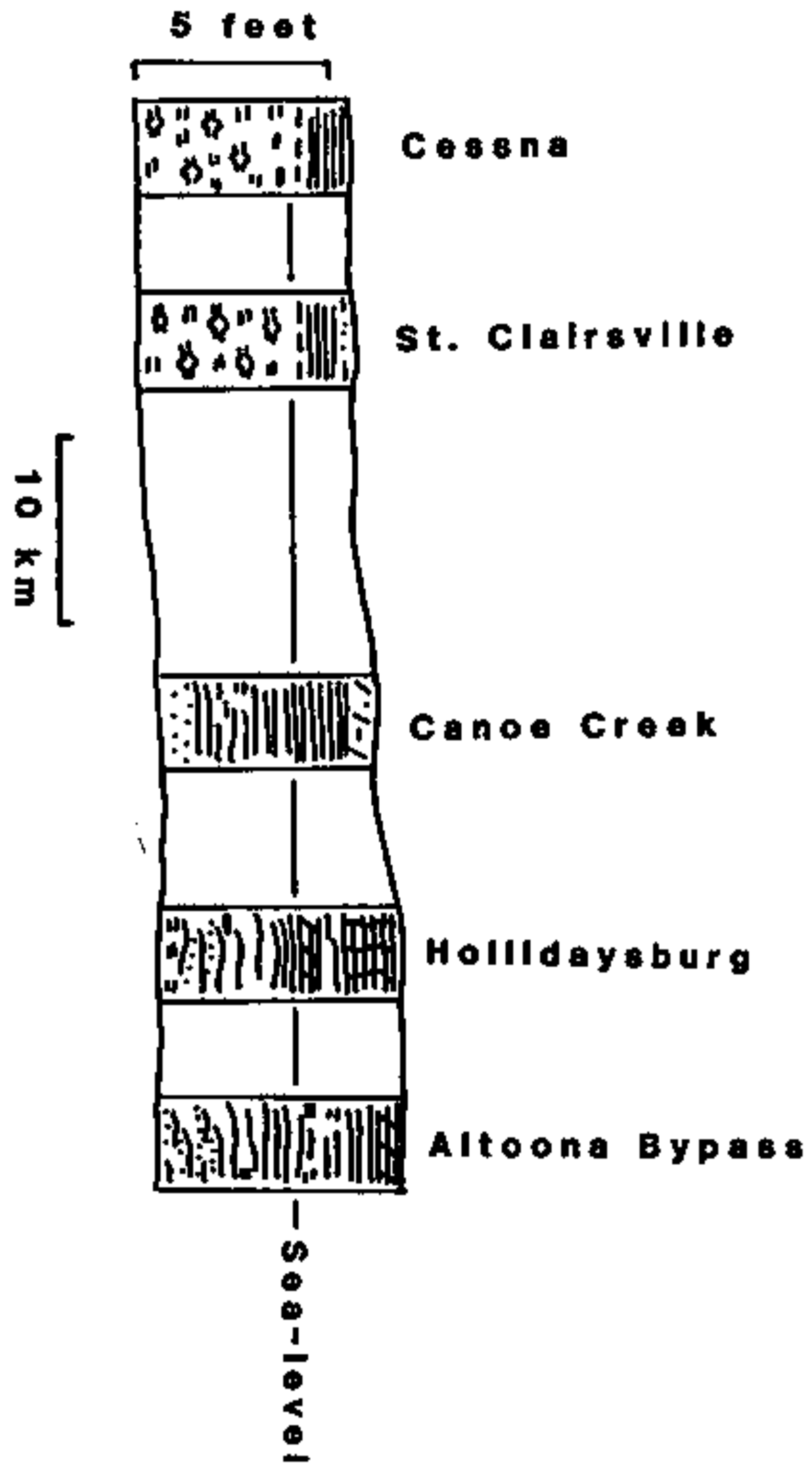
The facies in PACs 1-5 consist mostly of shallow subtidal, intertidal and supratidal environments. These PACs show limited lateral variation in facies and thickness (Plate 1). PAC 1, typical of this group, is exposed at

Figure 27.
Stratigraphic column with water depth curve, Canoe Creek.


CANOE CREEK
MANDATA
CORRIGAN-VILLE
NEW CREEK
KEYSER FORMATION
TONOLOWAY
UNCONFORMITY
S.L.F.
ZERO WATER DEPTH
DEEPER
PAC
32
31
30
29
28
27
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

CANOE CREEK

Figure 28.
Paleotopographic reconstruction of PAC 1.


5 feet
Cessna
St. Clairsville
10 km
Canoe Creek
Hollidaysburg
Altoona Bypass
Sea-level

PAC 1

five localities and is approximately 2.5 meters thick. Since the base of PAC 1 is a sea-level surface at every locality (Plate 1), this surface is construed to be essentially horizontal for the paleotopographic reconstruction (Fig. 28). Differential subsidence to the south allowed slightly more open facies to develop at the base of PAC 1 at Cessna and St. Clairsville. These facies consist of argillaceous calcisiltite containing small stromatoporoids, ostracodes and gastropods (Fig. 12). Lateral facies variation within PAC 1 show that the remainder of the PAC is nearly entirely intertidal, except for local supratidal environments in the Canoe Creek and Hollidaysburg area (Fig. 28). The intertidal facies consist of ribbon-bedded micrite and cryptalgal laminites overlying shallow subtidal, pelloidal and sorted calcarenite at Canoe Creek, Hollidaysburg and Altoona Bypass. At Hollidaysburg the cryptalgal laminites are mudcracked in the upper 1.5 feet and at Canoe Creek PAC 1 is capped by a massive dolomicrite.

PACs 6 and 7 represent environments transitional between the tidal PACs 1-5 and the shelf facies of PACs 8 and 9 (Plate 1). Both PACs 6 and 7 consist of either shallow subtidal or intertidal facies. The base of PAC 7 overlies the shallow subtidal or intertidal facies of PAC 6. The top of PAC 6 had an irregular topography, the cycle having shallowed to near sea-level at Canoe Creek and Allegheny Furnace while remaining subtidal elsewhere.

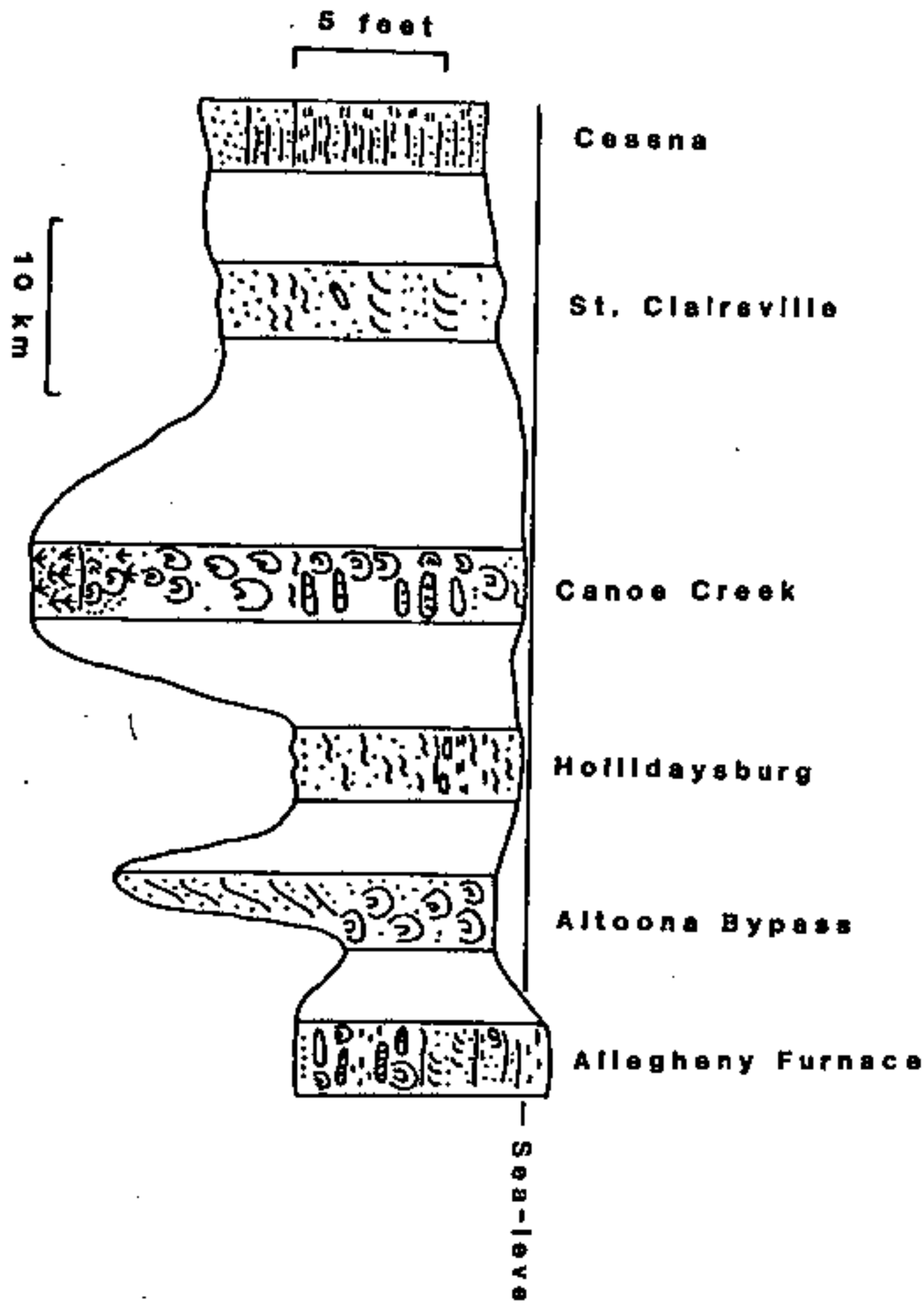
Thus, the base of PAC 7 cross-section (Fig. 29) is irregular owing to this inherited topography. PAC 7 ranges in thickness from 2 to 5 meters. The base of PAC 7 overlies the shallow subtidal or intertidal facies of PAC 6. This contact is locally erosional with as much as two meters of PAC 6 eroded by channeling and filled by the coarser facies of PAC 7 as observed at Altoona Bypass (Fig. 29).

PAC 7 consist of shoal facies and near-shoal facies expressed as bedded and current-sorted calcarenite at Cessna, St. Clairsville. At Canoe Creek, Allegheny Furnace and Altoona Bypass PAC 7 consists largely of biohermal facies as stromatoporoid and favositid-rich calcarenite (Fig. 25) which locally shallows to intertidal barren micrite.

The shoal and near shoal facies of PAC 7 are interpreted to be open subtidal facies while the biohermal facies are interpreted to be shallow subtidal to intertidal.

The deepening event which terminated the PAC 6 and 7 sequence, initiated deposition of PAC, 8 introduced the deepest facies of the interval and was sufficiently large to inundate the exposed surface at Allegheny Furnace and Tyrone (Plate 1). PACs 8-12 consist of shelf and subtidal facies. The deepest facies of the interval was deposited in PAC 8. PAC 12 is used as the 'typical' PAC of this group for its degree of lateral facies variation. PAC 12

Figure 29.
Paleotopographic reconstruction of PAC 7.


5 feet
10 km
Cessna
St. Clairsville
Canoe Creek
Hollidaysburg
Altoona Bypass
Allegheny Furnace
Sea-level

PAC 7

is also somewhat typical of this group in that it is nearly a single-facies PAC at every locality. Irregular inherited topography, differential subsidence and variation in sedimentation rates contributed to the facies variation with PAC 12 (Fig. 32). For example, the deepest facies in PAC 12 are at Canoe Creek, Hollidaysburg, and Altoona Bypass. Here these facies consist of subtidal, bioturbated calcarenites, capped by sorted calcarenites at Canoe Creek. To the south PAC 12 is generally shallower, consisting largely of current-sorted calcarenite. Slightly shallower facies occur at Allegheny Furnace and Tyrone as fossilliferous, bioturbated calcarenite that contain halysitid, favositid and rugose corals, bryozoans, stromatoporoids and various brachiopods (Figs. 30 and 31).

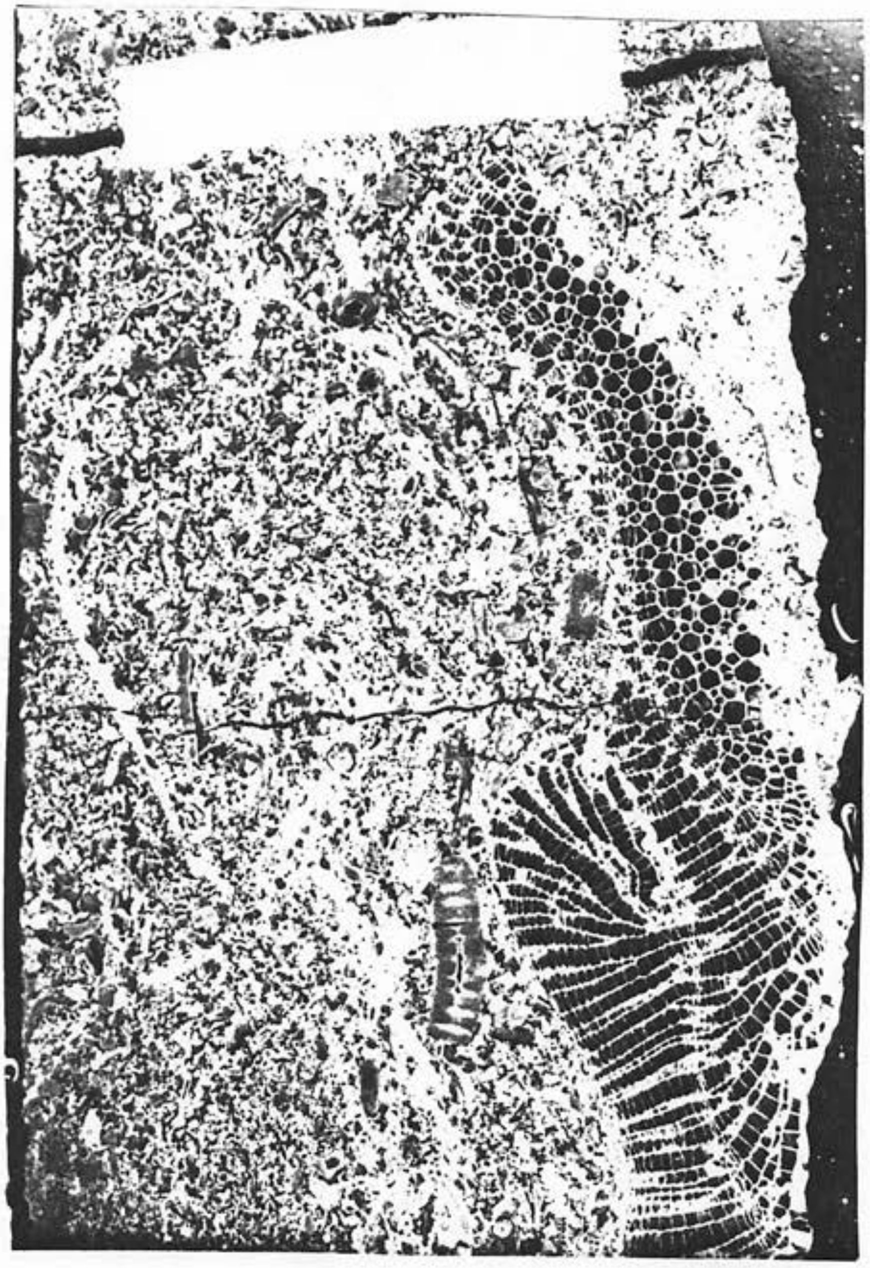
A major deepening event initiated PAC 13, as indicated by a marked facies change at all localities in the study area (Plate 1) and illustrated by a large deflection to the left in the water depth curve (Fig. 27). PACs 13-15 make up a group of PACs that contain facies transitional between the shelf facies of PACs 8-12 and the peritidal sequence of PACs 16-22. The lateral facies and thickness variations in PAC 13 are useful in demonstrating the paleoenvironments and paleogeography of this group of PACs. The cross-section of PAC 13 (Fig. 34) illustrates the basin was deeper to the south during deposition of this PAC, most likely due to differential subsidence.

The facies in the northern portion of the study area

Figure 30.
Thin-section photonegative (T-12). Fossiliferous calcarenite of base of PAC 12 at Tyrone. Note halysitid corals, top and middle and scattered fragments of brachiopods, trilobities. Bar scale = 1 inch. Up direction toward left side of page.

Figure 31.
Thin-section photonegative (T-11) from middle of PAC 12, Tyrone. Bioturbated fossiliferous calcarenite contains bryozoans, crinoids and brachiopod and trilobite fragments. Note large favositid coral at bottom. Bar scale = 1 inch. Up direction toward left side of page.

Figure 32.
Paleotopographic reconstruction of PAC 12.



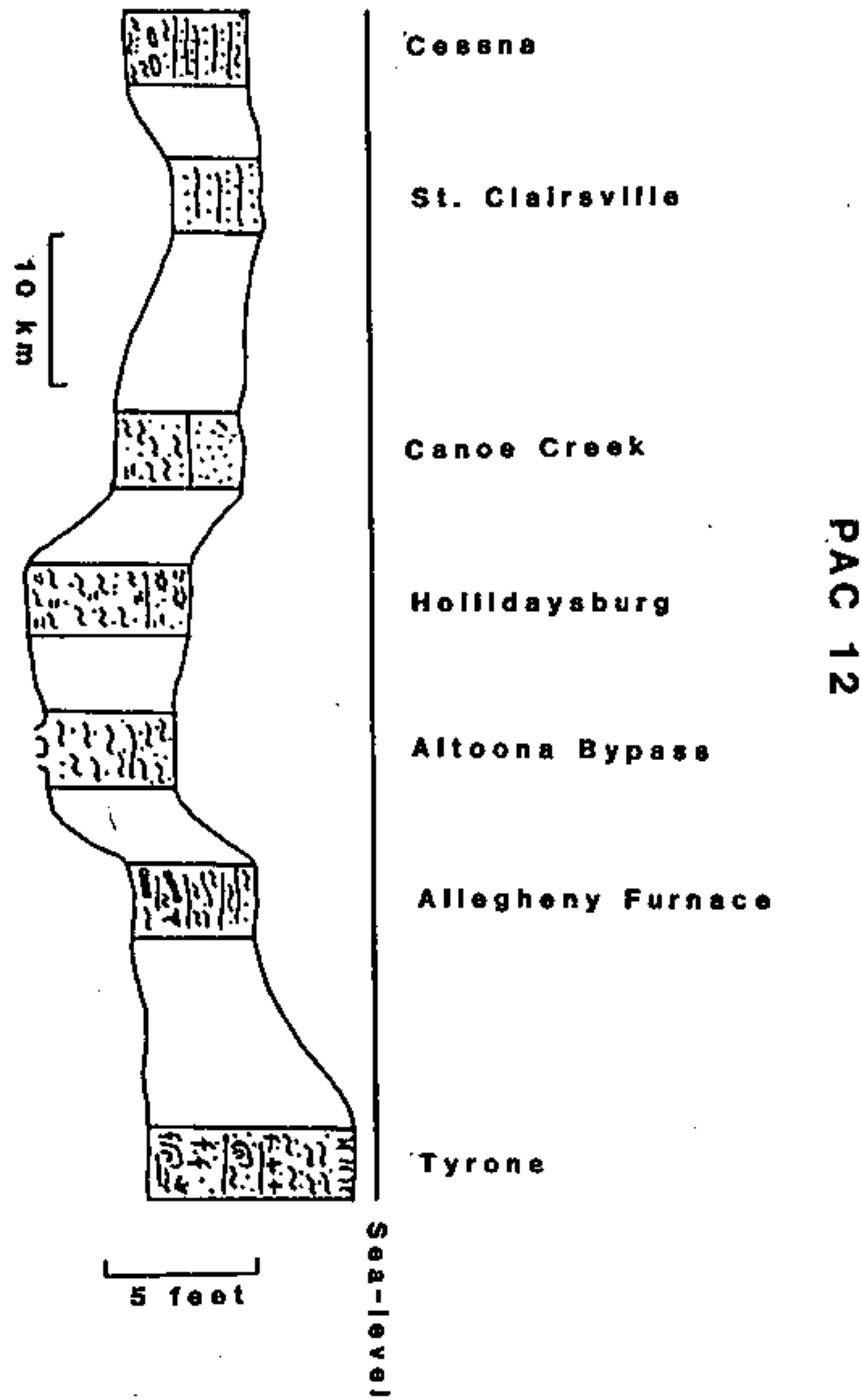
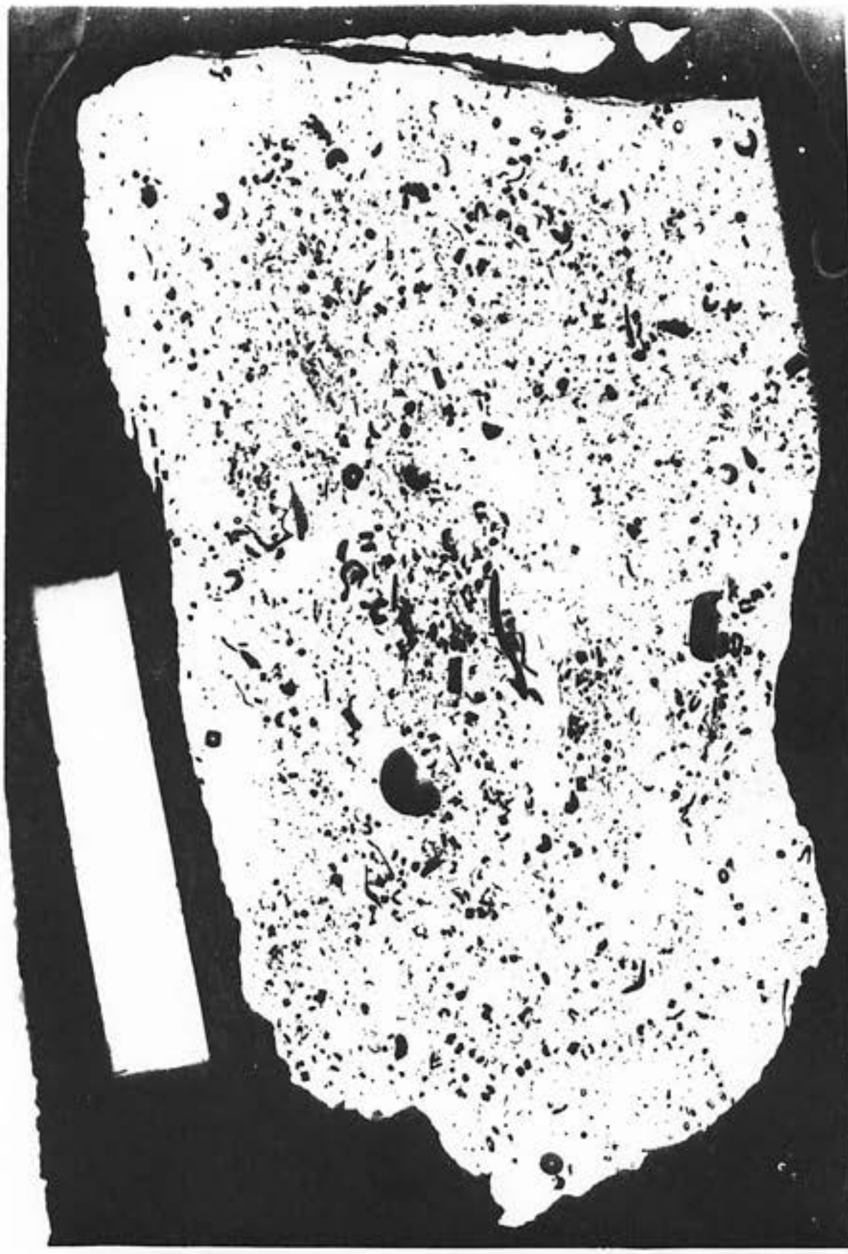

PAC 12
Cessna
St. Clairsville
Canoe Creek
Hollidaysburg
Altoona Bypass
Allegheny Furnace
Tyrone
10 km
5 feet
Sea-level

Figure 33a.
Thin-section photonegative (T-13). Bioturbated fine calcarenite from middle of PAC 13, Tyrone. Note fragments of trilobites, middle, and crinoid ossicles. Bar scale = 1 inch. Up direction toward left side of page.

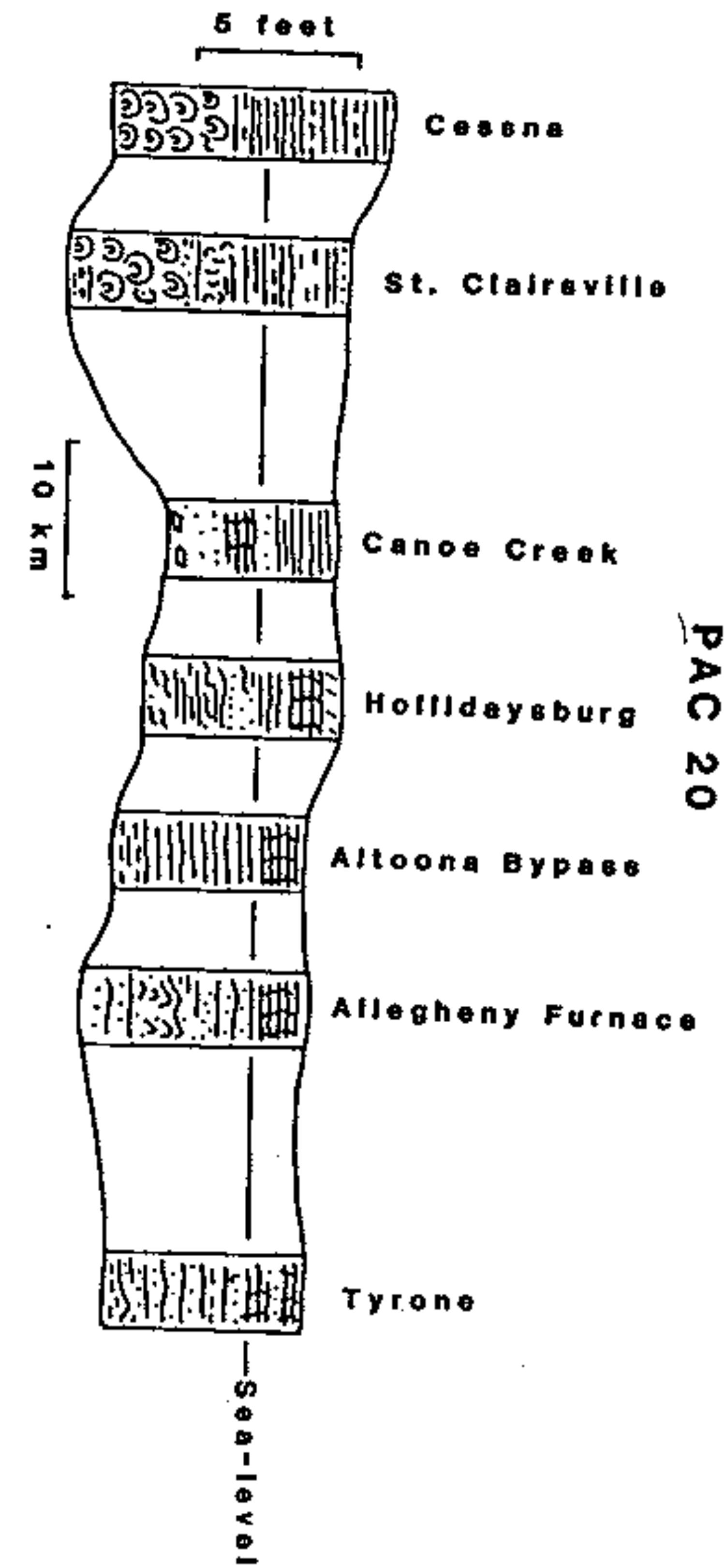


represent shallow subtidal environments, occurring as bioturbated calcarenite containing diverse and abundant faunas of favositid corals, stromatoporoids, bryozoans, crinoids, trilobites and brachiopods (Fig. 33). To the south the facies of PAC 13 represent open subtidal environments. The deposition in PAC 13 at Canoe Creek, St. Clairsville and Cessna is interpreted as turbiditic or tempestitic, as the facies consist of interbedded calcarenite, calcisiltite and shale containing a sparse fauna, consisting of *Atrypa reticularis*, favositid corals (Fig. 33) which becomes bedded and finer upward accompanying a decrease in faunal abundance.

PACs 16-22 comprise a group of peritidal facies PACs that represent the lower portion of a shallowing PAC sequence which continues to the top of the Keyser Formation. This sequence was initiated by a major deepening event that initiated deposition of subtidal facies in PAC 16. PAC 20 is a typical PAC in this shallowing PAC sequence. Because the top of PAC 19 is a sea-level surface the base of the cross-sectional paleotopographic reconstruction (Fig. 34) of PAC 20 should be essentially horizontal. However, differential subsidence and higher sedimentation rates contributed to deposition of locally deeper facies and accumulation of a thicker interval. The punctuation event that initiated PAC 20 introduced shallow subtidal facies at all localities. The lateral basal facies variations in PAC 20 are due to

Figure 33b.
Paleotopographic reconstruction, PAC 13.

Figure 34.
Paleotopographic reconstruction of PAC 20.


5 feet
Cessna
St. Clairsville
10 km
Canoe Creek
Hollidaysburg
Altoona Bypass
Allegheny Furnace
Tyrone
Sea-level
PAC 20

variations in circulation and sediment supply and are all approximately depth equivalents. These subtidal facies vary, including thrombolitic micrite and current-sorted calcarenite at Tyrone and Allegheny Furnace, bedded and bioturbated micrite at Altoona Bypass and Hollidaysburg, clast-bearing calcarenite at Canoe Creek and massive stromatoporoid basal calcarenite at Cessna and St. Clairsville. The upper portion of PAC 20 consists of tidal facies at all localities which consist largely of laminites, locally interbedded with micrite or fine-grained calcarenite. The cryptalgal laminites are locally mudcracked, generally in the uppermost portion of the PAC. A massive, supratidal dolomicrite developed at the top of PAC 20 at Hollidaysburg.

The reconstruction of paleogeography using PACs as fundamental time-stratigraphic units permits a much more detailed analysis of paleoenvironments than methods used by traditional workers. For instance, both Rickard [1962] and Head [1969] discuss the migration of facies belts with gradual migration during the Late Silurian and Early Devonian. The lateral relation of paleoenvironments to one another is better understood when lateral facies changes are traced within small-scale, time-stratigraphic units, PACs. Traditional stratigraphers reconstruct paleogeographies for basins or continents based on gross lithofacies relationships [e.g. Heckel, et al., 1979]. The variation of facies within a single PAC provides a much more detailed framework for paleogeographic reconstruction.

BASIN DYNAMICS

Correlations using PACs as fundamental allostratigraphic units "reveal basin dynamics not discernible from a gradualistic perspective" [Goodwin et al., 1986]. Correlation of PACs and their boundary surfaces makes possible the interpretation of detailed patterns of uplift, erosion, and differential subsidence, as well as the patterns of small-scale base-level fluctuations responsible for the stratigraphic sequence. In this section I will discuss the effects of uplift, erosion and differential subsidence on the study interval.

Because PACs are created by basinwide deepening events, PACs missing at any section may indicate uplift and erosion, or nondepostion [Anderson et al., 1984; Buggey and Goodwin, 1984; Sullivan and Anderson, 1986]. Within the study interval the most striking stratigraphic anomaly is the missing section at the Keyser-Tonoloway formation boundary at Tyrone. The Tonoloway-Keyser formation boundary here is marked by an abrupt change from tidal facies of the uppermost Tonoloway PAC to shelf facies of PAC 8. The major facies discontinuity at this boundary was created by a major punctuation event. Migration of shelf facies over tidal facies with gradual transgression is not a sufficient explanation for this vertical juxtaposition of facies because these environments could not have been contiguous. Correlations indicate that PACs 1-7 are absent at Tyrone, producing a major stratigraphic discontinuity.

Figure 35.
Diagram illustrating differential uplift to the north and subsidence to the south producing unconformity at Tyrone.

I interpret this stratigraphic discontinuity to be the result of uplift in the Tyrone area exposing this section. The basin to the south was simultaneously differentially subsiding and PACs 1 - 7 were being deposited (Fig. 35). No real evidence exists at Tyrone to suggest that a significant amount of erosion occurred there, but the presence of a dolomitic paleosol (Fig. 26) at this horizon indicates that this area was subaerially exposed prior to deposition of PAC 8 (Fig. 26). Uplift of the Tyrone area must have created a local topography too high to have been flooded by the punctuation events that initiated deposition of PACs 1 - 7. An alternative explanation is that at least some of the PACs 1 - 7 were deposited at Tyrone and subsequently eroded prior to depostion to PAC 8. However, no evidence exists for significant erosion in the interval containing PACs 1 - 7 at any of the six localities to the south (Plate 1). Evidently, the punctuation event that initiated PAC 8 was sufficiently large to inundate the topographic high at Tyrone depositing open subtidal facies directly upon the paleosol. Uplift in this area had apparently slowed or ceased by this time.

Other structural and stratigraphic information on this region seems to support this interpretation. Several authors have produced supportive evidence of a cross-strike lineament (Tyrone - Mt. Union lineament) in central Pennsylvania [Gold, 1973; Canich, and Gold, 1977; Rodgers and Anderson, 1984; and others]. Surficial evidence for this lineament includes alignment of stream and river valleys, wind and water gaps and fold terminations in Blair and Huntington counties. Canich and Gold [1977] completed a study of joint densitites and fracture traces as well as fold orientations in this area, and with utilization of landsat imagery have mapped this lineament trending aproximately 315 degrees through central Pennsylvania. Gravity and magnetic anomalies indicate this lineament is a basement feature extending from the Great Valley of southeastern Pennsylvania to near Erie in northwestern Pennsylvania [Rodgers and Anderson, 1984]. Lavin et al. [1982] suggest at least 60 kilometers of lateral displacement occurred along this "crustal block boundary" during late Precambrian to Ordovician time.

Rodgers and Anderson, [1984] maintain that activity occurred along this lineament from Silurian through Early Pennsylvanian time, stating nonspecifically that stratigraphic thickness and facies variations occur in several Devonian through Early Pennsylvania formations. They purport that the lineament is the southern boundary of an uplift in north-central Pennsylvanian, indicating that the Helderberg Group is among the stratigraphic intervals which show this effect of the lineament. "The apparent lack of influence of the lineament in certain stratigraphic units may be owing to a lack of information rather than inactivity along this zone" [Rodgers and Anderson, 1984, p.438]. Application of the Hypothesis of Punctuated

Aggradational Cycles has made it possible to discern the effect of the lineament on the Upper Tonoloway - Lower Keyser interval. This effect has eluded previous workers because of their failure to establish detailed correlations at a small scale.

Recognition of two synchronous paleoisotopographic surfaces in the interval makes it possible to discern a nearly absolute amount of differential subsidence between Tyrone and Cessna, a distance of 70 kilometers [Goodmann and Goodwin, 1985; Anderson et al., 1986; Goodmann et al, 1986] The two paleoisotopographic surfaces are sea-level surfaces which occur at the top of two PACs. Sea-level surface #1 is the top of the PAC directly below PAC 1 except at Tyrone, where the surface occurs at the top of the uppermost Tonoloway PAC directly below PAC 8; sea-level surface #2 is the top of PAC 22 (Plate 1). Because these two surfaces were essentially level at the time of deposition, inherited topography is eliminated as a contributor to differences in stratigraphic thickness between these two surfaces at different localities. Therefore, any thickness difference between these two surfaces is attributable only to differential subsidence, assuming equal compaction in similar facies (Fig. 36).

Specifically, the stratigraphic thickness between sea-level surface #1 and sea-level surface #2 is 25.5 meters at Tyrone and 43 meters at Cessna (Fig. 37). Thus, as much as 17.5 meters of differential subsidence has

Figure 36.
Differential Subsidence Model.

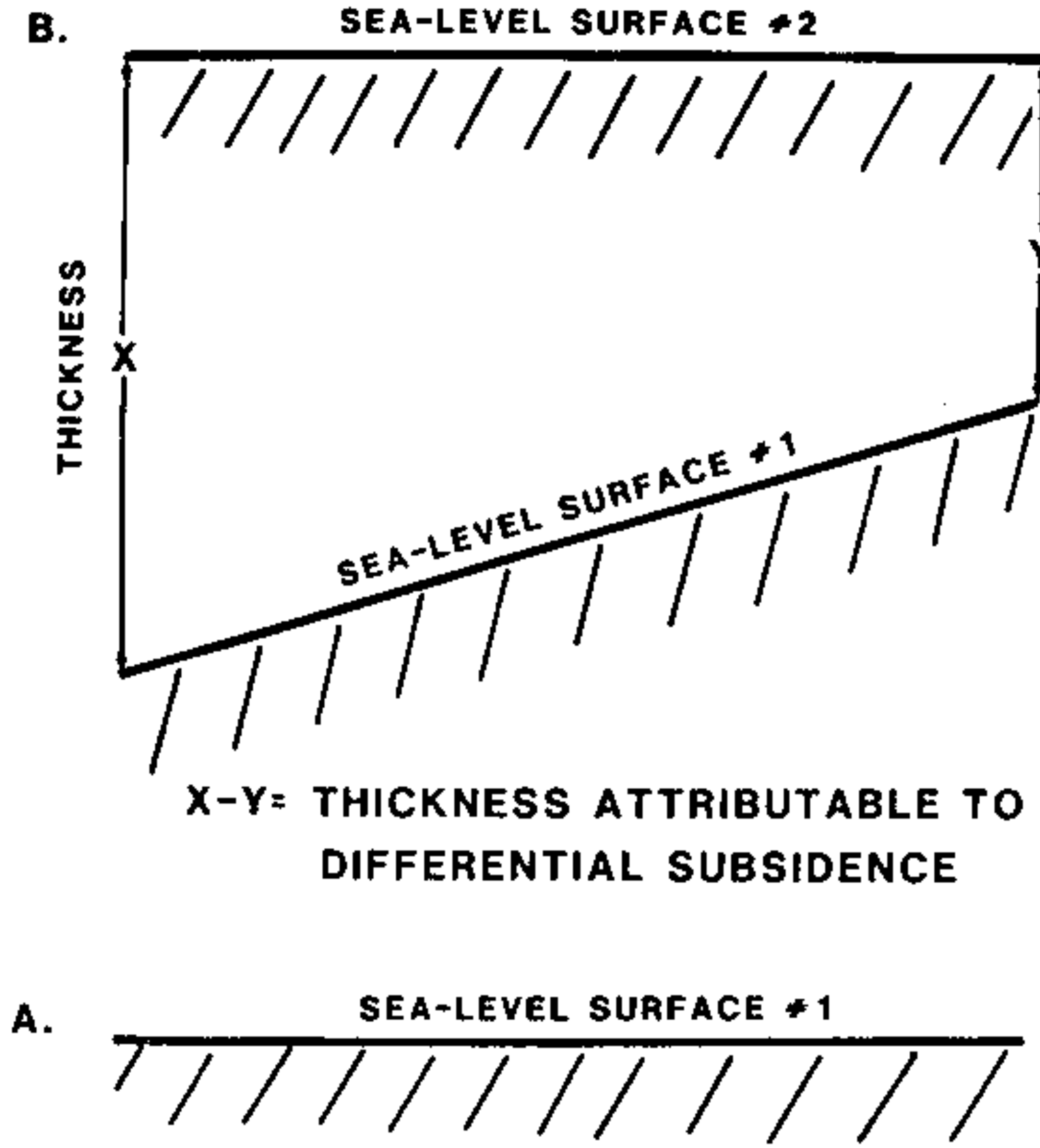
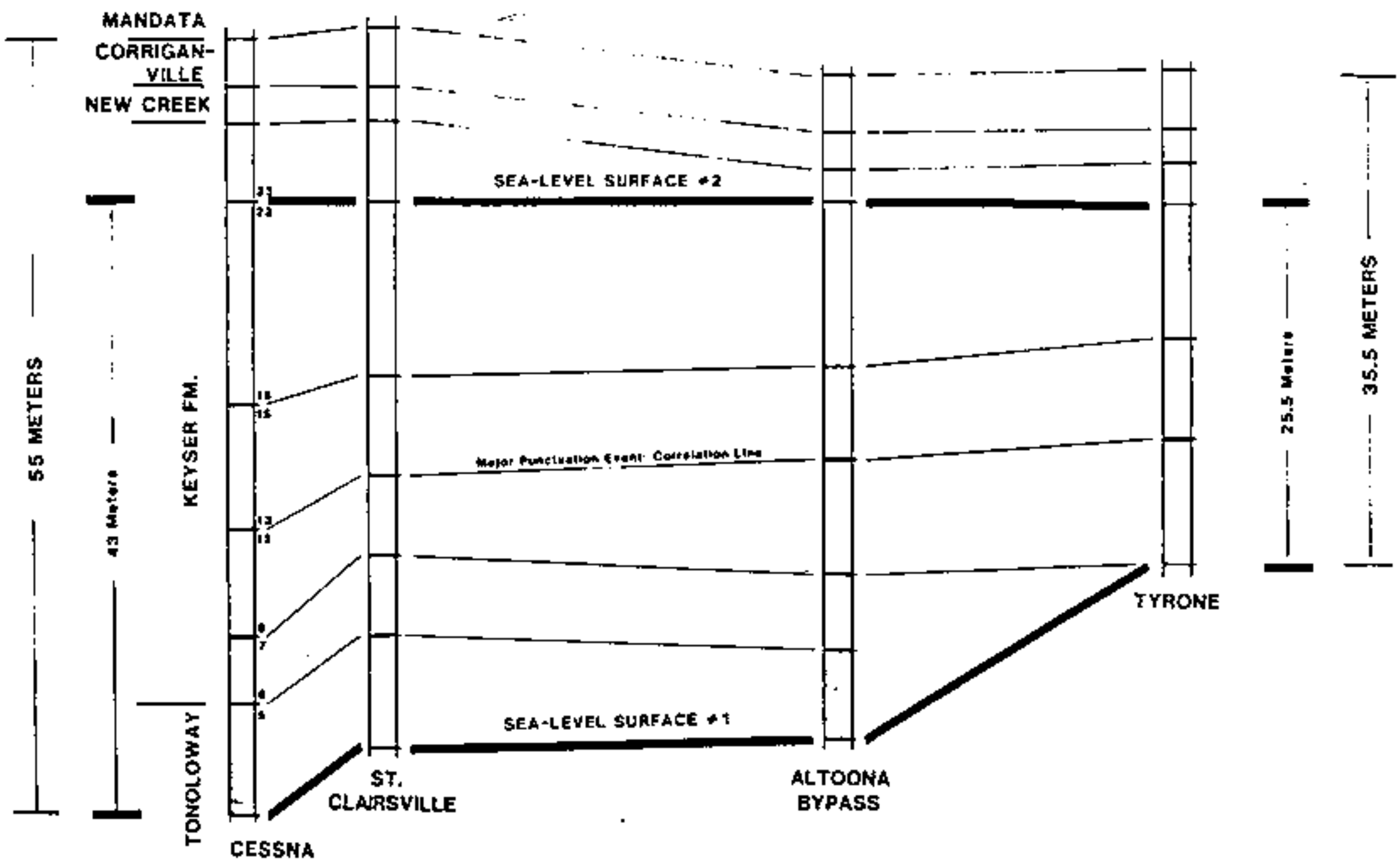

B.
SEA-LEVEL SURFACE #2
THICKNESS
X
Y
SEA-LEVEL SURFACE #1
X-Y= THICKNESS ATTRIBUTABLE TO
DIFFERENTIAL SUBSIDENCE
A.
SEA-LEVEL SURFACE #1

Figure 37.
Differential subsidence, Tonoloway-Keyser formations, in central Pennsylvania.


MANDATA
CORRIGAN-VILLE
NEW CREEK
KEYSER FM.
TONOLOWAY
55 METERS
43 Meters
SEA-LEVEL SURFACE #2
Major Punctuation Event Correlation Line
SEA-LEVEL SURFACE #1
CESSNA
ST. CLAIRSVILLE
ALTOONA BYPASS
TYRONE
25.5 Meters
35.5 METERS

occurred between Tyrone and Cessna (Fig. 37). Differential subsidence was progressively greater to the south and was introduced to the record nonuniformly (more in some PACs than in others). In particular, PACs 1-7 maintain a similar thickness at most localities, but PAC 14 for example, has a greater thickness at localities to the south.

By applying the Hypothesis of Punctuated Aggradational Cycles to this stratigraphic interval I have discerned that the Upper Tonoloway-Lower Keyser interval was deposited in response to abrupt base-level fluctuations (punctuation events) of two magnitudes which produced a series of synchronous PAC sequences. In addition, differential uplift and subsidence generated a small unconformity at Tyrone with as much as 13 meters of section missing. Finally, 17.5 meters of differential subsidence has been determined by noting this thickness difference between two paleoisotopographic PAC boundaries. Previously, all of these dynamics have been masked by the assumption of gradual accumulation.

CONCLUSIONS

Application of the Hypothesis of Punctuated Aggradational Cycles to the Upper Tonoloway and Keyser Formations at seven localities in central Pennsylvania yields the following conclusions:

1) The entire study interval is divisible into 22 PACs containing shelf, shallow subtidal, intertidal and supratidal facies.

2) These PACs, although internally variable, are correlative throughout the entire study area over an outcrop distance of 70 kilometers

3) Two scales of punctuation events are recognized in the interval. Smaller punctuation events show less marked facies changes at PAC boundaries and tend to be more common in the interval. Major punctuation events are recognized by marked facies changes at PAC boundaries. Three major punctuation events initiated deposition of PACs 8, 13 and 16.

4) Five groups of PACs are recognized in the interval and traced throughout the study area. Each of these groups of PACs is initiated and terminated by a major deepening event. PACs 1-5 comprise a group of PACs containing peritidal facies. PACs 6 and 7 contain subtidal, nearshore facies. PACs 8-12 consist of shelf and subtidal facies, and PACs 13-15 contain subtidal to nearshore facies. PACs 16-22 are the lower portion of a shallowing PAC sequence that continues to the top of the Keyser Formation.

5) Detailed correlations using PACs as fundamental time-stratigraphic units indicate that an unconformity, involving as much as 13 meters of missing section, exists at the Tonoloway-Keyser formation boundary at Tyrone. This unconformity is probably due to differential uplift that occurred in the Tyrone area north of the Tyrone-Mt. Union cross-strike lineament while subsidence and deposition was continuous to the south.

6) Recognition of two paleoisotopographic sea-level surfaces at the base of PAC 1 and the top of PAC 22 facilitate the discernment of 17.5 meters of stratigraphic thickness difference attributable to differential subsidence between Tyrone and Cessna.

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