Paleozoic Evolution of the Appalachians:  
**Tectonic Overview**

Three major tectonic episodes, all involving lateral accretion of terranes:  
*deformation, terrane migration, accretion, and continental convergence*

1. **Ordovician Taconic Orogeny** (~470-440 Ma)  
   - collision of Laurentian margin with one or more magmatic arcs
     *Shelburne Falls arc (475-470 Ma) and Bronson Hill arc (454-442 Ma)*  
   - or, continent-continent collision
     *between Laurentia and proto-Andean region of Gondwana*  
   - slope & rise sediments thrust westward over shelf deposits

2. **Devonian Acadian Orogeny** (~420-360 Ma)  
   - accretion of Avalon terrane
     *southward continuation of Silurian Caledonian Orogeny (NW Europe)*  
     *collision of Baltica with Laurentia to form Laurussia*  
   - deformation of Bronson Hill arc and sedimentary basins seaward of BH arc
     *at least 3 pulses of deformation*  
   - oblique accretion of Avalon and other terranes(?)  
     *much strike-slip displacement but also subduction (coastal volcanics)*  
   - large mountains
     *erosion creates thick clastic wedge (Catskills and Poccono Mtns.); thinned westward toward cratonic interior*

3. **Pennsylvanian-Permian Alleghenian Orogeny** (~325-275 Ma)  
   - collision with Gondwanaland
     *consolidation of supercontinent Pangea*  
   - extensive zone of deformation
     *New England - Georgia & Alabama (Appalachian Mtns.) - Oklahoma, Arkansas (Ouachita Mtns.) - Texas (Marathon Mtns.)*  
   - side-effects:
     *deep crustal shear in Mass., formation of Narragansett rift basin*
     *basement block faulting in western interior, uplift of ancestral Rockies*
**"Tectonic Cycles"**

- recorded by the creation of **foreland basins sedimentation** in eastern New York
- associated with **tectonic uplift and deformation** due to the accretion of island arcs to the east in Massachusetts (first the **Ordovician Taconic Orogeny** followed by the **Devonian Acadian Orogeny**)

### Ordovician Taconic Orogeny

*(generalized succession in eastern NY)*

<table>
<thead>
<tr>
<th>Age</th>
<th>Environment</th>
<th>Lithology</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>late Ordovician</td>
<td>deltaic and</td>
<td>molasse</td>
<td>Queenston Fm.</td>
</tr>
<tr>
<td></td>
<td>foreland basin fill</td>
<td>(sandstone,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>siltstone,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>mudstone)</td>
<td></td>
</tr>
<tr>
<td>middle Ordovician</td>
<td>deep</td>
<td>flysch</td>
<td>Utica &amp; Canojocharie Shales,</td>
</tr>
<tr>
<td></td>
<td>foreland basin</td>
<td>(sandst.</td>
<td>Schenectady &amp; Snake Hill Fms.,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>turbidites &amp;</td>
<td>Normanskill Fm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>black shale)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>buckling of crust</td>
<td>interbedded</td>
<td>Dolgeville Fm.</td>
</tr>
<tr>
<td></td>
<td>(drowning of</td>
<td>limestone &amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>carb. platform)</td>
<td>black shale</td>
<td></td>
</tr>
<tr>
<td>middle Ordovician</td>
<td>shallow water</td>
<td>limestone</td>
<td>Black River &amp; Trenton Groups</td>
</tr>
<tr>
<td></td>
<td>carbonate</td>
<td></td>
<td>*(Lowville, Napanee, Kings Falls,</td>
</tr>
<tr>
<td></td>
<td>platform/ramp</td>
<td></td>
<td>Sugar River Ls. &amp; Denley Ls.)*</td>
</tr>
</tbody>
</table>

**End of one tectonic cycle and the beginning of another:**

- Taconic highlands were subsequently eroded and the foreland basin filled
- Upper Ordovician molasse facies is overlain by Silurian - Lower Devonian shallow water carbonates (*base of the next tectonic cycle*)

### Devonian Acadian Orogeny

*(generalized succession in eastern NY)*

<table>
<thead>
<tr>
<th>Age</th>
<th>Environment</th>
<th>Lithology</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle to Late</td>
<td>basin fill &amp; thick</td>
<td>molasse</td>
<td>Catskill clastic wedge</td>
</tr>
<tr>
<td>Devonian</td>
<td>alluvial fans,</td>
<td>(conglomerates,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>alluvial plains, &amp;</td>
<td>sandstones,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>shallow marine</td>
<td>siltstones,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>mudstones)</td>
<td></td>
</tr>
<tr>
<td>Early to Middle</td>
<td>marine foreland</td>
<td>flysch</td>
<td>Tristates Group, Onondaga Ls.</td>
</tr>
<tr>
<td>Devonian</td>
<td>basin</td>
<td>(limestones,</td>
<td>Hamilton Group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>shale, siltstone, sandstone)</td>
<td></td>
</tr>
<tr>
<td>Early Devonian</td>
<td>shallow marine</td>
<td>limestone,</td>
<td>Helderberg Group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>marlstone</td>
<td>*(Manlius, Coeymans, Kalkberg,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>New Scotland, Becroft, Alsen,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Port Ewen)*</td>
</tr>
</tbody>
</table>
EARLY PALEOZOIC ERA
Cambrian and Ordovician Periods

Laurentia in tropics
passive continental margins surround much of Laurentia
• thick, deep water slope & rise deposits
• thinner sequences of shelf deposits

Gondwana
• large continent
  Africa + S. America + Antarctica + Australia +
  India + New Zealand
• remained intact throughout Paleozoic Era

High global sea level
• break-up of late Proterozoic supercontinent
  increased length of spreading ridges
• little or no continental ice
• vast areas of the continents flooded by shallow seas
  shallow water sandstones and carbonates cover much of Laurentia
Fluctuations in global sea level
• widespread **sandstone** ‒ **limestone sequences**
• separated by major **inter-regional unconformities**
  Sauk Sequence (Cambrian-Early Ordovician)
  Tippecanoe Sequence (Late Ord.-Silurian)

Ordovician Taconian Orogeny
• warped crust of eastern craton
• created intra-cratonic basins and arches
  *e.g.*, **Michigan Basin, Cincinnati Arch**
"Cambrian Explosion"

**rapid diversification** of marine animals with hard-parts

change from largely autotroph-dominated ecosystems of Proterozoic & Neoproterozoic:
1. cyanobacterial mats (**stromatolites**)
2. eukaryotic phytoplankton (**acritarchs**)
3. multicellular red & green algae (**"seaweed"**)  
4. multicellular animals (**Ediacaran biota**)

**rise of heterotrophs** at Proterozoic/Phanerozoic transition

*including scavengers and predators*

why?

- innovations & evolutionary thresholds
  - biomineralization, circulatory & nervous systems
- hard parts provided tissue support & protection
- increased oxygen levels
- rising sea level, widespread shallow marine niches
several phases of radiation:
1. lowermost Cambrian
   • tiny, simple, tube or vase-shaped skeletal fossils
2. Tommotian Fauna
   • oldest, diverse skeletonized fauna
   • 3-4 m.y.
3. typical "Cambrian Fauna"
   • radiation of larger skeletonized fauna

"Cambrian Fauna"
• trilobites* (calcium phosphate)
• inarticulate brachiopods (chitinophosphatic shells)
• sponge-like archeocyathids (bioherms)
• mid-Cambrian Burgess Shale (B.C.)
  exceptional preservation of soft-bodied organisms
  = "Lagerstätten": rare windows to true animal diversity

*index fossils (biostratigraphy and correlation)
Changes

- steady **decline of stromatolites**
  - grazing and burrowing by heterotrophs
- **extinction of archeocyathids** by mid-Cambrian
- several episodes of **trilobite extinctions**
  - evolution of better competitors or predators?

*beginning in Ordovician, faunas are different:*
**calcium carbonate shells** dominate:
- more rigid
- adaptations for anchoring to substrate
- muscle/organ support
- better protection

"Paleozoic Fauna" (Ordovician-Permian)
- **articulate brachipods***
- **bryozoans**
- **crinoids** (attached echinoderms)
- **cephalopods*** (nautiloids ⊆ ammonoids)
- rugose & tabulate **corals**
- **stromatoporoid sponges**
- **ostracodes**
- **conodons***
- **graptolites***

*index fossils
Late Ordovician to Devonian reefs: 
*stromatoporoid sponges* + *tabulate corals*

**Changes**
- **glaciation** at end of Ordovician
  - *lowering of sea level*
- end-Ordovician **mass extinctions**
  - 2 pulses: 1) *effects of cooling & glaciation*, 2) *global warming*
MIDDLE PALEOZOIC ERA
Silurian and Devonian Periods

During Silurian, Taconic highlands eroded molasse overlain by shallow water carbonates (Niagara Falls)
Barrier reefs develop in Great Lakes region

Formation of large continent: Laurussia "Old Red Sandstone Continent"

• Welding of Baltica (NW Europe) with NE Laurentia
  Late Silurian Caledonian Orogeny (Scandinavia & Great Britian)

• Accretion of microcontinent (Avalon Terrane) to N. Appalachians
  Mid- to Late Devonian Acadian Orogeny

Thick Catskill clastic wedge shed westward across eastern U.S.
  Catskill and Pocconos Mtns.
Recall: 2 episodes of extinctions of marine invertebrates at end of Ordovician

Biotic recovery during Silurian:
• "Paleozoic fauna" rediversified
• tabulate coral-stromatoporoid reefs
• jawless fish (ostracoderms) diversified
  marine & fresh water

Great diversification of fish during Devonian:
  "Age of Fishes"
• jawed armored fish (placoderms; all extinct)
• sharks, skates, rays*
• true bony fishes*
  includes lobe-finned fishes, gave rise to amphibians

*dominant fishes by end of Devonian

Important predators:
• eurypterid arthropods
  marine & fresh water
• ammonoid cephalopods
TERRESTRIAL ENVIRONMENTS:

Silurian
- vascular plants invade land
  *spore-bearing plants (require moisture for reproduction)*

Devonian
- rapid evolution of land plants
  *spore and seed-bearing plants*
  *first trees, spread of forests*
- earliest terrestrial arthropods
  *insects & scorpions*
- bivalve molluscs invade fresh water

Vast terrestrial lowlands
  *alluvial plains, wetlands, & deltas*
Reefs widespread and massive by early Late Devonian
important hydrocarbon reservoirs

Mass extinctions during Late Devonian
• tropical marine taxa hardest hit:
coral-stromatoporoid reefs completely wiped-out
pelagic & nektonic organisms hard hit:
  placoderms
  ammonoids
  eurypterids
  graptolites
  conodonts
• terrestrial plants unaffected

Cause(s)?
• Late Devonian glaciation in Gondwana
possible climatic feedbacks:
  spread of forests, burial of carbon, lowering of atmospheric CO₂, & global cooling?
Middle Devonian-Early Mississippian Antler Orogeny

- first Cordilleran orogeny of the Paleozoic
- partial closure of basin between Klamath island arc and Laurussia
  similar to Japan off of Asia
- deepwater slope & rise sediments thrust eastward over shallow water carbonates
  Roberts Mountain Thrust (Nevada)
**Late Paleozoic Era**

*Carboniferous and Permian Periods*

**Mississippian Period**  
*(Early Carboniferous)*

- last widespread Paleozoic carbonate-rich epicontinental sea on N. Amer. craton  
  *Kaskaskia Sequence*
- "Age of Crinoids"
- west & mid-continent: thick, shallow water carbonates  
  *today: cliff & ridge-forming limestones*
- east: black shales interbedded with prograding clastics from Acadian highlands
Pennsylvanian Period
(Late Carboniferous)

• collision of Laurussia & Gondwana
  consolidation of supercontinent Pangea

• large areas of craton uplifted
  east: Alleghenian Orogeny - last phase of Appalachian deformation
  south: Ouachita and Marathon Mtns.
  west: "ancestral Rocky Mtns."

• gradual draining of epicontinental seas
1. Alleghenian Orogeny
   • collision of eastern N. Amer. with NW Africa (Gondwana)
   • New England □ AL

2. Deformation of southern margin
   • collision with northern S. Amer.
   • OK & AR □ TX

3. Basement uplifts (mainly block faults)
   • due to compression from E, S, & W
   • uplift of Ancestral Rocky Mtns.
   • alluvial fans & alluvial plains
     thick deposits of conglomerate, arkosic ss & red mudstone

1-3: profound impact on sedimentation
   • great volume of sediment supplied to mid-continent
   • widespread terrestrial deposits:
     alluvial plain
     flood plain*
     deltaic/marginal marine*
*coal-bearing strata
PENNSYLVANIAN COAL

1. flood plain coals (e.g., PA)
   • peat accumulated in lowland swamps/overbank areas of flood plain*

2. deltaic coals (e.g., IL)
   • prograding deltas with retreat of epicontinental seas*

*high frequency oscillations of sea level due to **glacial cycles on Gondwana**
= cyclic deposits ("cyclothems") caused by both tectono- & glacioeustatic changes in sea level

idealized cyclothem:

transgressive-regressive sequence

\[ \text{lowstand} \quad \text{nonmarine clastics} \]
\[ \text{falling sea level} \quad \text{nearshore sandstone & mudstone} \]
\[ \text{highstand} \quad \text{shallow marine limestone} \]
\[ \text{offshore shale and mudstone} \]
\[ \text{shallow marine limestone} \]
\[ \text{nearshore sandstone & mudstone} \]
\[ \text{rising sea level} \quad \text{coal*} \]
\[ \text{lowstand} \quad \text{nonmarine clastics} \]

*coal swamps formed on nonmarine deposits as sea level began to rise
Pennsylvanian Fossils

Terrestrial

• first reptiles during Penn., but terrestrial faunas dominated by amphibians*
  *many were much larger than today's familiar amphibians

• terrestrial flora dominated by spore-bearing plants & trees*
  *e.g., fern-like plants and trees
  widespread coal swamps with Lycopod trees
  Sphenopsid trees (Calamites) on floodplains

*dominant fauna & flora required moist conditions for life cycle

Other important plant firsts:
  • first seed ferns (oldest seed plants) appeared during Late Devonian
  • first gymnosperms ("naked seed plants") appeared during Late Carboniferous
    Cordaite trees formed upland forests

Marine:

• typical "Paleozoic fauna"
• ammonoids & fusulinids (larger forams) *important for biostratigraphy*
Permian Period

• continued consolidation of Pangea
• continued glaciation on Gondwanaland
• major regression of epicontinental seas
• drying-out of continental interior climate
  widespread terrestrial red beds (with anhydrite)
  coastal dune fields
  salt deposition (more than during any other time)
• marine conditions restricted to western U.S. & Canada
  "Kaibab Sea"
Permian basins of W. Texas

*barrier reefs and oil*

1. deep basins (grabens) adjacent to reefs accumulate organic matter
   = *petroleum source rocks*

2. reef carbonates are fairly porous
   = *good reservoir rocks*

3. later, evaporites accumulated across entire area (impermeable layers)
   = *good cap rocks (seal)*
Permian fossils

TERRESTRIAL

• coal swamp floras replaced by seed-bearing gymnosperms (conifers)
  in seed plants, spores not released to environment,
  □ reproduce without moist conditions

• amphibians replaced by radiation of reptiles
  evolution of shelled egg (= amniote egg, "self-contained pond")
  □ reproduce away from water
  more advanced jaws & teeth, greater speed & agility than amphibians

• evolution of therapsids = mammal-like reptiles
  legs beneath bodies
  probably endothermic metabolism (warm-blooded; endurance)
  advanced & powerful jaws & teeth

MARINE:

• typical "Paleozoic fauna"
• ammonoids & fusulinids (larger forams)
  important for biostratigraphy
END-PERMIAN MASS EXTINCTION
"mother of all extinctions"
2 pulses of extinction

• ~90% of all marine species,
  ~50% of invertebrate families:
  all trilobites
  all rugose & tabulate corals
  all fusulinid forams
  most brachiopods, ammonites, lacy bryozoans,
  & crinoids
  many characteristic elements of the "Paleozoic
  Fauna"

• ~70% of terrestrial vertebrate families
  ~75% amphibian, ~80% reptile families

• fungal spore spike
Possible Causes?

1. **global regression**, draining of epicontinental seas
   *consequences?*
   - loss of marine niches & greater competition
   - increased aridity & seasonality on continents
   *specialist organisms unable to cope*

2. drop in **atmospheric O$_2$**?
   *this following Pennsylvanian build-up*
   - weathering & oxidation of organic matter
   - reduction in global productivity
   *perturbation in carbon cycle*

3. **volcanism**: eruption of **Siberian flood basalts**, explosive volcanism in S. China
   - CO$_2$ + sulfate aerosols
   - short-term cooling, long-term warming
   *climatic instability*

4. **anoxia** in deep ocean

5. reduction of **oceanic salinity** due to deposition of evaporites?
Summary of Paleozoic
First-Order Tectonic "SuperCycle"

1. LATEST PROTEROZOIC AND CAMBRIAN
   • continental dispersal & end of major glaciation
   • rising global sea level & flooding of continental areas
     Sauk Sequence
   • adaptive radiation of shelly marine animals
     "Cambrian explosion"
   • "Cambrian Fauna"
     radiations & extinctions

2. ORDOVICIAN TO MISSISSIPPIAN
   • widespread shallow carbonate-dominated epicontinental seas
   • transgressive-regressive sedimentary sequences deposited across N. Amer.
     Tippecanoe & Kaskaskia Sequences
   • tectonic pulses & growth of North America
     Taconian, Acadian, & Antler Orogenies
   • radiation of marine "Paleozoic Fauna"
     +/- stable lineages
   • biotic occupation of the land
     parallel evolution of plants & animals
   • 2 episodes of mass extinction
     end-Ordovician, Late Devonian

3. PENNSYLVANIAN TO PERMIAN
   • continental aggregation & creation of Pangea Supercontinent
   • major tectonic activity
     Alleghanian Orogeny & uplift of Ouachitas & Ancentral Rockies
   • lowering of global sea level & draining of epicontinental seas
     Absaroka Sequence
   • major coal accumulation, followed by drying-out of climate
   • faunal/floral evolution & turnover tracks sea level & climate
     from moist, humid climate to drier, more seasonable climate
   • End-Permian mass extinction
     regression, volcanism, climatic instability, perturbations of atmosphere & carbon cycle