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ON THE COVER

A catastrophic sinkhole, which opened on February 23, 1994, near center city Allentown, Lehigh County, caused disruption to local traffic and utility services and resulted in major structural damage to the Corporate Plaza building. The view is of the collapsed northwest corner; the building was later razed. The area is underlain by carbonate rocks of the Upper Cambrian Allentown Formation. Photograph by W. E. Kochanov.

PENNSYLVANIA GEOLOGY

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Geologists at the Pennsylvania Geological Survey generally spend most available time interpreting Pennsylvania's geological past to provide information of use in the present. For a brief period during the coming months, the staff of the Survey will be looking to the future, rather than the past, to examine issues and problems presently encountered for which problem-solving strategies will be developed. From this examination, we will prepare a strategic plan that should improve future services provided to you. Our efforts parallel those of the Bureaus of Forestry and State Parks, which have also recently engaged in strategic planning. The Bureau of State Parks released its plan as Parks 2000; the Bureau of Forestry is presently drafting its plan, entitled Heading into Our Second Century of Stewardship.

We are identifying major issues that we understand must be dealt with in order to more successfully accomplish our Bureau's responsibilities. After identifying issues and problems, we will conduct a series of public meetings throughout the Commonwealth to discuss these topics. If you wish to participate in these meetings, please let us know. You may also contact us directly about issues that you feel are important. Whether by attending a public meeting or by direct comment, your participation in our strategic planning will be invaluable.

One issue for which we seek your comment relates to the availability of published reports and maps of the Pennsylvania Geological Survey. Presently, completed investigations that are published by the Survey as maps or reports are transferred to the Pennsylvania Department of General Services to be sold through the State Book Store. Some maps and reports in high demand have been reprinted as stock runs low. Of late, the last copies of many high-demand reports have been sold and are now unavailable at the State Book Store. However, repository copies are available in public and academic libraries throughout Pennsylvania and neighboring states.

Available Bureau resources are presently devoted to publishing new reports; reprinting out-of-print maps and reports has low priority for allocation of resources. For out-of-print reports, does access

(continued on page 13)
INTRODUCTION. Have you ever wondered how the streams and valleys in Pennsylvania came to be in their present positions? Geologists have been pondering the subject for over 150 years and will likely do so for years to come as they are stimulated by new concepts and data. Henry Darwin Rogers (1858), director of the first Pennsylvania Geological Survey, believed the landscape and its drainage system to be a consequence of rapid uplift of the rocks from beneath ocean waters during convulsions that created the anticlines and synclines. The convulsions were caused by giant rippling in molten material deep beneath the earth's crust. He envisioned great torrents of water that rushed and swirled off the rising rocks, eroding the landscape to the form we see today. Large lakes developed in many valleys enclosed by mountain ridges. Eventually, these lakes overtopped the ridges and catastrophically cut the water gaps. Rogers' process would make a great sequence in the movie Fantasia.

A more realistic hypothesis based on better understanding of geological processes was offered by William Morris Davis in 1889. Davis believed that the "Permian deformation" created mountain ranges in central and eastern Pennsylvania, the highest peaks situated in Centre County and the Piedmont. He envisioned that water from the eastern side of the central Pennsylvania mountains flowed down the troughs of the synclines into a great lake covering the Anthracite region and that the lake drained through a river to the northwest. Water on the western side of the mountains flowed west across an alluvial plain. Davis was vague about the Piedmont mountains.

Davis attributed initiation of southeast-flowing drainage to development of the Gettysburg-Newark basin in southeastern Pennsylvania in the late Triassic Period. The new streams, particularly the Susquehanna River, eroded headward, and gradually all of Pennsylvania's drainage was reversed, except in the western part of the state. He believed that millions of years of erosion produced a pene-
plain, a relatively flat, low-relief surface, over all of Pennsylvania by
the end of the Cretaceous Period, about 70 million years ago. Davis
considered the landscape we see today to be the result of erosion
of the peneplain, and the even-crested ridges of central Pennsylvania
to be remains of the former peneplain.

There has been little challenge to the basic concept of Davis,
except for questioning the reality of the peneplain and suggestions
of alternate ways to form water gaps. However, the development
and widespread acceptance of the concept of plate tectonics since
1970 has given us a new understanding of what happened during
the “Permian deformation,” thus making it desirable to create a new
model of drainage evolution for Pennsylvania. A probable model is
presented here.

IN THE BEGINNING: THE ALLEGHANIAN OROGENY. The evolu-
tion of Pennsylvania’s present drainage system began with the Al-
leghanian orogeny. Prior to that orogeny, Pennsylvania was part of
the Appalachian basin, an elongate feature occupied by an inland
sea in which sediment had accumulated for almost 200 million
years. The sea ceased to exist when the continents of Africa and
North America collided between 260 and 240 million years ago, dur-
ing the Permian Period.

Compression from the collision created faults, called décolle-
ment faults, that paralleled bedding of the sedimentary rocks and
extended at great depths beneath the surface across much of Penn-
sylvania (Figure 1). Splays (faults that angle toward the surface
from the décollements) displaced rock upward, producing anticlines
throughout the central part of Pennsylvania. In eastern Pennsylva-
nia, large sheets of rock were thrust along faults and stacked to a

Figure 1. Cross section showing folds, faults, mountains, and alluvial plain
resulting from the Alleghanian orogeny.
depth of 5 or 6 miles (Beaumont and others, 1987). One of these sheets was thrust out over much of the Anthracite region (Levine, 1986). The stacked thrust sheets created a mountain range having 2 to 3 miles of relief and a width of 150 miles or more (Slingerland and Furlong, 1989). These mountains, the Alleghanian Mountains, were probably similar in size to the present Andes Mountains in South America.

Erosion occurred throughout this whole process. Streams flowing to the west and northwest carried away the sediment eroded from the Alleghanian Mountains and deposited it on an alluvial plain that extended from the base of the mountains to somewhere west of Pennsylvania (Figure 2). The crests of some anticlines, particularly those in Centre County, almost certainly rose above the level of the alluvial plain, but most of the anticlines, especially those closest to the mountains, were buried by alluvial sediments. The amount of sediment carried to the alluvial plain decreased as erosion lowered the mountains to hills. By the time deposition on this plain ceased, the westward-thinning wedge of sediment may have approached 2.7 miles in thickness in eastern Pennsylvania, 2.4 miles at the Al-

![Paleogeographic map of Pennsylvania in the early Triassic Period showing mountains, alluvial plain, streams, and protruding anticlines. Streams originated in the Alleghanian Mountains and flowed northwest.](image-url)
legheny Front, and 1.5 miles at the Ohio-Pennsylvania line (Zhang and Davis, 1993).

**THE NEXT STEP: RIFTING OF THE CONTINENTS.** This simple pattern of erosion in the east and deposition to the west would have continued indefinitely had it not been for plate tectonics. The forces that drove the continents together, convection currents deep within the earth, reversed their flow directions and forced the continents apart. Africa and North America began to separate about 210 million years ago, in the late Triassic Period. The tension created by the process of separation caused development along the eastern margin of North America of numerous small, elongate basins, such as the Mesozoic-age Gettysburg-Hammer Creek-Newark basin in southeastern Pennsylvania. These basins were filled with sediment eroded from adjacent areas. Most of the sediment came from highlands to the east, but in Pennsylvania some was brought in by new streams, the Susquehanna and Schuylkill Rivers and possibly the Delaware River, that entered the basin from the northwest (Figure 3).

![Figure 3. Paleogeographic map of Pennsylvania in the early Jurassic Period showing mountains, alluvial plain, Mesozoic basin, and northwest-flowing and southeast-flowing streams. Arrows indicate direction of headward erosion.](image_url)
Once established, the southeast-flowing streams began to erode headward. These new streams had steep gradients and eroded aggressively. The Susquehanna River probably eroded headward following the boundary between the rocks of the Alleghanian Mountains and the poorly consolidated sediments of the alluvial plain. Erosion along this boundary allowed it to progress rapidly and become the dominant stream in Pennsylvania (Figure 4). The Schuylkill and Delaware Rivers eroded entirely into rock and did not progress as rapidly. As the Susquehanna River lengthened its course, two important things happened: (1) it developed a larger drainage basin and, with more water available, it eroded more rapidly; and (2) it beheaded westward-flowing streams that carried water and sediment to the alluvial plain. Beheading of these westward-flowing streams deprived them of both water and sediment, and they changed from depositional streams to erosional streams. However, these beheaded streams had low gradients and relatively little water, so they were not very effective at erosion.

**MOVING RIGHT ALONG: THE PROGRESSION OF EROSION.**

When the Susquehanna River and its tributary the Juniata River eroded through the westward-sloping alluvium, they encountered

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**Figure 4.** Paleogeographic map of Pennsylvania in the Cretaceous Period showing remnant alluvial plain and positions of headward-eroding streams.
the underlying folded rocks. In many places, the streams were superimposed across structural trends, whereas in other places stream positions were altered by structure. Tributaries to the main streams adjusted to structural trends as they eroded headward. When the Susquehanna River eroded headward into the Appalachian Plateau northwest of Lock Haven, its course was controlled by structure. As a result, the principal elongation parallels fold trends, whereas tributaries cross fold trends (Figure 5).

In western and northwestern Pennsylvania, a much different process operated. There, the pre-Permian rocks dip gently to the south and southwest. When northwest-trending streams eroded through the alluvium to the underlying rocks, their tributaries began to erode preferentially updip (north and northeast) wherever a resistant rock, such as sandstone of the Pottsville Formation, was encountered (Lattman, 1954). These tributaries became elongated updip and eventually beheaded another northwest-flowing stream. The result was an integration of several different streams to form the present Allegheny River system (Figure 5), a process that may have been enhanced by glaciation.

Figure 5. Paleogeographic map of Pennsylvania in the early Tertiary Period showing positions of headward-eroding streams.
Southwestern Pennsylvania is the only area in the Commonwealth where drainage may be at least partly descended from the original west-flowing streams. The Youghiogheny and Conemaugh Rivers appear to be streams that cut through the former alluvial plain and became superimposed across fold trends (Figure 5). Tributaries to these streams are well adjusted to structure.

**WHAT NEXT: THE FUTURE.** What is the future of drainage evolution in Pennsylvania? The present drainage pattern will be around for a long time. Given enough time, it is probable that the Susquehanna River drainage will eventually include all of Pennsylvania north and west of the Anthracite region. Streams will continue to adjust to structure. If erosion in western Pennsylvania ever progresses to the point that rocks of pre-Silurian age are encountered, there will be a gradual reorientation of the streams as they adjust to the east-southeast regional dip of those rocks. How long will all of this take? Calculated rates of present erosion in the Appalachians are variable, but a rate of less than 100 feet per million years is reasonable. Unless something happens that dramatically increases the rate of erosion, such as climate change, the drainage pattern in Pennsylvania will not change significantly for many millions of years.

**REFERENCES**


Earthquakes 1993

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RECENT EARTHQUAKES IN THE MID- ATLANTIC REGION. On February 26, 1993, a 2.7-magnitude (Richter scale) earthquake was felt near Cherry Hill, N. J., and was the first of 24 small quakes within the mid-Atlantic region (Figure 1) recorded through May 20 by the three seismographs in northern New Castle County, Del., operated by the Delaware Geological Survey (DGS).

Later, areas nearby in two other states experienced multiple events. From March 10 to April 8, nine earthquakes were recorded in the Columbia, Md., area with magnitudes ranging from 1.0 to 2.7. These prompted many telephone calls to Maryland officials. As the DGS has the seismograph network closest to the Columbia area, we were asked by our counterparts at the Maryland Geological Survey to provide data on the events. Subsequently, the Baltimore and Washington news media contacted DGS staff for information and interviews. More recently, the Reading, Pa., area was the location of 10 or 11 events having magnitudes of less than 1.5 to 2.8, recorded from May 10 to May 20, 1993 (Figure 1).

Single earthquakes having magnitudes of less than 2.0 were detected near Bel Air, Md., on March 21 and the next day near Lancaster, Pa. On May 15, a coastal New Jersey event (just off the map shown in Figure 1) was estimated to be of 2.6 magnitude.

A quake of magnitude 2 is about the lowest limit normally felt by humans. At magnitudes of greater than 4 to 5, sleepers may be awakened and small objects are upset, and at greater than 5 to 6, some minor damage may occur. However, in the eastern United States, smaller magnitudes produce larger intensities than this, and slight damage may occur at magnitudes around 4. The Richter scale is

EDITORS' NOTE: While this issue of the magazine was in press, additional earthquakes occurred on January 15, 16, and 17, 1994, in the Reading area. The maximum magnitude was 4.6, the highest yet recorded in Pennsylvania. A follow-up article on these earthquakes will be printed in a later issue.
Figure 1. Locations of recent earthquakes in the mid-Atlantic region. Solid triangles mark areas of 1993 events; solid circles represent some previous events, including the 1984 earthquakes near Lancaster. The large single arrow indicates the direction of absolute motion of the mid-plate of the North American plate (after Zoback and Zoback, 1991). The large inward-pointing arrows show the orientation of the average compressive tectonic stress field of the region; small inward-pointing arrows indicate the local variation of NW­SE compression (after Zoback and Zoback, 1989). Exposed (northwest of the Fall Zone) and inferred (buried) Mesozoic rift basins are after Benson (1992); fault zones are indicated by hachures. Diabase dikes are after Emery T. Cleaves and James P. Reger, Maryland Geological Survey (written communication, 1993). The trend of the extended Delaware Bay fracture zone (F.Z.) is after Klitgord and Schouten (1986).

logarithmic; a recording of 6, for example, indicates ground motion 10 times as large as a recording of 5.

FRACUTURES, STRESSES, AND BODY WAVES. Earthquakes in the northeastern United States generally occur in the upper half of the earth's crust. The focal depths determined from a sampling of earthquake records for this region tend to cluster in a zone between 5 and 15 km beneath the earth's surface; the deepest generally are at 20 km, and the shallowest are at about 1 km.
An earthquake occurs when blocks on either side of a fracture in the earth's crust (termed a fault) suddenly break or "snap" to new positions. The earth's crust is constantly under stress as a result of forces operating on the earth's outer brittle layer, the lithosphere, which is subdivided into several tectonic plates. Friction along active faults keeps the blocks of crust from moving past one another continuously. Under constantly applied stress, the strains in the blocks build to a point until rupture occurs, releasing energy in the form of body waves that travel in all directions through the earth from the focal point of the earthquake. Body waves that reach the earth's surface generate surface waves, which usually have the strongest vibrations and probably cause most of the damage done by earthquakes.

There are two types of body waves: compressional, called primary or P waves, and shear, called secondary or S waves. As a P wave travels through the earth, it pushes particles of material ahead of it closer together, but behind it the particles rebound to positions farther apart from one another than when the material was at rest. S waves, on the other hand, displace material in directions at right angles to their paths of travel.

Because P waves travel through the earth at higher velocities than S waves, they are the first to be detected by seismographs. With knowledge of the velocity of P and S waves, the difference in arrival times between the P and S waves on a seismogram can be used to measure the distance between the seismograph and the epicenter of the earthquake, which is the location on the earth's surface directly above the focal point. The seismogram shown in Figure 2 for the May 18, 1993, Reading, Pa., earthquake of magnitude slightly greater than 2 indicates a 9.1-second difference in the arrival times of the P and S waves. This calculates to a distance of about 70 km between the seismograph in northern Delaware and the epicenter, which could be anywhere on a circle of that radius centered on the seismograph location. In order to locate the epicenter, there must be at least two more circles centered on other seismograph locations that intersect the first circle to define a single point. For the example shown, seismologists at the Lamont-
Doherty Earth Observatory of Columbia University determined the location of the epicenter near Reading.

**COMPRESSION STRESS FIELD AND ZONES OF WEAKNESS.** Earthquake activity in the northeastern United States is quite low compared to that of the boundaries of the earth's tectonic plates, which are located several thousand kilometers from this region. In the broad intraplate region of the North American plate, researchers, using a variety of methods, have measured the tectonic stress field and have concluded that the central and eastern United States, most of Canada, and possibly much of the western North Atlantic basin to within about 250 km of the Mid-Atlantic Ridge is under a uniform compressive stress field. Faulting (earthquakes) occurring under these conditions is dominated by reverse faults (one block of the earth's crust moves up and over another block along an inclined fault plane) and strike-slip faults (blocks move past one another along a near-vertical fault plane). The compression has an average ENE-WSW orientation that is also remarkably near parallel with the WSW direction of absolute plate motion of this large midplate province (Figure 1). The uniformity of the stress field suggests that it arises from forces that either drive (ridge push) or resist (basal drag) plate motions. A local variation of the uniform stress pattern is observed in Maryland and eastern Virginia, where reverse faults of Miocene and younger age indicate apparent northwest-southeast compression (Figure 1). Analysis of the Wilmington earthquake of February 28, 1973, also suggests northwest-southeast compression.

In California, faults responsible for earthquakes are well known, but for the northeastern United States, earthquake faults are difficult to identify. Faults that have been mapped at the earth's surface were zones of weakness under preexisting stress regimes in the geologic past, and researchers commonly explain northeastern United States earthquakes as the result of these ancient zones of weakness being reactivated if favorably oriented in the present-day stress field. Leading candidates are faults inherited from the extensional stress fields that characterized continental rifting and eventual breakup of the supercontinent of Pangea during the early Mesozoic Era, followed by the separation of Africa and Europe from North America. These faults, in turn, may have been inherited from zones of weakness created during the compressional tectonics that characterized the Appalachian mountain-building episodes of the Paleozoic Era.
Possible zones of weakness that may be responding to the current ENE-WSW compressive stress field or the local NW-SE compression in the mid-Atlantic region include Mesozoic rift basin border faults; faults associated with a series of Mesozoic diabase dikes extending from the area of Columbia, Md., to Lancaster, Pa.; the Fall Zone, which marks the boundary between the Piedmont and Atlantic Coastal Plain provinces; and, possibly, the Delaware Bay fracture zone of the western North Atlantic basin that if extended into continental crust would trend northwestward beneath Delaware Bay.

REFERENCES

Benson, R. N. (1992), Map of exposed and buried early Mesozoic rift basins/synrift rocks of the U.S. middle Atlantic continental margin, Delaware Geological Survey Miscellaneous Map Series 5, scale 1:1,000,000, with discussion.


Past, Present, and Future (continued from page 1)

to repository copies satisfy your needs? Would you accept likely higher unit cost if Commonwealth copyrights were assigned to private publishers for reprinting out-of-print reports? Your answer to these questions will be very useful as we develop strategies to continue public access to geoscience information.

Donald M. Hoskins
State Geologist
Students of Appalachian basin stratigraphy and structural geology will be interested in a new publication issued by the U.S. Geological Survey (USGS). The report is Miscellaneous Investigations Series Map I-2200, a cross section of the Lower Paleozoic stratigraphic interval between the Lower Silurian and the Precambrian compiled from drill-hole data by USGS geologist Robert T. Ryder. The cross section has been drawn from northeastern Ohio near Cleveland, across northern Pennsylvania to Potter County, and down across central Pennsylvania, where it terminates northwest of Harrisburg. Six colors and two patterns representing the dominant lithologies aid in distinguishing formations; additional symbols identify significant lithologic constituents such as anhydrite, oolites, chert, and red beds, and stratigraphic markers such as metabentonite (altered volcanic ash).

This cross section and others still in press provide important stratigraphic and lithologic information for the Lower Paleozoic interval. The cross section also delineates the top of the Precambrian basement rocks beneath the Appalachian basin. The top of Appalachian basement structure is inadequately known at present because only a few holes have penetrated the Paleozoic sedimentary cover, magnetic and gravity data have not been calibrated satisfactorily to known basement rock types and structures, and very little seismic information exists outside proprietary industry files. The inadequacy of the available information allows a great deal of speculation about the configuration of the basement in Pennsylvania. For example, published and open-file reports written about basement structure in western Pennsylvania since 1970 suggest the existence of the Rome trough, a large basement graben feature known to occur in Kentucky and West Virginia. Like many of these reports, Ryder's cross section uses a combina-
tion of stratigraphic and structural variations in the Paleozoic sedimentary rock cover, and published seismic survey and gravity data, to infer the existence of the trough and other basement faults and fault blocks. Ryder's interpretation of these data differs enough from previous interpretations, however, to provide a provocative twist to the entire concept of the Rome trough in Pennsylvania. This cross section should help stimulate some welcome new debate in the coming years.

Map I–2200 is entitled Stratigraphic Framework of Cambrian and Ordovician Rocks in the Central Appalachian Basin from Lake County, Ohio, to Juniata County, Pennsylvania. It is available from the U.S. Geological Survey, Map Distribution, Federal Center, P. O. Box 25286, Denver, CO 80225, for $3.25 plus $1.00 for handling. Payment must accompany the order. Please make checks payable to Department of the Interior—USGS.

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ANNOUNCEMENTS

Last Chance for 15-Minute Maps of Pennsylvania!

The U.S. Geological Survey (USGS) is officially abandoning the 15-minute (1:62,500-scale) topographic map series. The USGS has not reprinted or revised any of the 15-minute maps for many years. The supply of maps in the USGS Map Distribution Center has dwindled until only 26 of the nearly 260 15-minute quadrangles that include parts of Pennsylvania remain to be sold. Until June 1, 1994, you may purchase copies of these maps in lots of 100 each, at 50 cents per map (reduced from the previous price of $2.50 per copy). The minimum order is thus $50.00. After June 1, 1994, only microfilm or reproducible separates will be available.

The 15-minute series was replaced by the 7.5-minute series (nearly 880 individual quadrangles in Pennsylvania), which is maintained through a federal/state cooperative program of continual revision and reprinting. Addition-
ally, the USGS and the Commonwealth cooperate in maintaining a county topographic map series at the scale of 1:50,000, which is close to the now-abandoned 1:62,500 scale. The modern 1:50,000-scale county map series is useful for those who need the accuracy of the 7.5-minute maps but require a smaller map size.

If you like old maps or wish to have 15-minute maps for teaching or other purposes, now is your last opportunity to purchase original paper copies of these maps. The locations of the available 15-minute maps are shown on the map on the back cover of this issue, and the order number for each quadrangle is listed in the map explanation.

The maps may be purchased from the U.S. Geological Survey, Map Distribution, Federal Center, P. O. Box 25286, Denver, CO 80225. Please make checks payable to Department of the Interior—USGS.

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Pennsylvania Native Receives Hydrogeology Division Award of Distinguished Service

At the October 1993 meeting of the Geological Society of America (GSA), Dr. Paul Seaber, born in Lititz, Pa., and a 1954 graduate of Franklin and Marshall College in Lancaster, Pa., received the GSA Hydrogeology Division Award of Distinguished Service. Dr. Seaber served with the U.S. Geological Survey, Water Resources Division, in the Pennsylvania District, where he conducted an appraisal study of groundwater resources of the Susquehanna River basin that produced a pioneering analysis of the role of groundwater economics in river-basin planning.

Dr. Seaber also worked in Pakistan, India, Senegal, Kuwait, Oman, Alaska, and Florida as a member of the USGS, later joining the Illinois Geological Survey. He is now at the Desert Research Institute in Nevada. Dr. Seaber's long public service and pioneering investigations, as well as his service to local and national scientific societies in fostering understanding of groundwater, led to his award.

Pennsylvania can be justly proud of another native son.
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IN COOPERATION WITH THE U.S. GEOLOGICAL SURVEY
TOPOGRAPHIC MAPPING
GROUNDWATER-RESOURCE MAPPING
## Available 15-Minute-Quadrangle Maps

*(see article on page 15)*

### Map Names

- Alburtis
- Allentown
- Altoona
- Bloomsburg
- Carlisle
- Conrad
- Emporium
- Galetom
- Gettysburg

### Order Number

- TPA6
- TPA13
- TPA18
- TPA87
- TPA131
- TPA186
- TPA260
- TPA305
- TPA313

### Map Names

- Hamburg
- Harrisburg
- Kinzua
- Laporte
- Loysville
- Middletown
- Mifflinburg
- Millersburg
- Millerstown

### Order Number

- TPA339
- TPA351
- TPA417
- TPA443
- TPA475
- TPA531
- TPA535
- TPA545
- TPA548

### Order Number

- TPA545
- TPA552
- TPA557
- TPA593
- TPA596
- TPA696
- TPA694
- TPA929
- TPA841

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