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Structural Settings of Deep Natural Gas Accumulations in the Conterminous United States

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GEOLOGIC CONTROLS OF DEEP NATURAL GAS RESOURCES IN THE UNITED STATES

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Structural Settings of Deep Natural Gas Accumulations in the Conterminous United States

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ABSTRACT

Deep natural gas accumulations (>15,000 ft, >4,572 m) are associated with two structural settings: passive margin basins not associated with plate boundaries and basins associated with active or once-active plate margins. The first structural setting is relatively simple and is related to crustal cooling. The Western Gulf Basin is a prime example. The second structural setting is more complex and includes forearc basins as well as foreland basins. Foreland basins include major foredeeps such as the Appalachian and Arkoma basins and more complex plate-convergence related basins such as the Anadarko, Hanna, Wind River, and Paradox basins. Extensional and transtensional basins, also associated with active plate margins and crustal spreading, are generally typified by high heat flow and shallow hydrocarbon generation and are not appropriate settings for deep gas accumulations.

INTRODUCTION

Deep natural gas accumulations at depths greater than 15,000 ft (4,572 m) in the conterminous United States are associated primarily with one of two basically different structural settings (table 1, fig. 1): passive continental margin basins and basins associated with and inland from active continental margins. In terms of plate tectonics, the active margins of interest are convergent or transform plate boundaries, whereas passive continental margins are not plate boundaries, except at the very beginning of their development when they form the margin of a rift that then opens into a new ocean basin by sea-floor spreading. Rift basins that fail to open into new ocean basins provide a third type of basinal setting within the conterminous United States; however, these are not a likely structural setting for major deep natural gas accumulations. Intracratonic basins such as the Michigan, Illinois, and Williston basins are simple sag basins within the stable craton, are generally less than 15,000 ft (4,572 m) deep, and not treated in this report.

The following classification is modified from that offered by Bally and Snelson (1980). Active continental margin basins consist of three types: (1) forearc basins developed between an accretionary wedge of sea-floor sediments and volcanics above a continentward-dipping subduction zone and the magmatic arc generated inland from the partial melting of the subducted material (fig. 2); (2) foreland basins beneath and cratonward of the frontal zone of fold and thrust belts (fig. 3); and (3) extensional or transtensional basins cratonward of active continental margins. Forearc basins develop above downgoing slabs of oceanic crust beneath Pacific-type active continental margins (Dickinson and Seely, 1979), whereas foreland basins form as a result of thrust loading (Beaumont, 1981; Jordan, 1981) of and by continental crust inland from both Pacific-type margins and inferred continent-continent plate collision zones such as the Ouachita fold belt (fig. 4). Both forearc and foreland basins are favorable sites for deep gas accumulations if deep source rocks, seals, and traps are present. Extensional and transtensional basins form as the result of crustal thinning, are characterized by high geothermal gradients, and are not likely sites for deep gas accumulations.

It must be kept in mind that the North American craton has undergone a complex tectonic history beginning more than 2.5 billion years ago (Muehlberger, 1980), and, as a result, few if any Phanerozoic sedimentary basins in the conterminous United States have developed over undamaged (unflawed) continental crust. For example, the late Paleozoic Anadarko Basin is situated over the northern flank of the early Paleozoic southern Oklahoma aulacogen and trough (Perry, 1989a). The aulacogen in turn is above the older Grenville suture, a continent-continent zone of plate collision (Muehlberger, 1980, fig. 15.4).

In this report, I characterize the structural setting of major deep gas accumulations at depths greater than 15,000 ft (4,572 m) in a simple classification scheme in order to provide clues to discovering additional deep gas occurrences. Basin names used in this report are those shown by Frezon and Finn (1988).

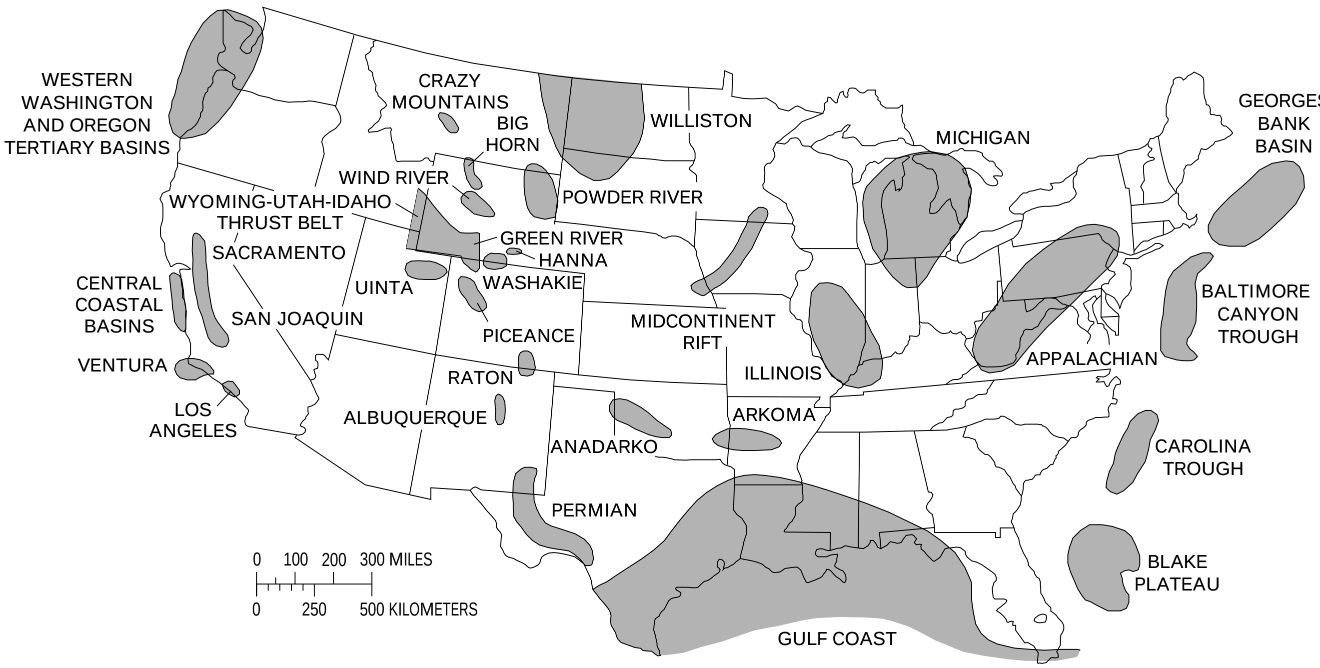

Figure 1. Map of the conterminous United States and offshore areas showing basins containing sedimentary rocks more than 15,000 ft (4,572 m) deep. Shading indicates entire basin area, in which some of the sedimentary rocks are at shallow depths. Basins having significant natural gas potential at depths greater than 15,000 ft are of several types: (1) passive continental margin basins including Georges Bank Basin, Baltimore Canyon trough, Blake Plateau, Carolina trough, and Gulf Coast Basin; (2) forearc basins including western Washington and Oregon Tertiary basins; and (3) foreland basins including Anadarko, Arkoma, Green River, Hanna, San Joaquin, Permian (Val Verde), Uinta, and Wind River basins.

Table 1. Basin settings and their relative favorability for deep natural gas accumulations and thermal history.

Setting	Favorability	Thermal history
Passive continental margin basin	Generally good	High heat flow during rifting, decreasing asymptotically with time.
Active continental margin basin		
(1) Forearc basin	Generally good?	Generally low heat flow except near magmatic arc..
(2) Foreland basin	Generally good	Generally low heat flow in cratonal settings, variable heat flow associated with thrust belts.
(3) Extensional and transtensional basins	Generally poor	High heat flow during extension.
Rift system	Generally poor	High heat flow during rifting, decreasing asymptotically with time.

PASSIVE CONTINENTAL MARGIN BASINS

Passive continental margins invariably begin as rifts within continents and represent the collapsed flank of the original rift (see, for example, Hoffman and others, 1974; Bond and Kominz, 1988), during and after sea-floor spreading has created a new ocean basin from the original rift (fig. 5). During the early phases of rifting, crustal stretching and thinning takes place and hydrocarbons may be generated at shallow depths as the result of initially high geothermal gradients (Sleep, 1971; Feinstein, 1981). Ocean and rift basin subsidence rates and geothermal gradients decrease as a fractional power of time *(t)* since rifting, $t^{1/2}$ for ocean basins (Parsons and Sclater, 1977; McKenzie, 1978; Feinstein, 1981). Passive margin basins considered favorable for deep gas include the Georges Bank Basin, Baltimore Canyon trough, Carolina trough, Blake Plateau Basin, Apalachicola (Eastern Gulf) Basin, and Western Gulf Basin. Of these, only the Western Gulf Basin is known to be a locus of abundant active growth faults and salt and shale flowage. Growth faulting and related structural processes have

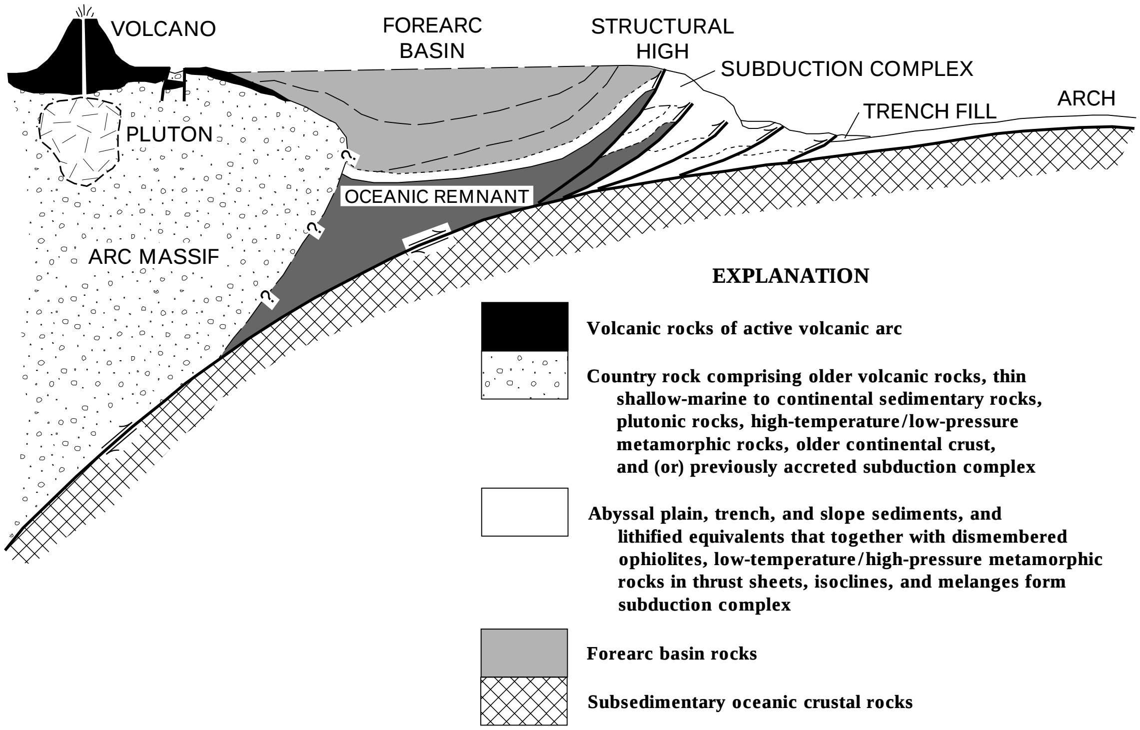

Figure 2. Schematic cross section across a Pacific-type plate margin showing position of the forearc basin with respect to volcanoes and plutons of the magmatic arc and the subduction complex (accretionary wedge) along the inner wall of the trench. Modified from Dickinson and Seely (1979, with permission of the American Association of Petroleum Geologists).

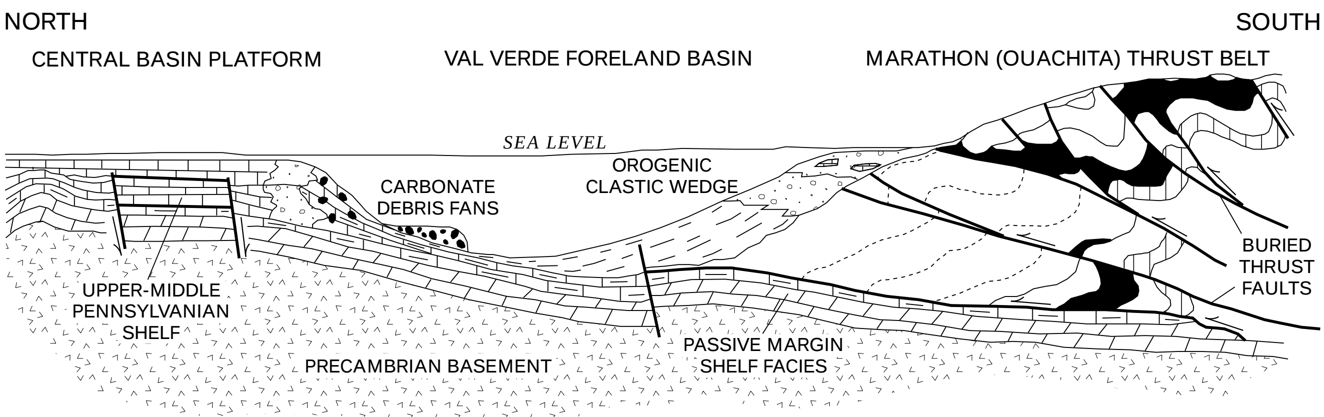

Figure 3. Schematic cross section across the Val Verde (Permian) foreland basin showing relationship to the Marathon fold and thrust belt. Modified from Wuellner and others (1986, fig. 10, with permission of Blackwell Science, Ltd.).

resulted in an abundance of structural traps for deep natural gas in the Western Gulf Basin, and this basin is a leader in hydrocarbon potential among passive margin basins in the conterminous United States.

FOREARC BASINS

To my knowledge, the only currently active forearc basin complex in and adjacent to the conterminous United States comprises the Western Washington and Oregon Tertiary basins (Frezon and Finn, 1988). In this complex, situated between the accretionary wedge of Tertiary and Quaternary sea-floor sediments and the active magmatic arc to the east represented by Mount Hood, Mount Rainier, Mount Saint Helens, only the easternmost basins should have a high geothermal gradient.

The Mesozoic Sacramento Basin is considered a type example of the forearc basin by Dickinson and Seely (1979);

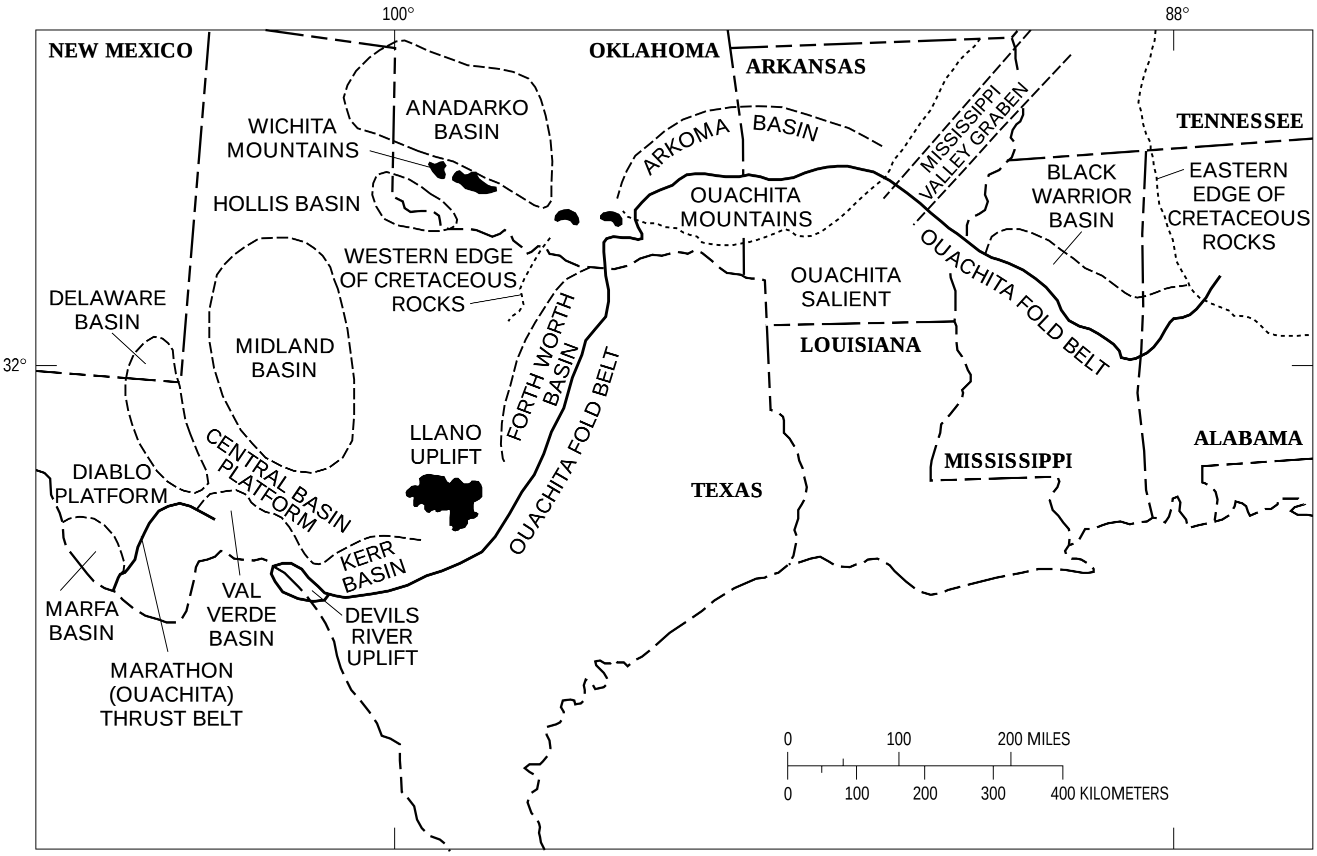

Figure 4. Generalized tectonic map of the southern Midcontinent. Modified from Perry (1989b).

however, the western part of this basin has been severely modified by Cenozoic thrusting (Wentworth and Zoback, 1989). Tectonic compaction, high geothermal gradients, and abnormally high fluid pressure development at depths of less than 8,000 ft (2,440 m) (Berry, 1973; Zeiglar and Spotts, 1978) probably are related to this compressional tectonism. The contiguous San Joaquin Basin to the south is a currently active narrow fold-and-thrust belt floored by a late Cenozoic blind thrust (Namson and Davis, 1988). The thick Cretaceous sequence of the San Joaquin Basin probably represents the same forearc basin complex as that of the Sacramento Basin to the north.

FORELAND BASINS

Foreland basins are generally considered to be the result of thrust loading (Beaumont, 1981; Jordan, 1981; Shuster and Steidtmann, 1988), and, as a consequence, their thermal history should be the inverse of that of the passive margin and rift basin development. The thermal gradient should be depressed within the basin during tectonism by thrust loading rather than elevated during tectonism by crustal extension and tectonic thinning as in the rift setting. The thermal history of foreland basins and overthrust terranes is discussed by Angevine and Turcotte (1983) and Furlong and Edman (1984). Foreland basins having deep gas potential and (or) production include the Anadarko and Arkoma basins of Oklahoma, Green River and Wind River basins of Wyoming, San Joaquin Basin of California, Uinta Basin of Utah, and Val Verde (Permian) Basin of Texas.

Low-permeability deep regions of all of these basins are overpressured (see, for example, Spencer, 1987), a likely result of active gas generation subsequent to basin development after reestablishment of normal geothermal gradients (Furlong and Edman, 1984). Continued basin filling subsequent to thrust loading, in the Anadarko Basin during the Permian may have been due to compaction and dewatering of the thick Upper Mississippian and Pennsylvanian basin sediments emplaced during transpressional thrust loading (Perry, 1989a).

Foreland basins of the Rocky Mountains, particularly those of Wyoming, may have reached their deepest burial about 18 million years ago (N.M. Denson, oral commun., 1989). Subsequent Neogene uplift to form present-day topographic relief and elevation is suspected to have resulted in cooling of the deeper parts of these basins. In the northern Green River Basin, cooling began 4–2 Ma, since which time “a relatively rapid temperature decrease of 20˚C (36˚F) or more” has taken place (Naeser, 1986).

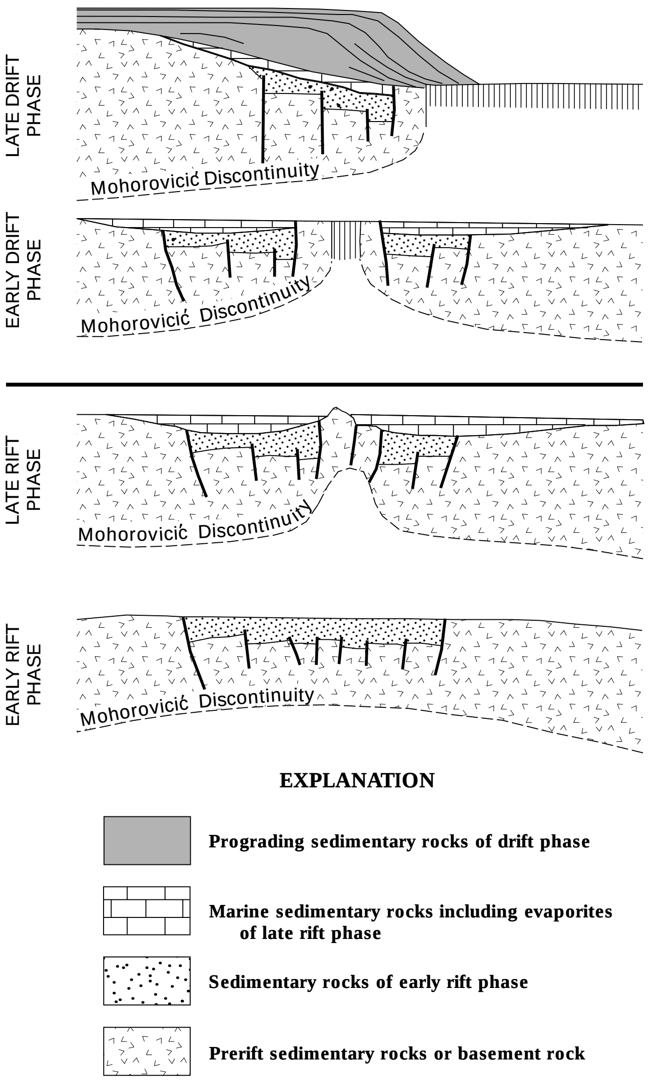

Figure 5. Schematic cross sections illustrating tectonic model of development of a passive continental margin from rifting. Modified from Schuepbach and Vail (1980.

EXTENSIONAL AND TRANSTENSIONAL BASINS ASSOCIATED WITH ACTIVE CONTINENTAL MARGINS

Inland from active continental plate margins, extensional or transtensional basins (table 1) form in two tectonic settings. Extensional or transtensional basins may form with their long axis perpendicular to a collisional plate margin of either Pacific-type (ocean-continent) or Himalayan-type (continent-continent). Examples of this type of basin include the Rhine graben in Europe and the Thai Basin in southeast Asia. I know of no examples of this type in the conterminous United States. Extensional or transtensional basins also may form subparallel to a transform or transtensional plate boundary, such as that of southern California. The Great Basin is the principal example of this type of basin in the conterminous United States. Such basins are generally typified by high heat flow and shallow hydrocarbon generation. Thermal gradients are such that little if any hydrocarbon source rock is anticipated to remain at depths of greater than 15,000 ft (4,572 m).

RIFTS AND AULACOGENS

Deep rift systems such as the Mississippi Valley graben (fig. 4) provide a possible structural setting for deep gas. One of the most densely drilled such systems, the Viking graben beneath the North Sea, probably does not contain significant quantities of natural gas at depths of greater than 15,000 ft (4,572 m). Aulacogens are simply rifts that widen toward their respective passive continental margins, having developed at the same time as the adjacent ocean basin opened. To my knowledge, no rift system has yielded significant quantities of deep natural gas. A likely reason for this is the thermal history of such systems discussed by Feinstein (1981), similar to that of extensional and transtensional basins associated with active margins. High rates of heat flow and high thermal gradients occur during early rift filling and decrease by $t^{1/2}$ with age to normal continental crustal values during basin development (McKenzie, 1978; Feinstein, 1981). Therefore, I no longer believe that rift basins are a likely structural setting for major deep natural gas accumulations.

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