Arkansas crustal xenoliths: Implications for basement rocks of the northern Gulf Coast, USA

Dennis P. Dunn

JACKSON SCHOOL OF GEOSCIENCES, UNIVERSITY OF TEXAS, AUSTIN, TEXAS 78712, USA

ABSTRACT

Crustal xenoliths recovered from the diamondiferous Prairie Creek lamproite province in southwestern Arkansas directly constrain the nature, age, and origin of Laurentian basement and indirectly provide a means to test models for development of the southeastern margin of Laurentia and the Ouachita trough. The majority of the crustal xenoliths are near-surface sedimentary rocks, and the rest are mainly amphibolite and both fresh and altered granitic rocks. K-Ar dates of four amphibolite samples average ca. 1.41 Ga and indicate an association with the Laurentian craton. Xenolith compositions and ages, in conjunction with published geophysical and drill data, can be used to test two tectonic models for the development of the southeastern margin of Laurentia and the Ouachita system. One model suggests that the Ouachita trough is a failed rift basin essentially contained within the North American craton. The second model suggests that the Ouachita trough is a rifted continental margin combined with late Paleozoic accretion of an island arc terrane. Application of these data to the two models of Ouachita development suggests that the Ouachita trough is extended and thinned continental lithosphere associated with a Paleozoic rift system that developed separately from the Appalachian continental margin.

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REGIONAL SETTING

Cretaceous diamond-bearing olivine lamproite occurrences of southwestern Arkansas straddle the geologic and physiographic boundary between the Gulf Coastal Plain and the Ouachita Mountains (Fig. 1). The Gulf Coastal Plain here is characterized by gently south-dipping Cretaceous sedimentary rocks that onlap and lie unconformably on intensely folded and faulted, east-west–trending, Paleozoic sedimentary rocks of the Ouachita Mountains. Rocks of this region are widely believed to lie near the southern margin of the midcontinent craton.

XENOLITH PETROLOGY

Approximately 2 kg of crustal xenoliths, 1–3 cm in size, were recovered from heavy media concentrates with a density of >2.82 g/cm^3. Representative xenoliths of each group were selected for thin section analysis based on their abundance and lack of visible alteration.

Approximately half of the crustal xenoliths are composed of near-surface sedimentary rocks, which include conglomerate, sandstone, and chert. These rocks are similar in appearance to Cretaceous and Paleozoic Ouachita facies sedimentary rocks, which are known to exist in the area. Two pink oolitic dolomite xenoliths with pellets and intraclasts are anomalous with respect to local lithologies.

Crystalline xenoliths are ~50% amphibolite, consisting dominantly of amphibole and lesser amounts of plagioclase with accessory biotite, chlorite, microcline, quartz, titanite, ilmenite, and apatite. The amphibolite specific gravity as measured in water ranges from 3.01 to 3.16, with an average value of ~3.08. Felsic composition xenoliths, consisting of granitic and rhyolitic rocks, are relatively rare, making up only ~5% of the deeper crystalline xenoliths. The average specific gravity of the felsic xenoliths is ~2.90. This high density is attributed to an abundance of iron oxides and epidote alteration, making them more susceptible to heavy media concentration.

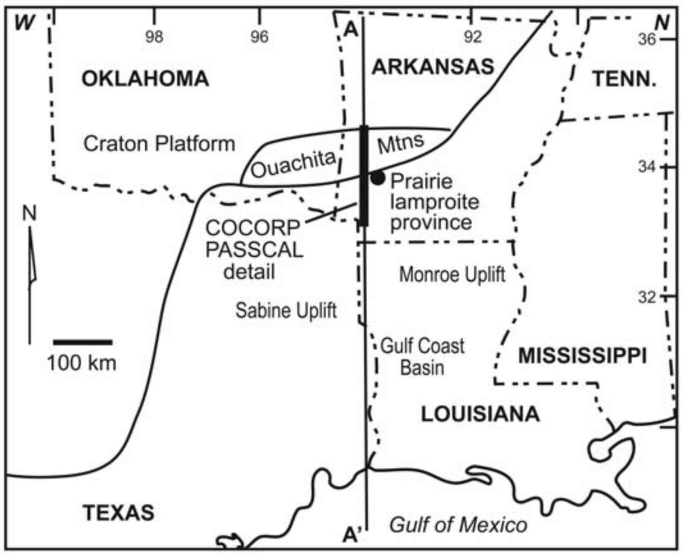

Figure 1. Geographic map of south-central United States. The location of the Prairie Creek lamproite province is shown in relation to selected tectonic features and to the lithospheric transect of Mickus and Keller (1992).

Approximately 40% of the recovered deep crystalline xenoliths are classified as epidote-rich rocks. The specific gravity of epidote-rich rocks is variable, but it typically ranges from 3.1 to 3.2. Some fine-grained felsic xenoliths have been almost completely replaced by epidote. Epidote alteration of amphibolite xenoliths is observed but is less common. Relatively rare (~5%) dark-colored xenoliths consist almost exclusively of coarse-grained (~7 mm), weakly aligned micas defining a foliation. Specific gravities of the micaceous xenoliths average ~3.10. Selected crustal xenolith data are presented in Table 1.

K-Ar AGES

One large amphibolite xenolith was submitted to Geochron Labs for K-Ar age dating, which yielded an isotopic age of 1431 ± 37 Ma. This surprising result was confirmed when an additional three amphibolite samples were selected for K-Ar isotopic age dating of hornblende. Separation of the hornblende from crushed samples was accomplished both by mechanical (magnetic separation) and visual (microscope) means to ensure sample purity. Amphibolite yielded K-Ar dates of 1471 ± 109 Ma, 1399 ± 55 Ma, and 1323 ± 30 Ma; analytical data and sources are given in Table 2. The four K-Ar isotopic ages indicate an average age of ca. 1.41 Ga for the amphibolites (Dunn, 2002).

TABLE 1. DEEP CRUSTAL XENOLITHS OF THE PRAIRIE CREEK LAMPROITES

Lithology	Density (g/cm^3)*	Abundance (%)	Provenance
Amphibolite	3.01–3.16	~50	Lower crust
Epidote-rich	3.10–3.20	~40	Upper crust
Felsic intrusives	~2.90	~5	Upper crust
Mafic intrusives	~3.10	~5	Mafic intrusion

*From specific gravity.

TABLE 2. K-Ar DATA

	K (wt%)	%^{40}Ar*	^{40}Ar* (ppm)	Age (Ma)	±1σ
BL†	0.95	96	0.1434	1431	37
BL 1§	0.886	98	0.1428	1471	109
BL 1b§	0.893	98	0.1326	1399	55
TK 1§	0.942	98	0.1242	1323	30

Constants: 4.963×10^{-10} yr^{-1}; 0.581×10^{-10} yr^{-1}; and –40K/K = 1.167×10^{-4}.
*Denotes radiogenic.
†Submitted by Steve Bergman to Geochron Labs for analysis.
§Analysis by Fred McDowell at University of Texas at Austin.

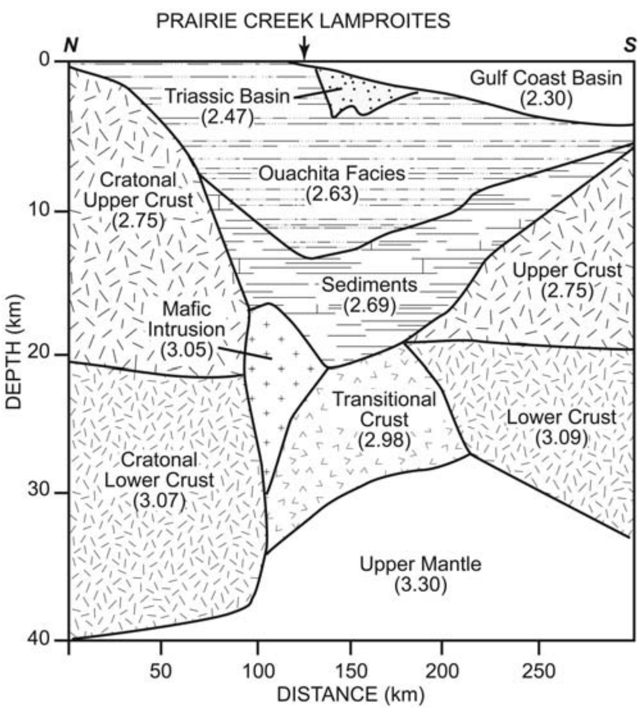

Figure 2. Detailed crustal section beneath the Prairie Creek lamproite province. Section was modified from the lithospheric transect of Mickus and Keller (1992). Model is based on seismic and gravity surveys along the PASSCAL/COCORP transect shown in Figure 1. Calculated rock density in g/cm^3 is shown in parenthesis.

DISCUSSION OF RESULTS

Petrography of the crustal xenoliths indicates that about half are near-surface sedimentary lithologies and half are deeper igneous and metamorphic rock types. Of the crystalline xenoliths, ~50% are amphibolites, ~5% are pelitic metamorphic rocks, ~5% are granitic/rhyolitic, and the remaining ~40% are epidote-rich varieties. Thin section examination indicates that the majority of the epidote-rich xenoliths were derived from alteration of felsic protoliths, and a lesser number were derived from amphibolite protoliths. In summary, these observations indicate the basement rocks beneath southwestern Arkansas consist largely of two types: granite/rhyolite and amphibolite.

These petrological data can be compared to a lithospheric transect model generated from gravity and seismic data in the region (Mickus and Keller, 1992). A regional transect originates in southwest Missouri, passes through southwestern Arkansas, and approximates the Texas-Louisiana border before extending offshore into the Gulf of Mexico (Fig. 1). A detailed section of this transect in the region of the Prairie Creek lamproite province, where the Gulf Coast Basin sediments onlap the Ouachita facies rocks, is shown in Figure 2. These data were derived from COCORP and PASSCAL studies. The simplified regional lithospheric transect from which this detailed section was derived is shown in Figure 3.

The Mickus and Keller (1992) profiles indicate that the model density of the lower cratonal crust is ~3.07 g/cm^3. Measured densities of amphibolite xenoliths averaged 3.08 g/cm^3, in good agreement with the modeled density. The modeled density of the upper cratonal crust is ~2.75 g/cm^3. This value is comparable to those expected for the granite/rhyolite terrane of the southern midcontinent, but it is lower than xenoliths concentrated during the heavy media processing.

The lithospheric transects of Mickus and Keller (1992) indicate that the majority of deep crustal xenoliths recovered from beneath the Prairie Creek lamproite province should be derived from "oceanic transition crust" with a density of ~2.98 g/cm^3. This transition crust has a thickness and calculated density that could be consistent with either thickened oceanic crust or thinned cratonic crust. A similar structural model developed for the central Gulf Coast shows that it is possible that the Ouachita orogen is underlain by thin continental crust rather than relict Cambrian age oceanic crust (Harry and Londono, 2004). A thinned cratonic crust origin is favored on the basis of abundant xenoliths with pervasive epidote alteration of both granite/rhyolite and amphibolite protoliths. The K-Ar dates, which range from 1.32 to 1.47 Ga, provide a more convincing argument that this oceanic transition crust might actually be thinned and altered cratonal crust. These dates are more consistent with the age of the granite/rhyolite province of a midcontinental craton and less consistent with an expected younger age associated with development of oceanic transition crust.

Approximately half of the crustal xenoliths recovered represent near-surface lithologies, including Late Cretaceous sedimentary strata and Paleozoic Ouachita facies sandstone and chert. The only modeled rock type not well-represented in the crustal xenoliths is "lower sediments?" with a density of 2.69 g/cm^3 (Fig. 2). These are believed to represent equivalents of Lower Paleozoic carbonate rocks found elsewhere in the Ouachita region (Nicholas and Waddell, 1989). The two dolomitized carbonate xenoliths are comparable to these Cambrian-Ordovician carbonate rocks

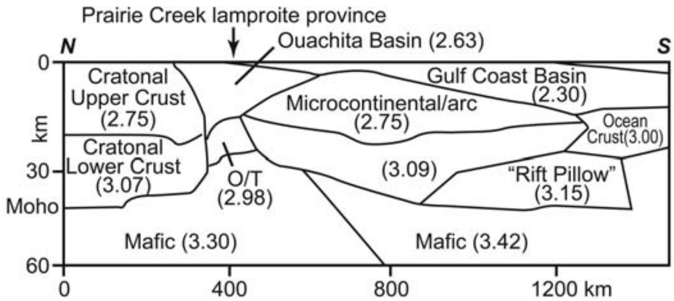

Figure 3. Simplified lithospheric transect model (Mickus and Keller, 1992). The approximate location of the Prairie Creek lamproite province is indicated. O/T indicates oceanic transitional crust. Calculated rock density in g/cm³ is shown in parentheses.

and are believed to be representatives of the "lower sediments." These rocks may be under-represented in the crustal xenolith suite because their relatively low density minimizes xenolith recovery or perhaps because extensive epidote alteration masks their true rock association. There is generally good agreement between the crustal xenoliths lithologies and densities predicted by the lithospheric geophysical transect of Mickus and Keller (1992).

K-Ar dates of deep crustal amphibolite indicate that they are associated with the granite-rhyolite terrane of the southern midcontinent region. Mosher (1998) has proposed that the Grenville-Llano deformation front, separating a 1.3–1.5 Ga granite-rhyolite terrane from the 1.0–1.2 Ga Grenville-Llano terrane to the south, continues northeast from central Texas toward the Arkansas border. The 1.41 Ga ages of xenoliths indicate that this significant age boundary must lie south of the Prairie Creek lamproite province.

The K-Ar age data are significant because they show no evidence of metamorphism associated with either the Grenville or Ouachita orogenies. The 1.41 Ga isotopic ages indicate that later tectonic events of the region (Grenville or Ouachita) were of insufficient thermal intensity (~500 °C) to exceed the hornblende K-Ar blocking temperature in the lower crust (Hanes, 1991). The amphibolite basement rocks indicate that the region was inboard and thermally isolated from the major continent-continent collision associated with the Grenville-Llano orogeny at ca. 1.1 Ga.

COMPARISON OF TECTONIC MODELS

Xenolith petrology, amphibolite K-Ar dates, and the lithospheric transect of Mickus and Keller can be used to test two existing models of the Ouachita salient and the northern Gulf Coast. One model treats the Ouachita trough as part of an early Paleozoic failed rift system within continental crust that included Grenville basement south of the Ouachita trough. Evidence supporting this hypothesis is early Paleozoic sedimentation patterns. The Ouachita trough was a narrow, two-sided basin with a southern bounding block that provided cratonic detritus well into the Ordovician (Lowe, 1985). A second model postulates that the southern margin of the midcontinent rifted in late Precambrian–early Paleozoic time along the Ouachita rift. Rifting extended from south-central Texas northeast toward the northwest-trending Alabama-Oklahoma transform fault (Thomas, 1991). The large block of continental lithosphere that was rafted out of the Ouachita salient is proposed to have docked with Gondwanaland, becoming part of the Precordillera of Argentina (Astini et al., 1995). Expected lithosphere characteristics of these two Ouachita models are compared in Table 3 and evaluated next.

Mantle xenoliths recovered from the Prairie Creek lamproite province in southwestern Arkansas record evidence of mantle lithosphere with a geothermal gradient consistent with a Lower Proterozoic–age stable craton (Dunn et al., 2000). The hypothesis of depleted, low-density mantle lithosphere is reinforced by the geophysical transect, which shows the presence of depleted (density of 3.30 g/cm³) mantle lithosphere beneath the Arkansas lamproite province (Fig. 3). More fertile "oceanic" mantle lithosphere with a density of ~3.42 g/cm³ is observed ~400 km south of the Prairie Creek lamproite province beneath southern Louisiana. Subcontinental mantle lithosphere xenoliths at Prairie Creek are thus more consistent with the continental-rift Ouachita model than the rifted-ocean-margin Ouachita model.

Deeper crustal xenoliths consist of amphibolite, rare granitic/rhyolitic rock, and significant amounts of altered epidote-rich rock. The 1.41 Ga K-Ar age of the amphibolite establishes an association with the granite-rhyolite terrane of the midcontinent. Xenoliths indicative of Cambrian-age ocean crust, as predicted by the rifted-ocean-margin model, were not found. The composition of the crustal xenoliths and the 1.41 Ga K-Ar amphibolites are consistent with continental extension of Laurentian craton.

The lithospheric transect geophysical model shows both structural symmetry and lateral continuity within the basement rocks (Fig. 3). The craton north of the Ouachita region consists of an upper crust that is ~20 km thick with a density of 2.75 g/cm³ and a lower crust that is ~20 km thick with a density of 3.07 g/cm³. This is nearly identical in thickness and density to the two-part "microcontinent" south of the Ouachita region. This continuity of basement features across the Ouachita trough is more consistent with the continental rift basin than the ocean margin–island arc model of genesis.

The structure of the Ouachita metamorphic belt has been described as consisting of a frontal zone, central zone, and southern Carboniferous province. The frontal zone consists of thrusts and folds involving mainly unmetamorphosed Carboniferous flysch. The central zone or core area consists of older pre-Carboniferous rocks, with greenschist-facies metamorphism, flanked by Carboniferous flysch. The southern province consists of faulted and folded Carboniferous strata, but with deformation decreasing southward until relatively undeformed Carboniferous strata are encountered (Nicholas and Waddell, 1989).

Stratigraphic correlation of the pre-orogenic rocks has been difficult due to the lack of deep drill data. However, pre-orogenic sedimentation patterns indicate that the Ouachita trough was a narrow two-sided basin with significant detrital input from the southern bounding block. The composition of this southerly derived detritus suggests a craton-derived passive-margin sequence (Lowe, 1985).

A deep well drilled east of Waco, Texas, within the core zone of the Ouachita belt, encountered massive carbonates that have been correlated with Ordovician carbonates of the adjacent foreland (Nicholas and Waddell, 1989). At depths of greater than 6.1 km (20,000 ft), this well penetrated a basal conglomerate and terminated within crystalline rocks of suspected Precambrian age (Rozendal and Erskine, 1971). This stratigraphy is in agreement with that observed from xenoliths recovered from the Prairie Creek lamproites. Another outcrop of metagabbro

TABLE 3. COMPARISON OF OUACHITA TECTONIC MODELS

	Aulacogen	Ocean margin
Stratigraphy	Regional correlation	No correlation
Metamorphic rock	Low grade	High grade
Basement rocks	Structural continuity	No continuity
Lower crust	Altered granite/gabbro	Ocean basalt
Upper mantle	Continental	Oceanic

located southeast of the Benton Uplift yielded a whole-rock K-Ar isotopic age of 1025 ± 10 Ma (Morris and Stone, 1986). These data indicate a possible correlation of Mesoproterozoic basement across the Ouachita fold belt.

Stratigraphic correlation of the synorogenic Carboniferous flysch is nearly impossible due to the extensive deformation within the sedimentary sequence. Probably the best chance for correlation of rocks across the Ouachita trough lies with dating of intersected volcanic units. Thin volcanic units are found throughout much of the Paleozoic, as indicated by exposed tuffs in Arkansas and drilled volcanics of 380 Ma to 255 Ma in the deep well east of Waco. Other wells drilled near Sabine, Texas, indicate that the deformed southern Carboniferous province is overlain by undeformed interbedded shale and rhyolite porphyry (255 ± 15 Ma) of Permian age (Nicholas and Waddell, 1989). This possible correlation across the Ouachita trough may indicate that the areas were in close proximity during much of the late Paleozoic. The observed low metamorphic grade, the apparent symmetry of the deformation, and possible stratigraphic correlation across the Ouachita trough are more consistent with a continental rift association than with a strongly deformed asymmetrically accreted island arc terrane.

Nd isotopes have been used to constrain sediment provenance for the Ouachita fold belt. Three sources are indicated by Nd-depleted mantle model ages (T_{DM}): a Lower to Middle Ordovician T_{DM} = 2.0 Ga source, an Upper Ordovician to Pennsylvanian T_{DM} = 1.6 Ga source, and a Mississippian volcanic tuff T_{DM} = 1.1 Ga source (Gleason et al., 1995). These data are consistent with the rift-basin origin, if the ca. 450 Ma shift in sediment source was from the Laurentian craton to the Grenville/Llano provenance to the south. The shift is consistent with previously interpreted source directions (Lowe, 1989). The Mississippian tuff age, T_{DM} = 1.1 Ga, would be expected if these volcanic units were derived from melting of Grenville-age crust located in the craton margin to the south. Therefore, both the low-grade metamorphism and Nd isotope data from Ouachita sedimentary assemblages are consistent with the rift-basin Ouachita model of formation.

CONCLUSIONS

Xenolith data, geophysical transects, and drill data across the Ouachita fold belt support the rift-basin model of the Ouachita trough as opposed to the rifted continental margin and late Paleozoic collision of an exotic island arc terrane. It seems likely that the Ouachita trough was part of an early Paleozoic failed rift system that developed separately from the older Appalachian continental margin (Lowe, 1989). The Ouachita trough may have been connected to both the early Paleozoic Wichita and Reelfoot rifts and consisted of two parts; the east-west–trending Ouachita rift in Arkansas and the northeast-trending Waco rift in Texas (Fig. 4). The Ouachita trough probably formed from distended continental crust, with the southern bounding block consisting of a Grenville basement and lower Paleozoic sediments. Inclusion of this bounding block extends the southern margin of the midcontinent craton into southern Louisiana (Fig. 4).

The rift system apparently deepened rapidly during the early Carboniferous with subsidence ending in the early Pennsylvanian with onset of the Ouachita orogeny. The Ouachita orogeny may have been initiated when the southern margin of the bounding microcontinent was impinged by an Appalachian-type orogeny. Tectonic forces associated with this orogeny at the southern margin were transmitted through this stable block, causing compression of the Carboniferous flysch and resulting in the thin-skinned fold-and-thrust belt of the Ouachita Mountains.

The Ouachita rift-basin model, through its association with the midcontinent rift system, helps to explain the shape of the Ouachita salient, the location of the existing Ouachita outcrops, and the lack of high-grade metamorphic rock or plutons within the Ouachita Mountains. This model predicts the existence of a cratonic block with Grenville basement beneath the Texarkana Platform and the resulting biostratigraphic correlation of the Carboniferous flysch across the Ouachita trough. The Ouachita rift model is inconsistent with the hypothesis that the provenance region of the Argentine Precordillera was the Ouachita rifted margin and instead suggests another area further south and east near the craton margin as a likely provenance region of Laurentia.

Other workers have observed that the Ouachita orogen exposed in Oklahoma and Arkansas developed as a thin-skinned system, without significant basement involvement like that recognized in west Texas and in the southern Appalachians (Harry and Londono, 2004). If so, the Ouachita style of deformation may vary significantly from those other areas. It has even been suggested that the thicker crust in the eastern Ouachita of Arkansas may be attributed to an eastward transition from a rift segment to a transform segment of the Paleozoic continental margin (Harry and Mickus, 1998). This transition from a rift zone in Arkansas to a transform boundary east of the Reelfoot rift in Arkansas would allow reconciliation of the data presented in this paper with the tectonic inheritance model proposed by Thomas (2006).

The Prairie Creek lamproite xenolith suite, in conjunction with geophysical data, provides important constraints on models of the origin of the Ouachita system. These data provide evidence for the association of the Ouachita trough with a Paleozoic continental rift system and suggest extension of the Laurentian craton ~400 km further south than previously suspected.

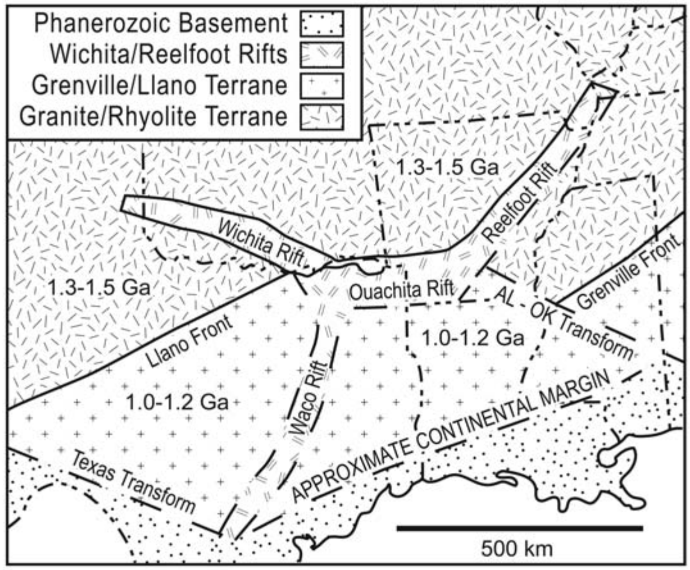

Figure 4. Idealized basement geology for the Ouachita aulacogen model. Map is modified from Proterozoic geology of the western midcontinent basement (Van Schmus et al., 1986).

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