Proterozoic basin in the southern Midcontinent of the United States revealed by COCORP deep seismic reflection profiling

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ABSTRACT

COCORP deep crustal seismic profiles in southwestern Oklahoma show strong, persistent, continuous, and undeformed layering in the basement over an area probably very much greater than 2,500 km^2. Such layering is very unusual, judging by COCORP experience with basement rocks elsewhere in the United States. The data can be interpreted as representing a Proterozoic basin filled with clastic sedimentary and felsic volcanic rocks 7 to 10 km thick, whose base lies 10 to 13 km deep. These rocks are believed, on the basis of sparse evidence from regional geology, to have been deposited or extruded about 1,200 to 1,400 m.y. ago, and some of them may now be metamorphosed. This basin lies on the south side of the Wichita Mountains, under the Paleozoic Hardeman Basin, and is similar in depth to the Paleozoic Anadarko Basin north of the mountains. The deep basement layering is truncated on the south side of the Wichita Mountains, probably by Precambrian faults in conjunction with granitic intrusions. Pennsylvanian compression probably reactivated these Precambrian trends. Extensive Precambrian basin deposits in this area were unexpected, on the basis of evidence from sparse well control, and reports of other layered basement reflections elsewhere in the southern Midcontinent suggest that Precambrian basins may be an important feature of this region. Simple models for the evolution of southwestern Oklahoma as an aulacogen must be reformulated in the light of these new data.

INTRODUCTION

COCORP (Consortium for Continental Reflection Profiling) deep crustal seismic reflection profiles were recorded in southwestern Oklahoma in 1979 partly to study the deep structure of the southern Oklahoma aulacogen and partly because the first COCORP surveys ever conducted, nearby in Hardeman County, Texas, in 1975 (Fig. 1), revealed that the basement in that area has a very distinctive layered character to depths of almost 10 km (Oliver and others, 1976; Lynn, 1979). In general, this layering is in striking contrast to the character of Precambrian crust profiled elsewhere in the United States by COCORP. The Oklahoma survey was originally intended to traverse both the Wichita Mountains and the Anadarko Basin, but because of logistical problems it was temporarily discontinued in 1979, with 268 km of line recorded, before reaching the Anadarko Basin. The total COCORP program in this area was completed in late 1980, but we summarize here the main results and geological implications of the initial surveys south of the Anadarko Basin. A more complete discussion of the data is forthcoming (Brewer and others, in prep.). For a review of COCORP data-collection techniques and results of other studies in the United States, see Schilt and others (1979).

The reason for the unusual layering in the basement is a fascinating problem; Lynn (1979) has suggested, on the basis of the original Hardeman County data, that it is caused by tabular granite intrusions underplated by gabbroic bodies. The new Oklahoma data reveal that the layering is in fact very extensive and truncated on the south side of the Wichita Mountains. On the basis of these new data, we propose an alternative interpretation for the layering: that it is caused by lithologic features related to sedimentary or volcanic processes and that a deep Proterozoic basin lies south of the Wichita Mountains. This basin is about as deep as the Paleozoic Anadarko Basin north of the mountains, and its hydrocarbon potential is unknown and untested.

GEOLOGIC AND TECTONIC SETTING OF SOUTHWESTERN OKLAHOMA

An aulacogen is a transverse linear trough that extends from a geosyncline far into the interior of a foreland platform (Hoffman and others, 1974). Some confusion exists over the exact definition of the term as applied to southern Oklahoma, but in this paper we follow the usage of Hoffman and others (1974) and King (1976, p. 74) in considering that the aulacogen includes both the Wichita Mountains and the Anadarko Basin. The COCORP lines described in this paper recorded south of, and within, the Wichita Mountains thus cross the southern part of the aulacogen. Aulacogens have been interpreted in a plate-tectonics framework by Burke and Dewey (1973), Hoffman and others (1974), and Burke (1980), who related them to initial continental rifting, failure of a rift "arm" (the aulacogen), followed by compression due to closure of the ocean basin formed by the "arms" that rifted successfully. The southern Oklahoma aulacogen is truncated to the southeast by the Ouachita-Marathon fold belt, which may mark the closure of such an ocean basin (see, for example, Viele, 1980), although details of timing and exact relationships are not clear (King, 1976, p. 77).

Ham and others (1964; see particularly Pl. 4) suggested that basin formation in southwestern Oklahoma began with deposition of the Tillman Metasedimentary Group (chiefly meta-graywacke) onto an eroded batholithic complex about 1,200 to

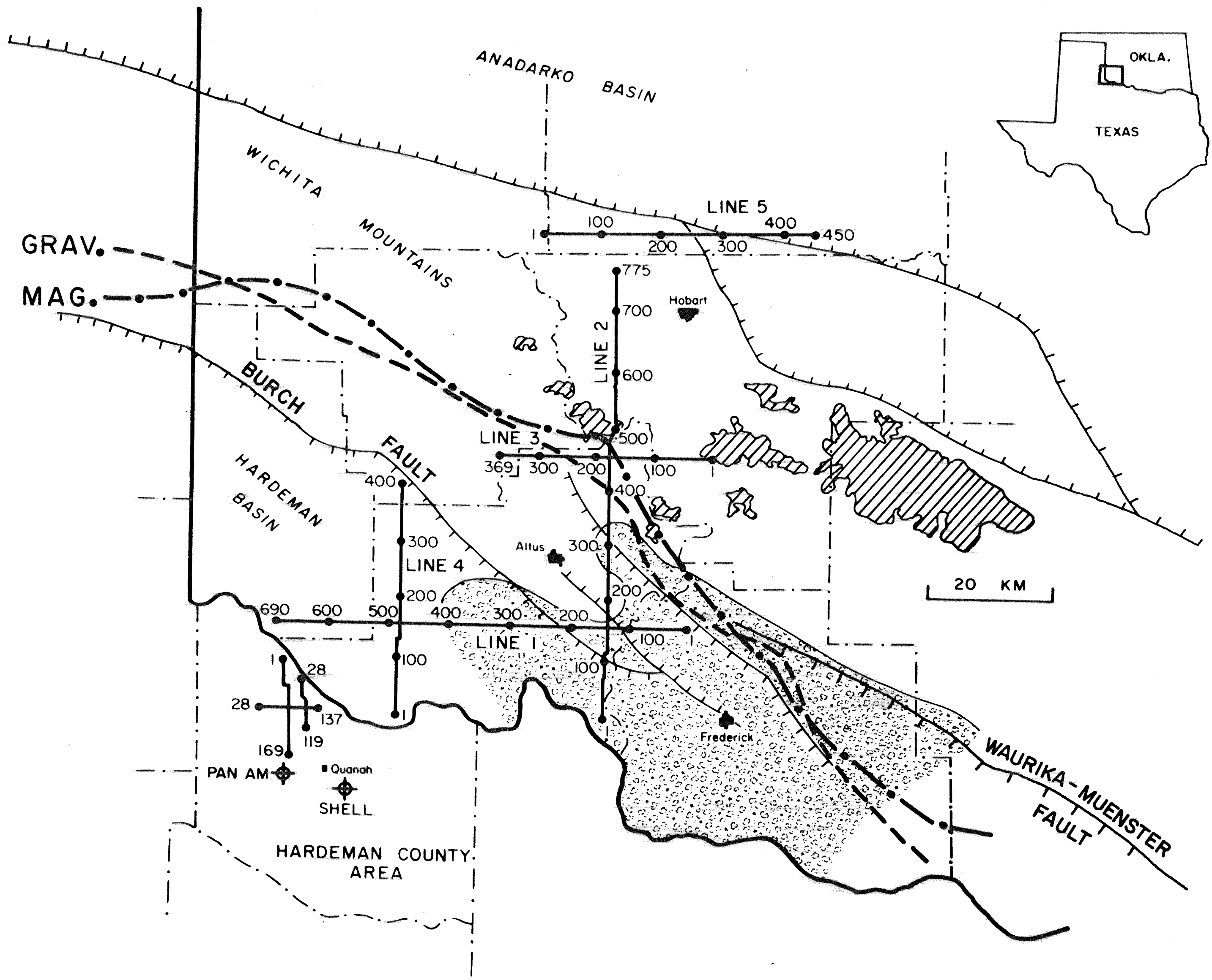

Figure 1. COCORP line location map showing Oklahoma Part 1 (1979) and Hardeman County, Texas (1975) surveys. Numbers along profiles refer to ground stations. Striped areas = outcrops of Wichita igneous province; stippled area = inferred subsurface extent of Tillman graywackes. PAN AM = position of Pan American No. 1 Bestwall well; SHELL = position of Shell No. 5 Conley well. Bestwall well bottomed in microgranite porphyry 1,265 ± 40 m.y. old; Conley well cut mesozonal granite that has not been dated. Faults shown are high-angle reverse (teeth on downthrown side). Structure and lithology simplified after Ham and others (1964). GRAV and MAG = position of gradients of southern flank of gravity and magnetic highs in Wichita Mountains (after Lyons, 1964; Jones and Lyons, 1964). Precambrian layering, probably Proterozoic basin, underlies all COCORP lines south of Burch fault and is inferred to extend at least 150 km to southeast, where it is observed south of Waurika-Muenster fault on Chevron seismic data (discussed in text). COCORP lines 3 and 5 are not discussed here.

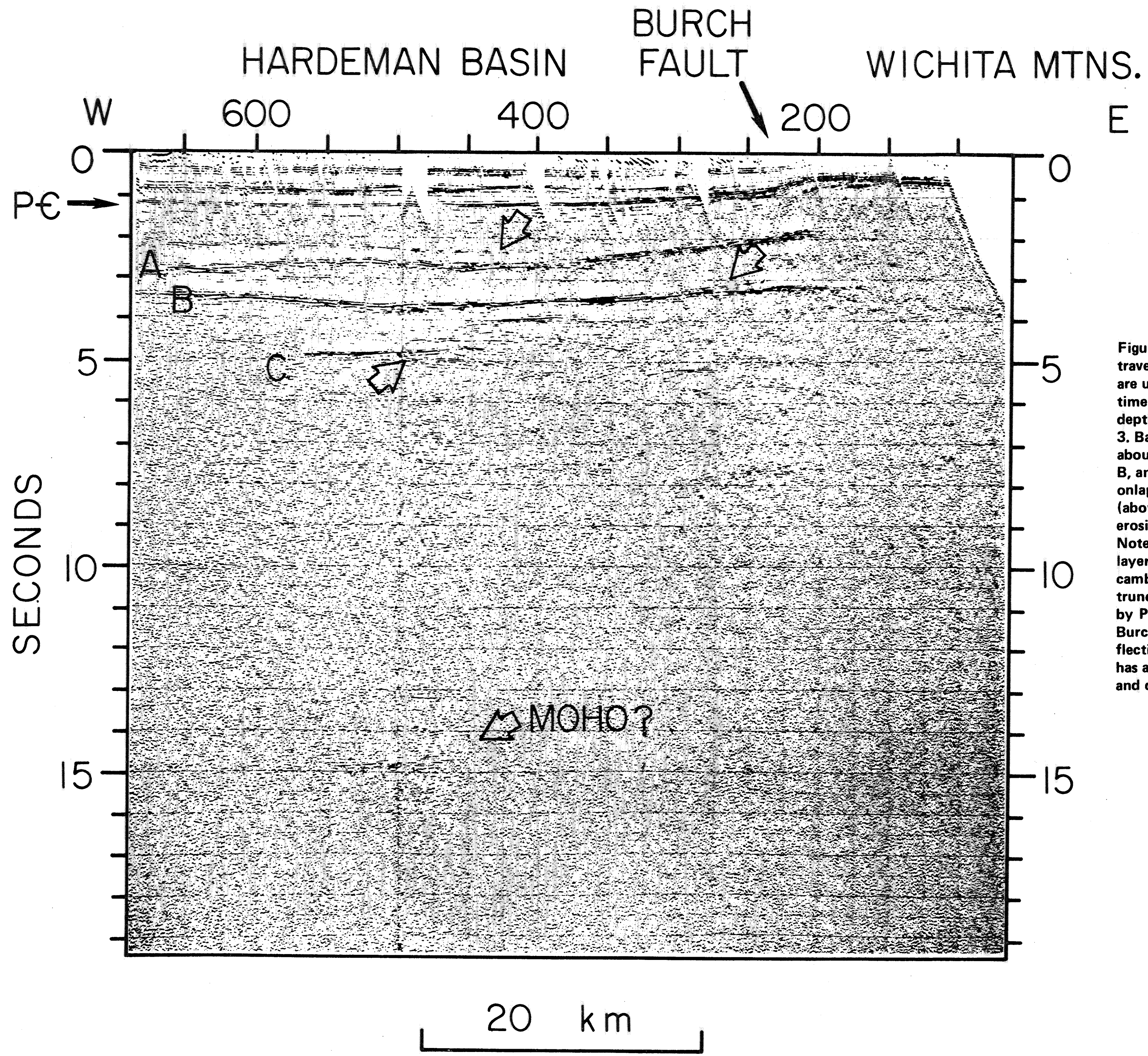

Figure 2. COCORP Oklahoma traverse line 1. These seismic data are unmigrated; to convert travel time in seconds to approximate depth in kilometres, multiply by 3. Base of Paleozoic section is at about 1.3 s; note strong events A, B, and C below. Arrows point to onlapping and downlapping events (above A and B) and possible erosional truncation below C. Note truncation of Precambrian layering at east end of line. Precambrian fault probably caused truncation, and was reactivated by Pennsylvanian movements as Burch fault. Possible Moho reflection is also seen on line 4 and has approximate strike of N70°E and dip of about 10°NW.

1,350 m.y. old. They thought that this began in Early Cambrian(?) time, although regional evidence (Muehlberger and others, 1967) suggests that the graywacke may be older than 1,000 m.y. Basalts and spilites were later deposited onto the graywackes, which were also intruded by gabbros in the area that later became the Wichita Mountains (Ham and others, 1964). The best available isotopic evidence suggests that this igneous activity occurred in Cambrian time, although a Precambrian age for the gabbros is indicated by paleomagnetic data (Roggenthen and others, 1981) and by geological arguments (Powell and Phelps, 1977). A brief period of intense faulting and differential erosion was followed in the Middle Cambrian by extrusion of thick sequences of silicic volcanic rocks and intrusion of comagmatic epizonal granite plutons and sills. Downwarping continued in the early Paleozoic but was concentrated on the north side of the Wichita Mountains (the Anadarko Basin). The present configuration of the basement is due to intense Pennsylvanian deformation and subsequent erosion.

MAIN RESULTS OF COCORP SURVEYS IN OKLAHOMA PART 1 (1979) PROGRAM

Layered Precambrian Crust South of Wichita Mountains

Seismic data from lines 1 and 2 (Fig. 1) are shown in Figures 2 and 3. Oklahoma lines 1 and 4, in the Hardeman Basin, are similar in many respects to the original Hardeman County data (Oliver and others, 1976) and are striking because they show strong layering in the basement south of the Wichita Mountains over a wide area. Extrapolations based on the extent of the layering on the COCORP profiles recorded in the Hardeman Basin suggest that it underlies at least 2,500 km², and other industry data (discussed below), recorded about 150 km along

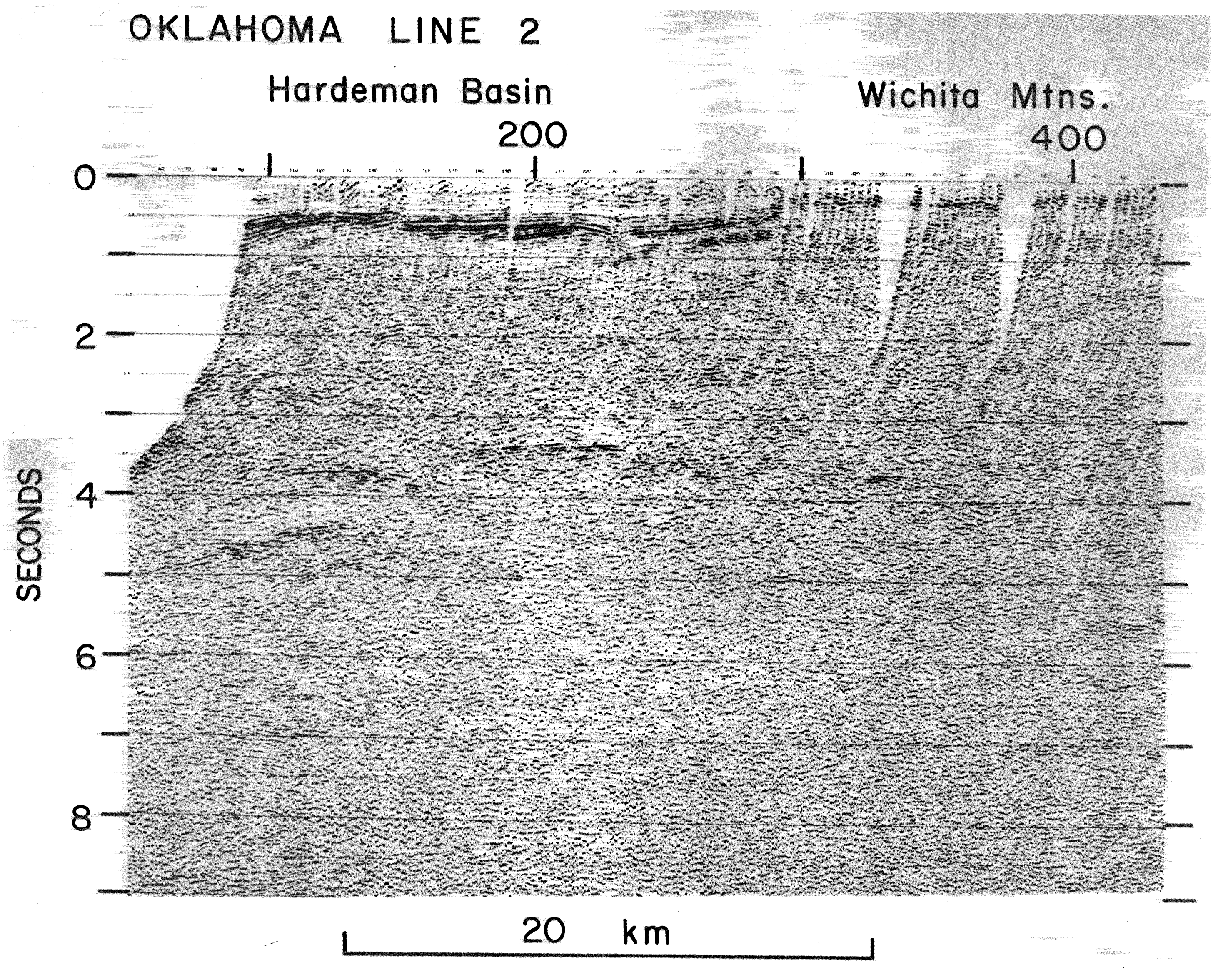

Figure 3. Southern end of Oklahoma line 2 showing discontinuous events that might be remnants of Precambrian layering within mountains, presumably much disrupted by faulting and intrusions.

structural trend to the southeast, indicate that the layering is probably widespread south of the mountains. Well control indicates that the base of the Paleozoic section in the Hardeman Basin occurs at about 1.3 s (about 3 km depth). The Paleozoic section is only slightly deformed and faulted. Below 1.3 s the deep layering is represented by two very strong and continuous seismic horizons, events A and B, at depths of about 7.5 and 10 km (Fig. 2). A third event, C, at about 13 km depth, is less continuous than event A or B and on line 1 appears to truncate some events below, suggesting an erosional unconformity (Fig. 2). A second type of seismic horizon present in the basement south of the Wichita Mountains consists of continuous events of moderate amplitude which onlap or downlap onto lower horizons (Fig. 2). Layering in a crustal sequence could correspond to a variety of features, including sedimentary bedding, volcanic or intrusive layering, tectonic layering (such as stacks of thrust sheets), or gneissic banding (which would probably have to have an effective thickness of at least 40 to 80 m to cause the strong layering on the COCORP data). However, sedimentary or volcanic bedding seems most likely because of the widespread extent and undeformed character of the layering. Also, the high amplitudes and undulating and locally complex seismic character of these events are somewhat similar to that of unconformities seen on published seismic data (for example, Tucker and Yorston, 1976, p. 39). Onlapping or downlapping seismic characters also suggest depositional horizons (Mitchum and others, 1977), which in this case might be due to volcanic flows or shifting sedimentary patterns. Salt flowage patterns could conceivably also cause this seismic character. Below event C, extensive coherent reflections are rare and interspersed with zones of little or no reflected energy (opaque or transparent zones). The deepest distinct seismic horizon (Fig. 2) occurs between 14.5 and 15.0 s (about 40 to 43 km depth) and is seen on both lines 1 and 4 at their crossing. It strikes about N70°E, at a considerable angle to the N60° to 75°W Paleozoic structural grain, and dips about 10° to the northwest. A refraction line north of the Wichita Mountains indicates a Moho depth of about 46 to 51 km (Mitchell and Landisman, 1970; Tryggvason and Qualls, 1967); thus, the 40- to 43-km-deep event may be a reflection from the Moho south of the Wichita Mountains.

Because of the continuity and high amplitude of the upper crustal layering, well-determined stacking velocities (which are rough approximations to average velocities; Dobrin, 1976) were obtained. They are laterally quite variable and when averaged yield an approximate velocity between the top of the Precambrian and event A of 6.1 ± 0.3 km/s, between events A and B of 6.3 ± 0.3 km/s, and between events B and C of 6.5 ± 0.2 km/s. Velocities alone are rarely unambiguously diagnostic of lithology, but these figures are consistent with average velocities expected from such rocks as granite, granodiorite, gneiss, and quartzite, generally higher than velocities obtained from other metasedimentary rocks at equivalent temperatures and pressures, and lower than more basic rocks (Clark, 1966). Alternatively an interlayered sequence of, for instance, graywackes and basalts (both found in the subsurface of the Wichita Mountains) might also have these velocities. The small reflection coefficients expected from the similarity of the average velocities suggest that the strong reflections A, B, and C are due to velocity and density changes at these horizons themselves. Resolution of velocities within horizons A, B, and C could provide further lithologic constraints; a decrease of velocity at A, B, or C might suggest unconformities, whereas an increase might be more consistent with alternative possibilities for their high-amplitude reflection character—for example, thick basalt flows or carbonate beds.

Truncation of Precambrian Layering

Figure 2 shows that events A and B, and possibly C, are truncated close to the southern edge of the Wichita Mountains. The distinctive layered seismic character is not present beneath the mountains. The truncation is coincident with the Burch fault, one of a series of en echelon faults running along the south side of the Wichita Mountains (Fig. 1; Ham and others, 1964). This fault has about 0.6 km of down-to-the-south Pennsylvanian movement (Ham and others, 1964), which the COCORP data imply is in a reverse dip-slip sense.

Important additional evidence for the existence and regional extent of the truncation of the basement layering and the character of the Pennsylvanian faulting comes from a Chevron Oil Company seismic line recorded about 150 km southeast of, and along strike from, the position of the truncation on the COCORP lines (C. Frazier, 1981, personal commun.). This line shows that the basement south of the mountains in that region is also distinctly layered and is truncated in a similar fashion coincident with the trace of the Pennsylvanian Waurika-Muenster fault, the southeasterly continuation of the Burch fault (Fig. 1).

The truncation of the Precambrian layering could be due to normal or reverse faulting, intrusions, or a combination of these. The age of the truncation is pre–Late Cambrian, since rocks of this age overlie the Burch fault with only a moderate offset resulting from Pennsylvanian movements (Ham and others, 1964, Pl. 1). Some relatively discontinuous horizons of moderate amplitude occur within the Wichita Mountains block northeast of the Burch fault (Fig. 3). These horizons may be continuations of the crustal layering, much disrupted by faulting or later intrusions, under the Wichita Mountains. In this case, if a Precambrian fault caused the truncation, it is probably normal, downthrown to the north and thus of opposite sense to the Pennsylvanian Burch fault. Farther north, in the middle of the Wichita Mountains, the discontinuous events die out, probably because of disruption by the gabbros and granites that core the mountains. Inclusions of quartzite (Meers quartzite; Ham and others, 1964; Powell and others, 1980) are found in both the Cambrian Wichita granites and the gabbros. These inclusions may indicate sandstone horizons extending under the Wichita Mountains, and they support the idea of a Proterozoic basin predating the formation of the Wichita Mountains block (Ham and others, 1964).

If the discontinuous events under the mountains are not correlative with the layering to the south and if a Precambrian fault caused the truncation, it would be reverse, upthrown to the north, with at least 7 km of dip-slip movement. This interpretation is possibly supported by the Chevron data, which contain very few events in the mountain block north of the Waurika-Muenster fault which might correlate with the basement layering. However, a large reverse fault would imply regional compression and is generally not favored because greater deformation might be expected in the downthrown block than is evident from the seismic data.

The truncation might also correspond to an intrusion. However, it is probably not due to the gabbros, because magnetic and gravity maps (Lyons, 1964; Jones and Lyons, 1964) show that the density and magnetic gradients that apparently delineate the subsurface extent of the gabbro (Pruatt, 1975) lie north of the truncation (Fig. 1), and no strong gravity or magnetic contrasts exist across the Burch fault. Truncation by the Wichita granites cannot be ruled out, although the granites are not known to the southeast (Ham and others, 1964, Pl. 1), where the Chevron data show that the truncation also occurs.

DISCUSSION

The layered Precambrian basement south of the Wichita Mountains is probably a very thick sequence of undeformed, but possibly metamorphosed, sedimentary and volcanic rocks. The age of these rocks is very important to the history of the southern Oklahoma aulacogen and can only be accurately determined with drill control and isotopic dating or by identifying the rocks in outcrop or subcrop. However, just to the south of the Hardeman County COCORP lines, a well to basement (Pan Am of Fig. 1) penetrated a micrographic microgranite porphyry yielding a whole-rock Rb-Sr age of 1,265 ± 40 m.y. (R. E. Denison, unpub. data). This rock is probably intruded at a shallow level into an unknown host, which may be the same layered rocks seen on the COCORP lines. In this case, some of the layered rocks are probably older than 1,265 m.y.

Some constraints can also be placed on the age of the basement layering from regional geologic information. There is a strong possibility that Tillman graywackes (Fig. 1), which well and isotopic data from the Texas Panhandle (Muehlberger and others, 1967) suggest are older than 1,000 m.y., occur in the thick sequence of layered basement rocks. Rhyolites known from several wells drilled in Greer County (Ham and others, 1964) about 30 km north of COCORP line 4 may also compose part of the basement layering. Isotopic ages from two of these wells indicate an age around 1,200 m.y. (R. E. Denison, unpub. data), probably equivalent to rocks of the Panhandle Volcanic Terrane (Muehlberger and others, 1967).

The scanty available age data suggest that most, if not all, of the layered basement in southwestern Oklahoma is at least 1,200 m.y. old. The oldest reported rocks in adjacent parts of Texas are granitic gneisses slightly less than 1,400 m.y. old (the Chaves Terrane; Wasserberg and others, 1962; Muehlberger and others, 1966); to the east, granites and granite gneisses in the eastern Arbuckle Mountains have zircon ages of 1,370 to 1,400 m.y. (Bickford and Lewis, 1979). On the basis of these data it seems most likely that the layered basement was laid down on granite gneisses no older than 1,400 m.y. However, the oldest rocks in the southern Midcontinent area are granites and gneisses at least 1,600 m.y. old, found in central New Mexico (Muehlberger and others, 1966, 1967), and possibly the undeformed basement layering was laid down on rocks as old as this. If this was the case, perhaps the relatively discontinuous character of layer C (Fig. 2) is due to intrusion and disruption by 1,400-m.y.-old granites.

Truncation of the layered rocks must have occurred after their deposition and prior to the transgression that deposited Upper Cambrian Reagan Sandstone. Precambrian regional extension in southern Oklahoma is suggested by diabasic and granitic and rhyolitic dikes in the Arbuckle Mountains aligned parallel to the aulacogen. These have two sets of ages—one near the age of the host granites (1,370 to 1,400 m.y.) and a younger set of Cambrian age (Denison, 1973, and unpub. data). If normal faulting truncated the basement layering, it probably occurred in Cambrian time if the layering is underlain by 1,400-m.y.-old rocks, or it may have occurred about 1,400 m.y. ago if the layering is underlain by 1,600-m.y.-old rocks. The truncation might also be caused by the Cambrian granitic intrusions found in the Wichita Mountains (Ham and others, 1964), perhaps also in conjunction with normal faulting.

It is important to understand the relationship of the deep basement layering, inferred to be a Proterozoic basin, to the southern Oklahoma aulacogen. It is possible that the Tillman graywackes [considered by Hoffman and others (1974) to mark the beginning of the southern Oklahoma aulacogen] are very thick and are responsible for all or part of the deep layering. In this case, the Precambrian history of deposition in the aulacogen is just as impressive as the Paleozoic history in the Anadarko Basin. Alternatively, the deep basement layering predates the Tillman graywackes, in which case the basin might represent an earlier aulacogen, a continental margin sedimentary sequence, or an epicratonic basin. Mid-Proterozoic basins are found on most ancient cratons and are typically fault bounded and filled with coarse red sandstone and conglomerate, arkose and quartzite, siltstone, argillite, and slate with abundant silicic volcanics, welded tuffs, ignimbrites, and breccia (Salop, 1977; Windley, 1977). Examples occur in the Baltic Shield (sub-Jotnian Group), the Ukrainian Shield (Ovruch Group), the Siberian Shield (Akitkan Group), and the Churchill Province (Dubawnt Group) (Salop, 1977). The Precambrian geology of the southern Midcontinent of the United States is in general poorly understood because of lack of exposure. However, there are great areas known of little-deformed anorogenic felsic volcanic rocks and associated epizonal granites 1,200 to 1,500 m.y. old that extend from Ohio into eastern New Mexico, cropping out in the St. Francois mountains of Missouri (Muehlberger and others, 1967; Flawn and Muehlberger, 1970; Denison and others, in prep.). Sedimentary rocks of the Midcontinent Precambrian are typically coarse clastics, sandstones, and arkoses (Denison and others, in prep.), and the overall geology of the area is quite similar to that of the better exposed Proterozoic basins known on other cratons, suggesting that felsic volcanic and clastic sedimentary (or metasedimentary) rocks might be the major constituents of the inferred Proterozoic basin south of the mountains.

Proterozoic basins may exist elsewhere in the southern Midcontinent of the United States. Scattered reports from oil-industry surveys suggest that Precambrian reflecting horizons also occur in the Texas Panhandle, in eastern New Mexico, and to the northeast of the Anadarko Basin, possibly representing parts of other such basins. The hydrocarbon potential of the Proterozoic basin south of the Wichita Mountains is unknown and untested. Although old rocks are generally less productive of petroleum, Murray and others (1980) have assembled abundant evidence that hydrocarbons are found in Proterozoic basins elsewhere in the world.

SUMMARY AND CONCLUSIONS

COCORP profiling in the Hardeman Basin and Wichita Mountains has revealed that the basement south of the mountains has an unusual layered seismic character. On the basis of interpreting this layering as depositional in nature, the following inferences are made.

1. A Proterozoic basin lies south of the Wichita Mountains. It contains about 7 to 10 km of layered rocks, its base is about 10 to 13 km deep, and it may be filled with felsic volcanic and clastic sedimentary (possibly metamorphosed) rocks. On the

basis of regional data, the deposition occurred earlier than 1,200 m.y. ago and later than 1,400, or possibly 1,600, m.y. ago.

2. The distinctive layering of the Proterozoic basin is truncated on the south side of the Wichita Mountains, probably by Precambrian normal faulting, although intrusion of granitic rocks is a possibility. The basin may have once underlain the mountains, where the distinctive layering was subsequently disrupted by the younger gabbros and granites and perhaps by later faulting.

3. Extensive Precambrian basin deposits in this area are surprising; they may represent either a much longer history of Precambrian subsidence of the southern Oklahoma aulacogen than previously thought, or an earlier aulacogen, or an epicratonic basin. Reports of layered basement rocks elsewhere in the southern Midcontinent suggest that other Proterozoic basins exist, and possibly they are an important feature of the area.

4. On the south side of the Wichita Mountains, Precambrian trends were reactivated during Pennsylvanian time.

5. Simple models for the formation of aulacogens must be treated with caution because, in the southern Oklahoma case at least, inherited Precambrian structures may have played a very important role in determining the position and trend of the aulacogen.

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