DEPOSITIONAL ENVIRONMENTS, UPPER PIERRE SHALE, DENVER BASIN, COLORADO

by

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ABSTRACT

Two marine sandstones separated by a marine shale are present in the transitional member of the upper Pierre Shale in the Denver basin. The lower sandstone, varying in thickness from 50 to 60 m, and found mainly near the outcrop on the southern flank of the Denver basin, was deposited in shoreface and foreshore environments. The more widespread upper sandstone is considered to be a delta-front deposit. Both sandstone units are marginal to delta systems which prograded seaward in Late Cretaceous (Maestrichtian) time.

INTRODUCTION

Along the eastern flank of the Colorado Front Range (Fig. 1) outcrops of the Pierre Shale, Fox Hills Sandstone, Laramie and Arapahoe formations form a narrow band extending southward to Jarre Creek Canyon (T. 7 S., R. 68 W.) where the Pierre Shale is reasonably well exposed (Scott, 1963; Nwangwu, 1974). South of this location, the Pierre Shale and the Fox Hills Sandstone are exposed poorly. At Pope's Bluff, north of Colorado Springs (T. 13 S., R. 67 W.), the Pierre Shale, Fox Hills Sandstone, Laramie and Dawson formations are well exposed and can be traced in a southeast direction for 10 km. to the Hanover quadrangle. In this southern area, marine shales and sandstone units of the transitional member of the upper Pierre Shale, and the Fox Hills Sandstone are well exposed as steplike bluffs of moderate relief which merge into vertical white cliffs. Soft-weathering, lenticular sandstones, carbonaceous shales and coal beds of the Laramie Formation overlie the Fox Hills. The Dawson Formation forms the most prominent feature of the topography.

The Fox Hills Sandstone, representing a transitional depositional phase, is a friable, buff to white, marine sandstone with some interfingered marine shales; the overlying Laramie Formation consists of nonmarine clays and sandstones. The underlying Pierre Shale is marine, dominated by dark, greenish-gray, arenaceous shales and fine-grained, argillaceous sandstones.

The purpose of this paper is to describe the sedimentology and depositional environments of the upper Pierre Shale, with particular attention to the marine sandstone units occurring just above the base of the transitional member. The upper Pierre Shale, exposed at Pope's Bluff (Fig. 1) was measured in detail, and was correlated with well logs to the north and southeast (Fig. 2). The subsurface study area is bounded on the west and south by the Fox Hills-Laramie outcrops, and includes all parts of the Denver basin eastward to R. 59 W., and northward to T. 4 S.

Kiteley (1976) has studied the Pierre Shale in southeastern Wyoming and concludes that the marine sandstones of the upper Pierre are, indeed, reservoir sandstones prospective for oil and gas exploration. This paper attempts to define the limits of similar sandstone units in the southern Denver basin, and to evaluate their economic potential.

GEOLOGIC SETTING

Precambrian rocks are exposed along the western margin of the Denver basin. Complicated faulting and folding, present mainly within the Precambrian crystalline rocks, has also caused much deformation of the sedimentary rocks. Cretaceous rocks from Boulder to just north of U.S. Highway 25 at Colorado Springs are overturned or have steep east dip, commonly in excess of 70°. This dip decreases rapidly in magnitude eastward into the Denver basin. In the Colorado Springs area, deformation is restricted quite close to the Front Range and outcrops of Cretaceous rocks, especially in the Corral Bluffs and Hanover quadrangles (eastward from R. 66 W.) have low dips of between 3° and 5° to the east.

Much of the Pierre Shale is not exposed well enough to permit detailed stratigraphic measurement and study because of the soft weathering character. However, three major subdivisions can be made on general lithologic composition. These are,

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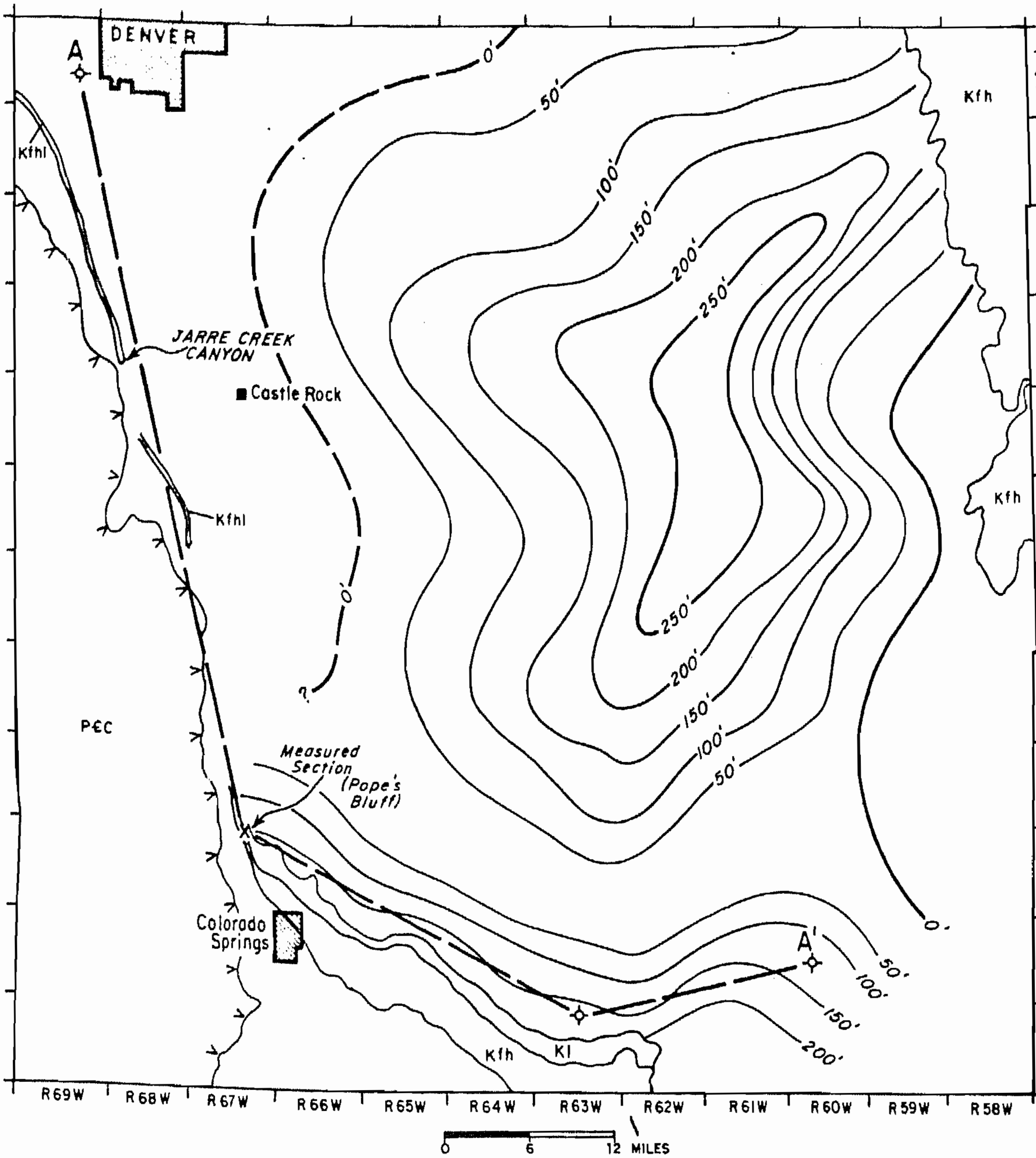

Fig. 1 — Location map of study area, including isopach of sandstone units "A" and "B" of upper Pierre Shale, Denver Basin.
Kp = Pierre Shale, Kfh = Fox Hills Sandstone, Kl = Laramie Formation.
P€C = Precambrian.
Kfhl = Outcrop of Fox Hills and Laramie Formations combined.

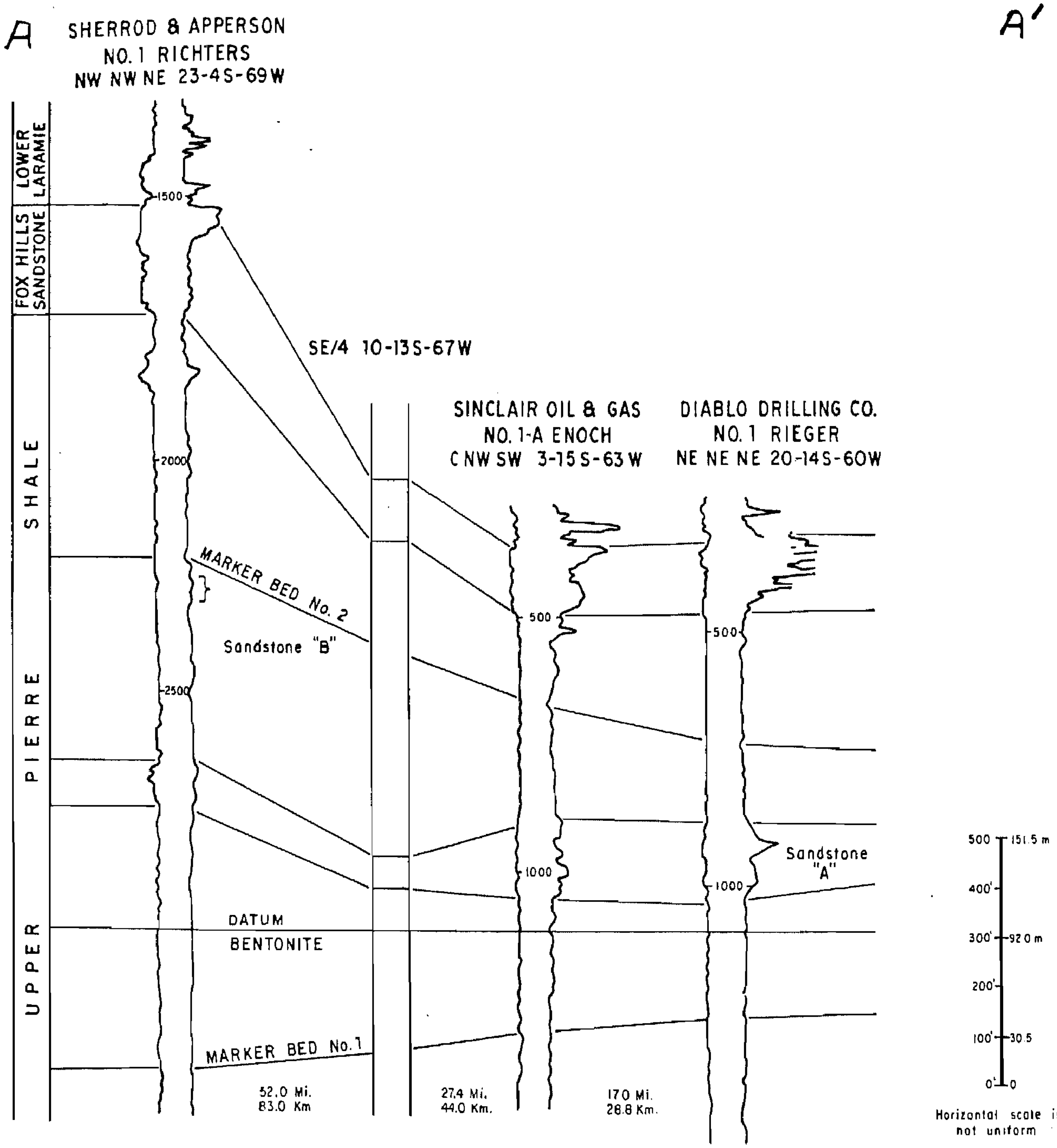

Fig. 2 — Subsurface correlation section of upper Pierre Shale and Fox Hills Sandstone, western edge of Denver basin, Colorado.

(1) the main body of the formation (mostly shale), (2) a sandstone unit occurring just above the base of the upper transition zone and (3) the main part of the upper transition zone below the Fox Hills Sandstone.

The main body of the Pierre Shale consists of shale, minor siltstone, very fine-grained sandstone, and thin concretionary limestone beds. The shale units are mostly dark to light-gray and olive-gray in color, and marine fossils are present in some beds. In general, this interval is very poorly exposed. About 370 m is exposed in the Corral Bluffs and Hanover quadrangles (El Paso County), southeast of Colorado Springs. Here, the total thickness of the Pierre Shale is about 1,500 m. Northward, the thickness is estimated at 2,400 m.

The sandstone unit above the base of the upper transition zone (sandstone "A", Fig. 3) is mostly grayish-yellow, although the lower 10 m (30 ft) is light-yellowish-gray to dark-yellowish-orange. It is medium-to-coarse-grained and mostly cross-bedded. The lower half is partly ferruginous, and thin shale interbeds and laminae are also present. The lower portion also contains *Ophiomorpha* burrows, numerous pea-sized, iron-cemented sandstone concretions, and a few flecks of carbonized plant material. Some phosphate nodules and calcite cone-in-cone structures occur locally. The unit reaches 50 to 60 m in thickness. In the Golden area, west of Denver (T. 35., R. 70 W.), the unit is not well developed.

The main part of the upper transition zone, about 130 m thick, consists of gray to yellowish-gray shales, siltstone and thin beds of very fine- to fine-grained sandstone. Thin limestone beds and numerous calcareous concretions containing an abundant ammonite fauna, particularly *Baculites clinolobatus*, are dispersed throughout the unit. Small phosphate nodules are present locally.

The Fox Hills Sandstone, between 10 and 30 m thick in the Golden area, and 30 to 70 m thick in the Colorado Springs area, has a conformable and gradational contact with the Pierre Shale. It is tan to buff, fine- to medium-grained or coarse-grained marine sandstone and contains interbedded gray shales and large sandy concretions.

The Laramie Formation, overlying the Fox Hills Sandstone, is beween 200 and 300 m thick in the north, and about 65 m thick in the south. It consists of interfingering massive sandstones, sandy shales and gray, plastic clays.

STRATIGRAPHY AND SEDIMENTOLOGY

Unit 1 of the measured section (Fig. 3) is typical of the main part of the Pierre Shale in the Denver basin. It consists of olive-gray to dark gray parallel-laminated and fissile shales, and interbedded argillaceous or calcareous cemented siltstone beds. Carbonaceous detritus is present on bedding surfaces, and calcareous concretions up to 1.2 m in diameter are common. Bioturbation is common, but only a few burrows are distinctly preserved. In the Colorado Springs area, pea-sized phosphate nodules are present. Pelecypods are abundant, as well as *Baculites* sp.

Above the shale units of the main part of the Pierre Shale, and about 180 m below the Fox Hills Sandstone, especially in the Colorado Springs area (El Paso County), are two sandstone units designated by this author as sandstones "A" and "B" (Fig. 3). Sandstone "A" is 17.5 m thick and sandstone "B" is 7.8 m thick. They are separated by 23.0 m of shale and siltstone. In well logs east of the measured section (Fig. 2), these sandstones range in thickness from a few meters to 60 m or more, especially sandstone "A." The thickness from well logs of the intervening shale unit between sandstones "A" and "B" is from one hundred to several hundred meters. The top of sandstone "B" is marked by a thin bentonite bed on electric logs (marker bed 2).

Sandstone "B" (unit 8, Fig. 3) is tan, buff or brown, medium-to-coarse-grained and pebbly. Mean grain size varies from 1.25 phi to 1.84 phi. Sandstone beds consist of 80 to 90 percent quartz, 5 to 10 percent feldspars, and less than 5 percent rock fragments. Mica, dark minerals and glauconite are present. Bed thickness is medium to massive, and bioturbation is present. Planar and tangential cross stratification (Fig. 4) are present in lower parts of the unit, and ripple stratification with alternating parallel lamination is present to the top of the unit. Thin shale lenses are very common, as well as ball-and-pillow

Fig. 4 — Cross-stratified medium-grained sandstone (Sandstone B) of upper Pierre Shale. Location is SW NW 6-15S-64W. Note the ball-and-pillow structures on which rock hammer rests.

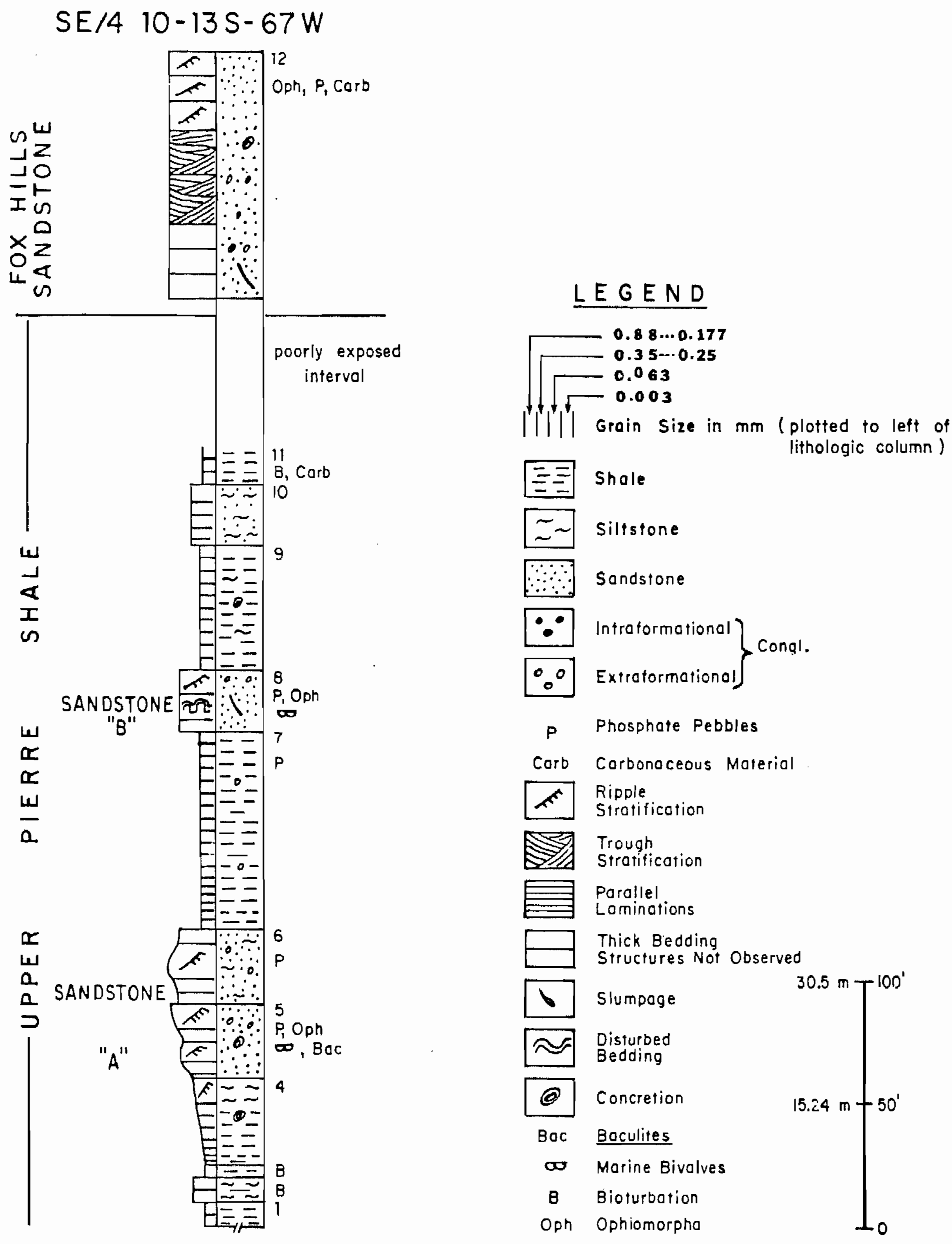

Fig. 3 — Measured section of the upper Pierre Shale at Pope's Bluff; SE/4, 10-13S-67W.

structures, local faulting, and slumpage features. Few *Ophiomorpha* are present. The top of Sandstone "B" (unit 8) is marked by a dense concentration of phosphate pebbles which also occur thinly scattered throughout the unit.

Sandstone "A" (units 5 and 6, Fig. 3) is generally fine to coarse grained and tan, buff or brown. Sorting is moderate to good as shown by standard deviation which ranges from 0.443 to 0.851 phi. Individual grains are subrounded to well rounded, and matrix content (silt plus clay) is 20 to 30 percent. The sandstones are generally friable, but may be indurated locally due to a sparry calcite cement. Replacement of glauconite and feldspars by calcite is present, followed by strong phosphatization along grain boundaries. Parallel lamination and ripple stratification are general bedding characteristics. Bed thickness and grain size increases upward. Pebbles of phosphate, mudstone, chert and limonite occur throughout the units.

Pelecypods, one species of brachiopod, gastropods and other skeletal debris are abundant. Several microfossils occur as glauconite casts. *Baculites clinolobatus* is found in several calcareous concretions. Bioturbation is present in lower parts of the units, and small *Ophiomorpha* burrows, as well as other unidentified sand-filled burrows about 2.5 cm long and 0.2 cm across also are present.

Fig. 5 — Interbedded sandstones, siltstones and shales of upper transition zone of Pierre Shale; SE/4, 24-14S-65W.

Between Sandstone "B" and the Fox Hills Sandstone is the upper transition zone of the Pierre Shale which consists of very fine- to fine-grained sandstone interbedded with an equal amount of siltstone, silty shale, and shale (Fig. 5). Several thin limestone beds are also present. The sandstones are buff and tan, and contain 70 to 80 percent quartz, and 10 to 15 percent feldspars. Glauconite and dark minerals are present, and both phosphate pebbles and phosphatic debris are abundant, particularly in the Colorado Springs area. Both sorting and rounding are good. Cement is argillaceous, or, more commonly, calcareous. Matrix in the sandstone beds is variable, ranging from 20 to 60 percent. The sandstones are generally friable, as are the siltstones and shales. Sandstone beds, 0.6 to 0.9 m thick, commonly interfinger with gray shales.

Carbonaceous materials in most places line bedding surfaces. Stratification is generally subparallel laminations, but some ripple laminated strata also are present. Symmetrical ripple marks and shale pods are present locally. It is not uncommon to see a completely bioturbated sandstone bed sandwiched between nonbioturbated beds.

Fig. 6 — *Rhizocorallium* burrows on bedding surfaces of upper transition zone; SW/4, 24-14S-65W.

The trace fossil content of these beds is very significant. Trails, and burrows of *Rhizocorallium* occur on bedding surfaces (Fig. 6). These are large U-shaped burrows, about 15 cm long and 5 cm across. *Rhizocorallium* is a deposit-feeding organism commonly associated with bioturbated zones. Small forms of *Ophiomorpha* also are present.

Calcareous concretions 1.0 to 1.2 m in diameter and smaller-sized ferruginous concretions are abundant. Calcareous concretions commonly contain several fossils, of which *Baculites* sp. is the most significant.

DEPOSITIONAL ENVIRONMENTS

The Pierre Shale is a marine formation of Late Cretaceous Campanian to Maestrichtian age (Scott, 1963). The upper part represents both prodelta and shelf environments of deposition.

The main part of the Pierre Shale is assigned to the shelf (deeper neritic) environment. The depositional energy was low, the sediments having been deposited below wave base in an environment of weak bottom currents. Thin parallel laminations and fissility are characteristic features.

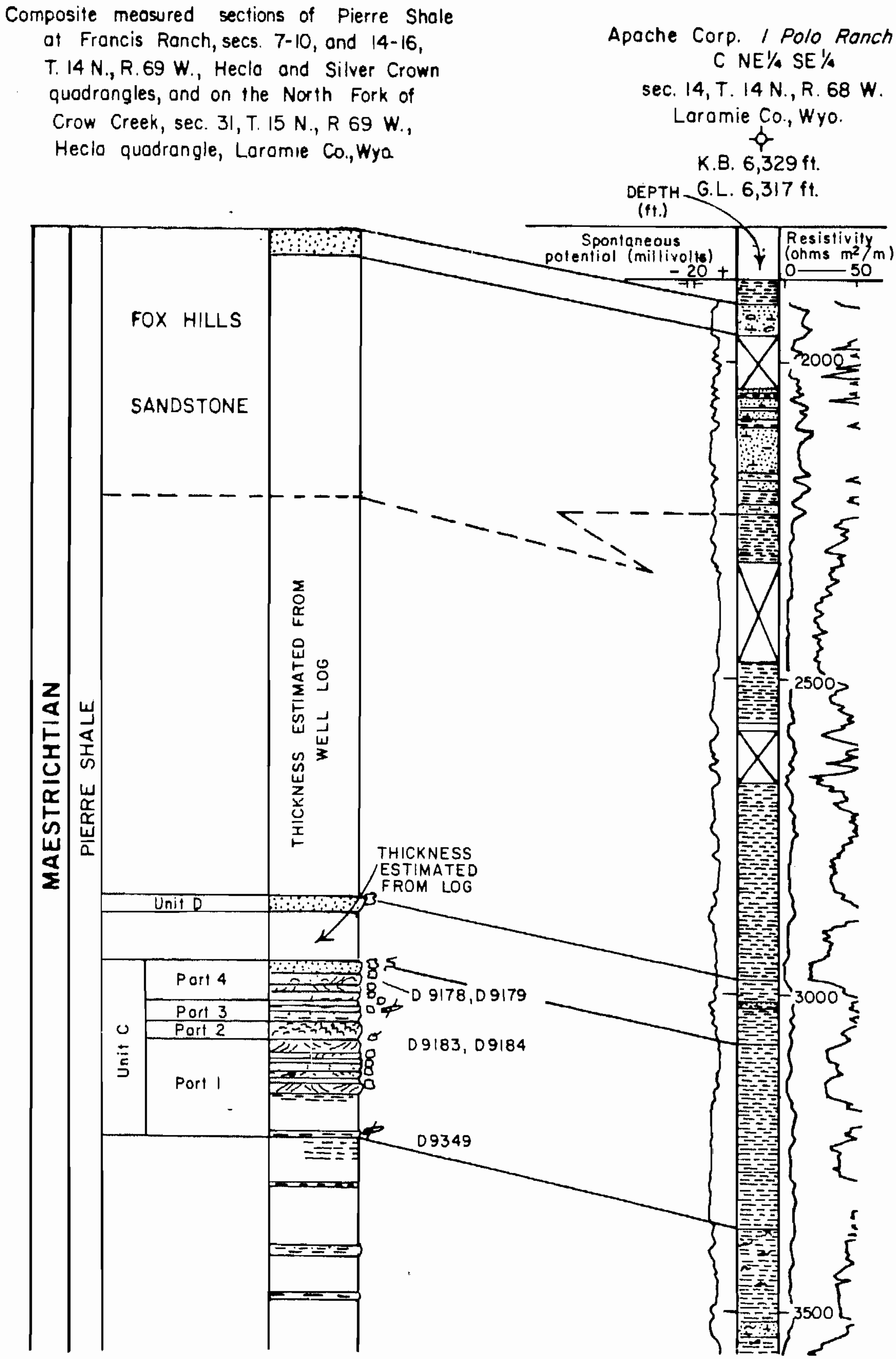

Fig. 7 — Sandstone units of the upper Pierre Shale at Francis Ranch, Wyoming (from Kiteley, 1976), correlated with well log.

Units of sandstone "B" are part of a delta-front platform deposit. The diagnostic criteria are:

1. Variability in cross stratification
2. Large occurrence of slumpage features
3. Presence of clay clasts in association with pebbles of phosphate and mudstone suggesting a lag-type deposit.

Sandstone "A" was deposited in the shoreface and foreshore environments. This interpretation is based on:

1. Lack of deformational structures
2. Gradual increase of bed thickness and grain size upward
3. Better sorting and rounding of grains
4. Decrease in bioturbation from base to top

The uppermost transition zone contains a profusion of fauna. Of these, *Baculites clinolobatus* is the most significant. Pelecypods include *Nymphalucina occidentalis* (Morton); *Cymbophora emmonsi* (Meek), a pelecypod found in marine, shallow water, sandy environments; *Pseudoptera subtortuosa* (Meek and Hayden); *Clisocolus moreauensis* (Meek and Hayden), both diagnostic marine pelecypods. A marine scaphopod, *Dentalium* sp., and a marine brachiopod, *Terebratula helena* (Whitfield), and several gastropods, were also collected from this environment, interpreted to be subshoreface. This environment represents a period of gradual but regular withdrawal of the Pierre sea from the Rocky Mountain Cretaceous basin, until the beginning of Fox Hills deposition when sands were deposited (Griffiths, 1949). The most significant criteria for the recognition of this environment include the following:

1. Bioturbation which in places is quite intense
2. Abundance of shallow marine fauna
3. Beds progressively coarser grained and thickening upward, with sandstone beds also increasing in number upward.

The overlying Fox Hills Sandstone consists of delta-front sandstones to the north, and a combination of delta-front, barrier island, and estuarine deposits in the Colorado Springs area.

REGIONAL CORRELATION AND SEDIMENT SOURCE

Figure 1 incorporates an isopach map of sandstone "A" and "B" in the lower part of the upper transition zone of the Pierre Shale in the Denver basin. Kiteley (1976) has studied similar sandstone units (Fig. 7) at Francis Ranch (Secs. 7-10, and 15-16, T. 14 N., R. 69 W., Hecla and Silver Crown quadrangles, Laramie County, Wyoming). Kiteley recognizes sandstone units A through D approximately between the subsurface interval designated by this writer as marker beds 1 and 2 (Fig. 2).

Kiteley's unit C (55.8 to 61.9 m) corresponds to this writer's sandstone A, while her unit D (6.4 m) corresponds to sandstone B. Within unit C, Kiteley describes four component parts which represent depositional environments including upper shoreface to foreshore (part I), estuarine channel or bay (part II), transitional offshore marine (part III), and upper shoreface (part IV). Unit C is therefore similar to unit A which this writer has interpreted to be shoreface and foreshore deposits. Kiteley's unit D consists of clayey and silty sandstone. This unit is fine grained with poor to fair sorting and poor porosity and is thinly laminated to very thinbedded, contains *Ophiomorpha*, and is interpreted to be upper shoreface. In the Colorado Springs area, the corresponding sandstone B is parallel with the trend of the delta-front sandstone units of the Fox Hills Sandstone from which it is separated by prodelta or subshoreface units. Because of the associated sedimentary structures which include large-scale penecontemporaneous deformational structures, this writer considers it to be a delta-front sandstone.

The isopach map (Fig. 1) which also contains siltstone units (probably parts III and IV of Kiteley's unit C), shows a slightly northeast to southwest-trending sandstone body that indicates offshore sedimentation along a trend almost normal to the northwest to southeast depositional axis of the delta-front sandstone units of the Fox Hills Sandstone, and corresponds to sediment transport directions at the time of deposition (Nwangwu, 1976).

The upper Pierre Shale is part of the large deltaic system that

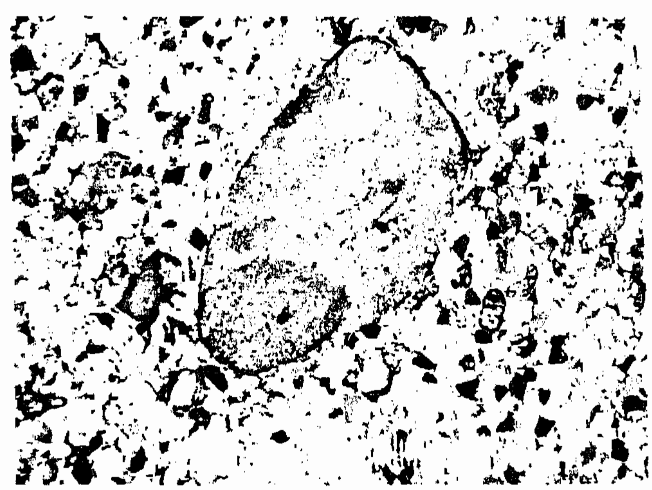

Fig. 8 — Photomicrograph of Sandstone B, upper Pierre Shale. Note abundance of matrix (silt- and clay-sized particles), and black phosphate rim around mudstone pebble, presumably a lag type deposit. Location is SE/4, 10-13S-67W, scale in mm.

formed in Late Cretaceous time. Haun and Weimer (1960), Gill and Cobban (1973), and several other authors postulate predominantly western and southwestern sources for the sediments of the delta system in this area. Much of the clastic sediment supplied to the epicontinental Pierre sea came from a narrow, north-trending Cordilleran highland to the west, in the present position of western Nevada, Utah, and southwestern Arizona. However, local sources of sediment, probably from the Colorado Front Range, are evident. In the Golden area, Fox Hills sedimentation was strongly influenced by rising land areas nearby (Weimer and Land, 1975). A similar local source is also applicable to the Colorado Springs area where quartzite, phosphate and mudstone pebbles are present as lag deposits in upper Pierre and Fox Hills sandstones. These local source areas rose as a result of uplift of crustal blocks during the early movement associated with the Laramide orogeny.

ECONOMIC POTENTIAL

Kiteley's work (1976) in southeastern Wyoming indicates that marine sandstone bodies of the upper Pierre Shale, equivalent to this writer's "A" and "B" sandstones in the Denver basin, are potential reservoirs for oil and gas. In the southern Denver basin, however, these sandstones do not appear to be highly prospective. Data from several wells penetrating this stratigraphic interval have so far failed to show any promise with regard to oil or gas occurrence. Sandstone "B" (Fig. 8), although fairly well sorted, contains too much matrix (silt and clay), either deposited contemporaneously with detrital grains, or resulting from the decomposition of feldspars. Sediments of this environment (delta-front) were deposited rapidly in a medium devoid of storm and tidal current activity, hence the absence of winnowing.

Sandstone "A" (Fig. 9) is well sorted and rounded, and does not contain much matrix. The depositional environment (shoreface-foreshore) shows the effect of storm and tidal activity during which clay-sized particles were winnowed out. However, calcite cement is commonly present as a crystalline mosaic between quartz grains. In some cases, there is a reaction between cement and framework grains, and the cement corrodes the detrital grains, forming irregular and embayed contacts. In the bottom center of the photomicrograph in Fig. 9, replacement of quartz grains (white) by calcite (dark) is so intense that very little remains of the original grain. The replacement of quartz by calcite is consistent with Waldschmidt's findings for the Rocky Mountain sandstones studied by him (Waldschmidt, 1941). The calcite probably resulted from the solution of shells of organisms and precipitation as cement. These factors, added to the fact that the sandstones and their associated shale units lack the depth of burial required for petroleum formation, are responsible for their apparent uneconomic potential as reservoirs for hydrocarbons.

Fig. 9 — Photomicrograph of Sandstone A, upper Pierre Shale. Note replacement of white quartz grain (bottom center) by calcite (dark), and absence of matrix. Scale in mm. Same location as Fig. 8.

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