SEDIMENTOLOGY AND PROVENANCE OF THE PALEOCENE-EOCENE ARKOSE RIDGE FORMATION, COOK INLET–MATANUSKA VALLEY FOREARC BASIN, SOUTHERN ALASKA

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ABSTRACT

The Paleocene–Eocene Arkose Ridge Formation consists of 1,600+ m of sedimentary and volcanic strata that were deposited along the arcward margin of the Cook Inlet–Matanuska Valley forearc basin, southern Alaska. This study reports new petrologic and sedimentologic data from the Arkose Ridge Formation that are used to interpret the provenance, depositional systems, and paleogeography of the forearc basin during the early Cenozoic. Light mineral provenance studies, conglomerate clast counts, and paleocurrent indicators suggest that detritus was derived from local source terranes exposed north of the Castle Mountain fault system. Arkose Ridge Formation sandstones are enriched in quartz and feldspar (%$Q_{23}F_{67}L_{10}$; %$Qm_{21}F_{68}Lt_{11}$) and can be divided into a lower petrofacies rich in metamorphic detritus (%$Lv_7Ls_0Lm_{93}$) and an upper petrofacies rich in volcanic detritus (%$Lv_{70}Ls_0Lm_{30}$). Initially, metamorphic-rich detritus was eroded from the plutonic roots of a remnant early Mesozoic magmatic arc, whereas during the later stages of sedimentation erosion of an active Cenozoic magmatic arc provided detritus rich in volcanic lithic fragments. Sedimentological analysis of the Arkose Ridge Formation reveals a progressive upsection change in sedimentary deposystems from gravelly, alluvial fans to sandy, braided streams to tidally influenced, sinuous streams. A relative rise in sea level during the Late Paleocene to Middle Eocene resulted in northward onlap of tidally influenced deposystems towards the basin margin and increased preservation of fine-grained sediment adjacent to the magmatic arc. Interbedded lava flows indicate relative proximity to active volcanic centers during deposition of the Arkose Ridge Formation.

INTRODUCTION

The general sedimentologic model for forearc basins predicts a gradual evolution from deep-marine, through shallow-marine, to nonmarine deposystems with progressive infilling of the basin (Ingersoll, 1979; Dickinson, 1995). Numerous past studies have examined the sedimentology and petrofacies of ancient marine depositional systems in forearc basins (for example, Ingersoll, 1979; Heller and Dickinson, 1985; Busby-Spera, 1986; Morris and Busby-Spera, 1988; Morris and others, 1989). In contrast, few sedimentological studies have been reported from ancient nonmarine deposits of forearc basins (exceptions: Kuenzi and others, 1979; Vessel and Davies, 1981; Fulford and Busby, 1993). The Cook Inlet–Matanuska Valley forearc basin in southern Alaska (fig. 1) contains thick sequences of well exposed nonmarine strata and thus provides a unique opportunity to better understand nonmarine sedimentation in forearc basins. This paper examines the Arkose Ridge Formation, a 1,600+-m-thick sequence of Paleocene–Eocene sedimentary and volcanic strata deposited along the arcward (northern) margin of the Cook Inlet–Matanuska Valley forearc basin. The main goals of this paper are to describe the sedimentology and petrofacies of the Arkose Ridge Formation in order to reconstruct the evolution of depositional systems, sediment source terranes, and paleogeography of the arcward margin of the forearc basin during the early Cenozoic. In addition to its contributions toward a better general understanding of forearc basin systems, this study may be useful to persons evaluating Cenozoic deposits in the upper Cook Inlet and lower Matanuska Valley for potential oil and gas reservoirs (Oil and Gas Journal, 1998).

GEOLOGIC SETTING

The Cook Inlet–Matanuska Valley forearc basin, a northeastern continuation of the Aleutian forearc basin, is bounded on the southeast by Mesozoic meta-sedimentary rocks of the Chugach subduction complex and on the northwest by late Mesozoic–Cenozoic igneous rocks of the Alaska Peninsula–Aleutian magmatic arc as well as early Mesozoic igneous, metamorphic, and sedimentary rocks of the Talkeetna magmatic arc (figs. 1, 2; Magoon and others, 1976; Csejtey and others, 1978; Winkler, 1992). The northeastern part of the forearc basin has been uplifted and exposed (Matanuska Valley/Talkeetna Mountains) whereas the southwestern part of the basin (Cook Inlet) is still subsiding (figs. 1, 2; Fisher and Magoon, 1978). The forearc basin strata disconformably overlie early

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Mesozoic sedimentary, igneous, and metamorphic rocks of the Talkeetna magmatic arc, an allochthonous andesitic island arc assemblage that formed at low paleolatitudes, was translated northward, and accreted to southern Alaska during the late Mesozoic and early Cenozoic (Plafker and Berg, 1994). The forearc basin fill consists of 1,000–4,000 m of Cretaceous marine strata and 3,000–7,000 m of mostly nonmarine Tertiary strata (fig. 3; Kirschner and Lyon, 1973; Winkler, 1992). Volcanic and plutonic rocks exposed along the northern margin of the basin record late Mesozoic–Cenozoic arc magmatism in response to northward- to northwestward-directed subduction of the Farallon, Kula, and Pacific oceanic plates (Engebretson and others, 1983; Plafker and Berg, 1994). The Border Ranges fault system, a Mesozoic thrust fault (MacKevett and Plafker, 1974) with localized Cenozoic dextral displacement (Pavlis and Crouse, 1989), separates the forearc basin from the Chugach subduction complex (figs. 1, 2; Plafker and others, 1977). Along the arcward margin of the forearc basin are northeast-trending high-angle reverse faults, including the Castle Mountain fault, which experienced Eocene–Oligocene dextral strike-slip displacement and Neogene dip-slip displacement (figs. 1, 2; Grantz, 1966; Fuchs, 1980; Little, 1990).

The Paleocene–Eocene Arkose Ridge Formation, the focus of this study, has a maximum preserved thickness of 1,600+ m and consists mostly of conglomerate and sandstone with subordinate mudstone, coal, tuff, and lava flows (Martin and Katz, 1912; Silberman and Grantz, 1984). Exposed in a narrow, discontinuous outcrop belt 100 km long and 5–10 km wide, outcrops of the Arkose Ridge Formation are confined to the north side of the east–west trending Castle Mountain fault system in the Talkeetna Mountains (fig. 2; Winkler, 1992). The base of the Arkose Ridge Formation unconformably overlies pre-Cretaceous igneous and metamorphic rocks of the allochthonous Wrangellia

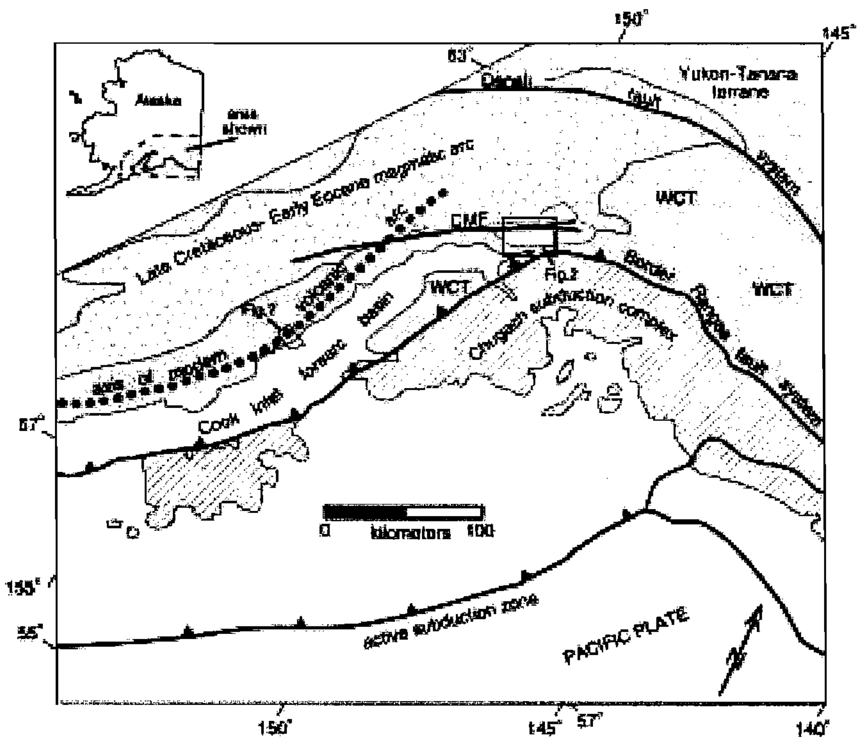

Figure 1. *Generalized map showing major tectonic elements of the southern margin of Alaska. Cook Inlet represents part of an actively subsiding forearc basin located between the modern Aleutian magmatic arc to the north (dotted black line) and the Chugach subduction complex to the south (hatched pattern). Uplifted ancient sedimentary deposits of the forearc basin (open-circled pattern) are exposed in the vicinity of the Castle Mountain fault (CMF). Note that the ancient forearc basin deposits unconformably overlie the allochthonous Wrangellia composite terrane (WCT) and the Late Cretaceous–Eocene magmatic arc. Map adapted from Little (1988). Area of detailed geologic map shown in figure 2 is outlined by rectangle along the eastern part of the Castle Mountain fault.*

composite terrane. Cretaceous forearc basin deposits were either never deposited locally or were uplifted and eroded during the latest Cretaceous and/or Early Paleocene. The Arkose Ridge Formation is overlain by Eocene volcanic rocks and/or Quaternary surficial deposits in the eastern Talkeetna Mountains, and Miocene and younger sedimentary rocks in upper Cook Inlet (Winkler, 1992). In the western Talkeetna Mountains the top of the formation has been eroded and is not exposed (Winkler, 1992). Paleontologic studies of megafossil floras (Martin and Katz, 1912; J. Wolfe *in* Silberman and Grantz, 1984) and K-Ar radiometric dating of interbedded volcanic rocks (Silberman and Grantz, 1984) define the age of the formation as Late

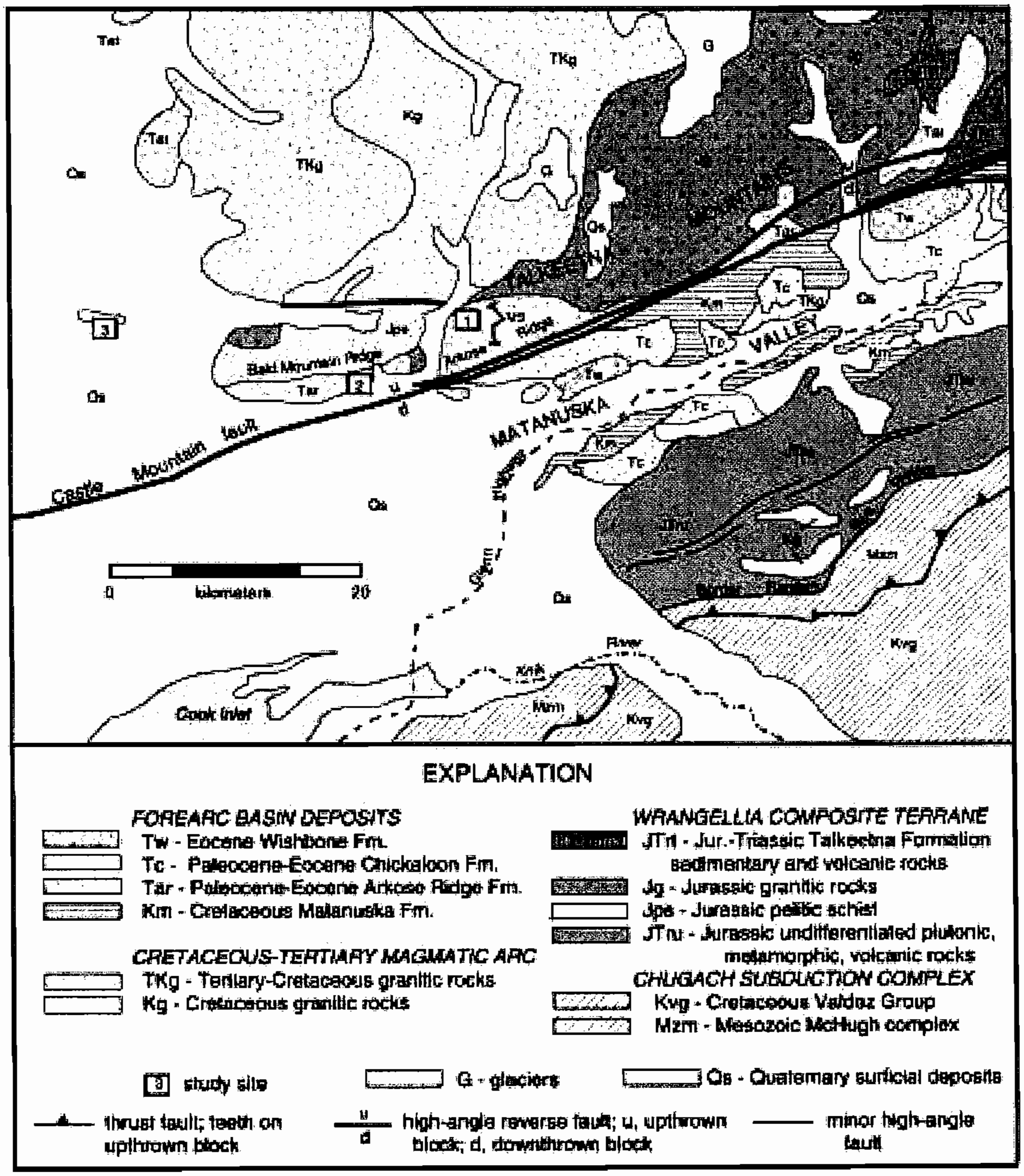

Figure 2. *Generalized geologic map of the Matanuska Valley and western Talkeetna Mountains in the western Anchorage 1x3 degree quadrangle. MS = measured stratigraphic section shown on figure 4. See figure 1 for map location. Geology is from Csejtey and others (1978), Winkler (1992), and this study.*

Paleocene to Middle Eocene (fig. 3; Winkler, 1992). Age-equivalent finer-grained sedimentary strata and volcanic ash of the Chickaloon Formation are exposed between the Castle Mountain and Border Ranges faults in the Matanuska Valley and northern Chugach Mountains (fig. 2). The Chickaloon Formation consists of ~1,500 m of Paleocene–Eocene fluvial–lacustrine mudstone, sandstone, coal, and minor conglomerate (fig. 3; Barnes, 1962; Little, 1988).

PROVENANCE

Compositional data from the Arkose Ridge Formation afford an opportunity to study the petrofacies of forearc basin strata deposited adjacent to an active magmatic arc. The "magmatic arc" provenance field of global sandstone provenance schemes is derived primarily from marine strata deposited in arc-related sedimentary basins (Dickinson, 1988; Marsaglia and

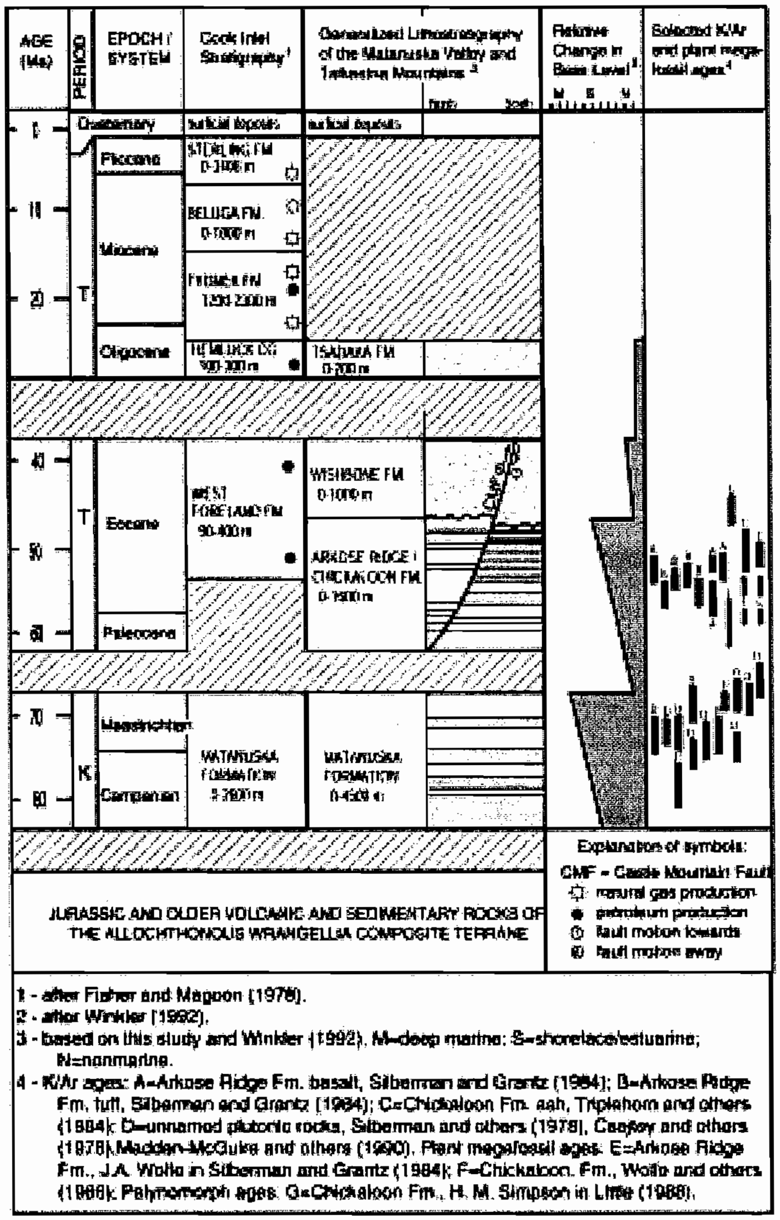

Figure 3. *Age-event diagram showing stratigraphy of Cook Inlet and Matanuska Valley/Talkeetna Mountains, inferred relative base level changes, and published geochronologic and paleontologic data.*

Ingersoll, 1992). Notably underrepresented in the global schemes are data from nonmarine strata deposited proximal to the magmatic arc. We also use our compositional data to better define the Paleocene–Eocene paleogeography of the Cook Inlet–Matanuska Valley forearc region by identifying which source terranes were exposed during deposition of the Arkose Ridge Formation.

METHODS

Our analysis of the Arkose Ridge Formation is from three study sites located in the western Talkeetna Mountains (see fig. 2 for locations). The most laterally and vertically extensive outcrop exposures were observed along the northern flank of Arkose Ridge (fig. 2). A new 1,600+-m-thick measured stratigraphic section from that location forms the basis for most of the compositional and sedimentological data presented in this paper (fig. 4). We recognize three major lithologic successions within the Arkose Ridge Formation based on distinct upsection changes in lithofacies assemblages, sedimentary structures, bed geometries, and bed thicknesses (fig. 4). The sedimentology and depositional systems of each succession is discussed in a section below.

Thirteen sandstone samples were collected over the entire measured section at Arkose Ridge, including each of the three lithologic successions (see fig. 4 for sample distribution). Medium to coarse-grained sandstones were cut into standard petrographic thin sections, stained for potassium and plagioclase feldspar identification, and point-counted using an automated stage. Separate tabulations of grain parameters were kept using both the Gazzi-Dickinson and "traditional" methods (Ingersoll and others, 1984). Recalculated data are presented in table 1 and figure 5 in terms of the Gazzi-Dickinson method so that they can be compared with previous provenance studies such as Dickinson (1988). Two clast counts from conglomerates in the lowermost part of the section at Arkose Ridge were also obtained (fig. 4).

PETROLOGY

Arkose Ridge Formation sandstones are moderately to poorly sorted, contain little matrix, and have angular to subrounded framework grains. Sandstones have average framework grain modes of $Q_{23}F_{67}L_{10}$ and $Qm_{21}F_{68}Lt_{11}$ and average framework mineral modes of $Qm_{23}P_{76}K_1$ (table 1). Sandstones classify as feldspathic arenites and arkoses that plot mainly within the "continental block–basement uplift" provenance field (QmFLt and QFL plots on fig. 5). Lithic grain populations consist of igneous and metamorphic varieties ($Lv_{21}Ls_0Lm_{79}$). Lathwork grains composed of plagioclase phenocrysts in a dark glassy matrix (fig. 6A) dominate the volcanic lithic population. Foliated phyllosilicate lithic fragments are the dominant metamorphic grain types. There is a pronounced upsection increase in volcanic lithic fragments relative to metamorphic lithic fragments. (fig. 5; successions 1, 2 = $\%Lv_7Ls_0Lm_{93}$; succession 3 = $\%Lv_{70}Ls_0Lm_{30}$). Plutonic rock fragments are common in all Arkose Ridge Formation sandstones and consist predominantly of coarse-grained granitic fragments comprising plagioclase feldspar, monocrystalline quartz, biotite, and muscovite (fig. 6B). Individual plutonic rock fragments comprise several mineral grains greater than 0.0625 mm. Therefore, our point-count tabulations using the Gazzi-Dickinson methodology reflect the individual framework minerals within the rock fragments. For this reason, the lithic populations on table 1 and figure 5 do not include plutonic rock fragments (Ingersoll and others 1984). Granitic clast types with minor amounts of amphibolite, quartz, and siliceous tuff dominate conglomerates from the lower part of the Arkose Ridge Formation (fig. 4).

INTERPRETATION OF COMPOSITIONAL DATA

On the basis of modal composition and paleocurrent data we interpret the Arkose Ridge Formation as being derived from local igneous and metamorphic source terranes exposed north of the Castle Mountain fault (Jg, Jps, Kg, TKg on fig. 2; Csejtey and others, 1978; Winkler, 1992). This interpretation is in agreement with the results of a sandstone petrography study of the Arkose Ridge Formation by Winkler (1978). Igneous clast types constitute more than 80 percent of the conglomerate composition (fig. 4) and are petrographically similar to early Mesozoic plutons exposed immediately north of the studied outcrops (Jg on fig. 2). Diagnostic clast types include quartz–biotite granite, hornblende quartz diorite, hornblende–biotite granodiorite, amphibolite, and foliated quartz diorite. The early Mesozoic granitic rocks likely contributed a large part of the quartz, feldspar, and mica framework grains that are abundant in Arkose Ridge Formation sandstones. On the basis of petrographic characteristics, mica schist fragments containing biotite, muscovite, and chlorite were most likely derived from pelitic schist presently exposed on and around Bald Mountain Ridge (fig. 2). Volcanic lithic fragments common in the upper part of the section are interpreted as being derived from Paleocene–Eocene volcanic rocks, mainly mafic lava flows, along the northern margin of the basin. Paleocene–Eocene extrusive volcanic rocks are exposed throughout the eastern Talkeetna Mountains (Csejtey and others, 1978; Winkler, 1992) but only the plutonic roots of the arc are exposed in the western Talkeetna Mountains (TKg on fig. 2). Volcanic lithic fragments were eroded, mixed with epiclastic nonvolcanic detritus,

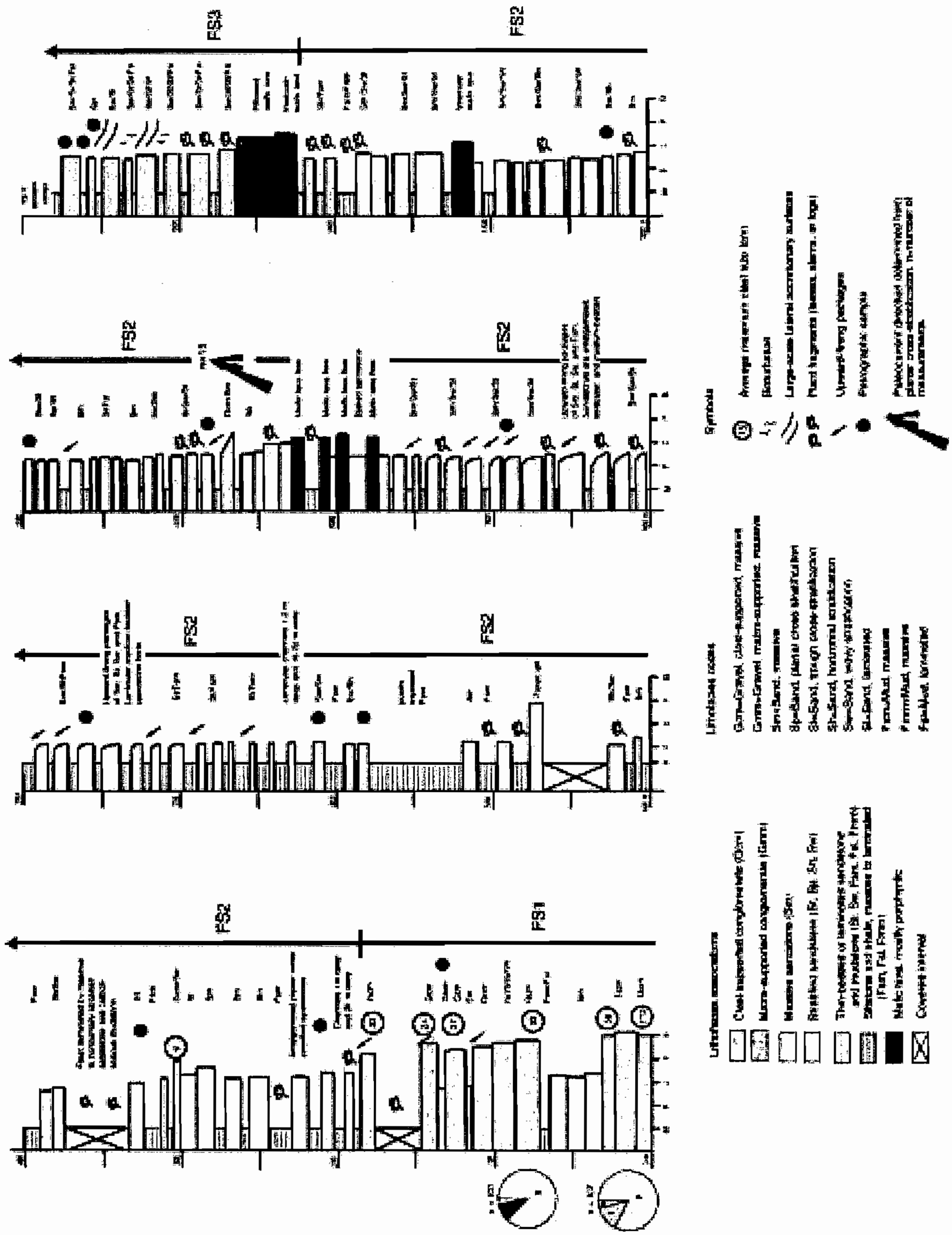

Figure 4 (left). *Detailed measured stratigraphic section of the Arkose Ridge Formation using the lithofacies schemes of Miall (1978). See figure 2 for location of measured section. Stratigraphic range of major lithofacies successions shown by black vertical bars: FS1 = succession 1; FS2 = succession 2; FS3 = succession 3. Grain sizes on horizontal scale: M = mud; F = fine-grained sand; C = coarse-grained sand; P = pebble; B = boulder. Rose diagram at 1,060 m represents paleocurrent data collected from planar cross-stratification in succession 2. Solid circles represent sandstone samples collected for modal analysis. Pie diagrams in succession 1 (0 m and 82 m) represent conglomerate clast compositions. Clast compositional data was obtained by counting all pebble-, cobble-, and boulder-sized clasts within a delineated rectangle on an outcrop face. Note the relative abundance of plutonic clasts (P). Other clast types include tuff (T), quartz (Q), minor metamorphic and sedimentary varieties (O). N = number of clasts counted.*

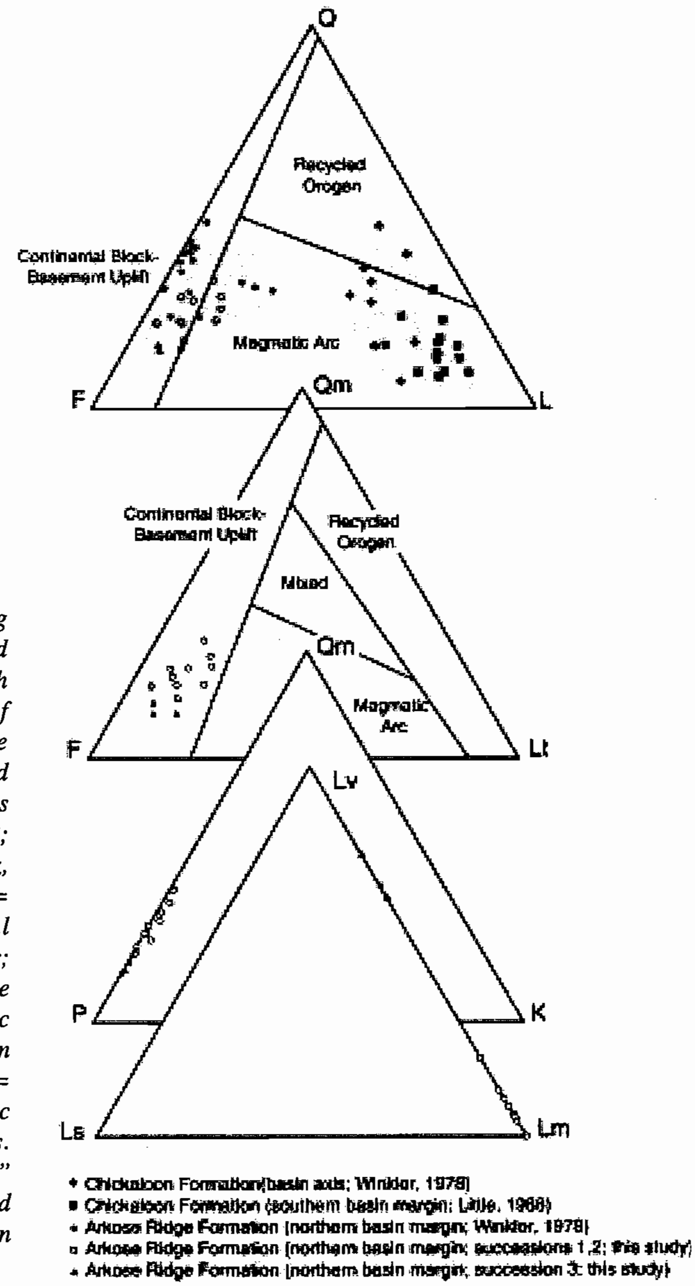

Figure 5 (right). *Ternary diagrams showing modal compositions of Arkose Ridge and Chickaloon Formation sandstones. Each symbol represents one modal analysis of 400 or more framework grains using the Gazzi-Dickinson point-count method (Ingersoll and others, 1984) as part of this study or previous studies (Winkler, 1978; Little, 1988). Q = monocrystalline quartz, chert, and polycrystalline quartz; Qm = monocrystalline quartz; Qt = total quartzose grains; P = plagioclase feldspar; K = potassium feldspar; F = plagioclase and potassium feldspar; Lt = total lithic grains; Lv = volcanic lithic fragments; Lm = metamorphic lithic fragments; Ls = sedimentary lithic fragments; L = lithic grains except quartzose lithic types. "Recycled orogen," "magmatic arc," "continental block-basement uplift," and "mixed" provenance fields from Dickinson and others (1983).*

Table 1. *Recalculated point-count data from the Arkose Ridge Formation*

Stratigraphic position (m)	Facies succession	Q	F	L	Qm	F	Lt	Qm	P	K	Lv	Ls	Lm
LONE1-132	1	28.17	62.91	8.92	24.22	64.27	11.51	27.37	70.73	1.90	8.11	0.00	91.89
LONE1-208	2	22.25	68.50	9.25	19.70	69.19	11.11	22.16	75.57	2.27	5.41	0.00	94.59
LONE1-326	2	26.06	57.75	16.20	24.76	58.57	16.67	29.71	69.14	1.14	5.80	0.00	94.20
LONE1-577	2	33.57	55.48	10.95	31.71	56.83	11.46	35.81	63.36	0.83	0.00	0.00	100.00
LONE1-612	2	29.02	65.12	5.85	24.04	68.29	7.67	26.04	73.96	0.00	4.17	0.00	95.83
LONE1-766	2	22.98	60.39	16.63	19.85	62.85	17.30	24.00	75.69	0.31	0.00	0.00	100.00
LONE1-892	2	22.72	68.64	8.64	21.89	69.15	8.96	24.04	75.96	0.00	0.00	0.00	100.00
LONE1-1071	2	17.63	70.30	12.06	16.12	70.79	13.08	18.55	80.91	0.54	21.15	0.00	78.85
LONE1-1197	2	22.25	74.08	3.67	19.35	75.29	5.36	20.44	79.56	0.00	12.50	0.00	87.50
LONE1-1225	2	29.10	56.22	14.68	27.48	57.51	15.01	32.34	65.87	1.80	10.17	0.00	89.8
Average (successions 1, 2)		25.38	63.94	10.69	22.91	65.27	11.81	26.05	73.08	0.88	6.73	0.00	93.2
LONE1-1570	3	15.85	71.95	12.20	12.13	73.02	14.85	14.24	85.47	0.29	76.00	0.00	24.00
LONE1-1572	3	16.59	76.59	6.83	14.95	76.96	8.09	16.27	83.47	0.27	67.86	0.00	32.14
LONE1-1575	3	15.26	76.99	7.74	12.06	78.42	9.51	13.33	86.67	0.00	64.71	0.00	35.29
Average (succession 3)		15.90	75.18	8.92	13.05	76.13	10.82	14.61	85.20	0.19	69.52	0.00	30.48
Average (all data)		**23.19**	**66.53**	**10.28**	**20.64**	**67.78**	**11.58**	**23.41**	**75.87**	**0.72**	**21.22**	**0.00**	**78.78**
Standard deviation (all data)		5.80	7.52	3.97	5.87	7.31	3.66	6.87	7.29	0.81	28.24	0.00	28.24

Grain parameters: Q=quartzose grains (monocrystalline quartz, chert, and polycrystalline quartz); F=feldspar grains (plagioclase and K-spar); L=lithic grains (sedimentary, volcanic, and metamorphic lithic grains); Qm=monocrystalline quartz; Lt=total lithic grains (chert; polycrystalline quartz; and sedimentary, volcanic, metamorphic lithic grains); Qp=polycrystalline quartz; P=plagioclase feldspar; K=potassium feldspar; Lv=volcanic lithic grains; Lm=metamorphic lithic grains; Ls=sedimentary lithic grains.

and transported southward. The mixing of Cenozoic volcanic detritus with Mesozoic granitic and metamorphic detritus produced a more feldspathic and volcanic lithic-rich petrofacies than found in sandstones from the lower part of the section (fig. 5). Sediment derivation from northern source terranes is consistent with southwestward-directed paleocurrent indicators (1,060 m on fig. 4) and regional textural data that record a southwestward reduction in grain size of Paleocene–Eocene strata from the Talkeetna Mountains to the upper Cook Inlet (Barnes, 1962; Kirschner and Lyon, 1973; Little, 1988; Winkler, 1992; J.M. Trop, unpublished data).

Available compositional data from Paleocene–Eocene forearc basin strata document substantial spatial variation in sandstone petrofacies. Compared to age-equivalent sandstones deposited along the southern margin of the forearc basin, sandstone petrofacies from the Arkose Ridge Formation are more quartzofeldspathic (QFL plot on fig. 5; Winkler, 1978). Sandstones deposited along the southern basin margin are interpreted to have been derived largely from the Chugach subduction complex on the basis of paleocurrent, lithologic, and compositional data (Little, 1988). Uplift and erosion of the subduction complex provided abundant sedimentary and metasedimentary lithic fragments and a paucity of feldspathic framework grains. In contrast, sediment deposited along the northern basin margin received abundant feldspathic detritus from the inactive Mesozoic and active Cenozoic magmatic arcs.

SEDIMENTOLOGY

The Arkose Ridge Formation has been mapped and described, but no detailed sedimentological data have been previously reported. On the basis of the general lithologies and absence of marine megafossils, previous workers interpret the strata as being deposited in nonmarine environments (Winkler, 1992). Measured stratigraphic sections, lithofacies analysis, maximum particle size data, and paleocurrent analysis from our study document three lithofacies successions that better define the depositional systems of the Arkose Ridge Formation. Each succession is described and interpreted below.

DESCRIPTION OF SUCCESSION 1

The lowermost 200 m of the Arkose Ridge Formation is characterized by clast-supported cobble and boulder conglomerate containing poorly sorted, subrounded to rounded clasts (figs. 4, 6C). Average maximum clast sizes range from 6 to 113 cm and progressively decrease upsection (fig. 4). Clasts as large as 360 cm are present locally. Lithofacies assemblages are dominated by amalgamated, massive to crudely bedded conglomerate packages that are 5–15 m thick and laterally continuous at the outcrop scale (10–50 m). Some conglomerate packages fine upwards into 2–5 m thick units of sandstone or, more rarely, mudstone. Sandstones are medium to thick bedded, are laterally persistent, and commonly exhibit medium-scale, planar cross-stratification. Mudstones, which constitute less than 20 percent of succession 1, are generally massive, carbonaceous, and rich in plant debris. Matrix-rich conglomerates, although rare, are also present in succession 1. The matrix-rich conglomerates are laterally continuous and 10–50 cm thick. Clasts in these conglomerates are more poorly sorted and more angular than clasts in the clast-supported conglomerates.

INTERPRETATION OF SUCCESSION 1

The coarse grain size, sedimentary structures, and upward-fining trends of succession 1 indicate that streamflow processes were important during deposition. In particular, lithofacies of this succession are characterized by textures and structures typical of deposits on modern proglacial outwash fans (Boothroyd and Ashley, 1975) and gravelly braided streams (Rust, 1977). We interpret succession 1 to represent deposition on gravelly bedload streams on an alluvial fan and/or alluvial braidplain. Organized conglomerate beds at the base of each fluvial sequence were likely deposited by downstream migration of longitudinal and transverse gravel bars (Nemec and Steel, 1984). Overlying sandstones are interpreted as being deposited in shallow channels and on emergent bars. Thin mudstone sequences record abandonment of gravelly streams and deposition in adjacent floodplain and paludal swamp environments. Rare matrix-rich conglomerates most likely represent debris flows based on the poor sorting, abundant matrix, and absence of internal organization and stratification (Johnson, 1965; Middleton and Hampton, 1976).

DESCRIPTION OF SUCCESSION 2

Overlying the coarse conglomeratic strata of succession 1 is a thick sequence of medium-bedded amalgamated sandstones with interbedded mudstone. Individual sandstone bodies are 0.6–2.0 m thick, lenticular over 10–20 m, and comprised of fine- to medium-grained sandstone (fig. 4). Although individual sandstone beds are lenticular, beds are highly amalgamated forming broad sandstone sheets (figs. 6D, E). Medium-scale planar, trough, and horizontal cross-stratification are common in the sandstones (fig. 6E). Basal scours have relief of ~0.25–0.80 m and commonly include fossilized tree branches and leaves. Succession 2 is characterized by 2–20 m thick upward-fining sequences (fig. 4). Typical sequences consist of

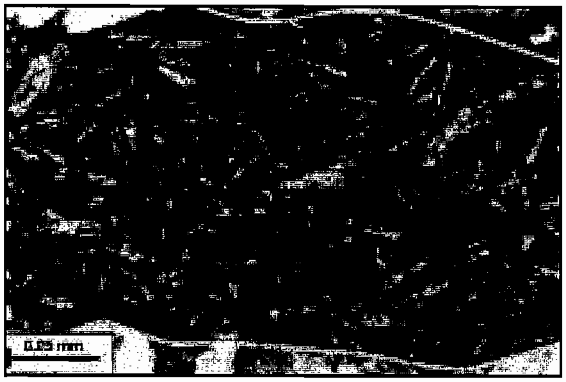

Figure 6A. *Photomicrograph of lathwork volcanic lithic fragment common in the upper part of the Arkose Ridge Formation. Grain boundary is outlined by white line.*

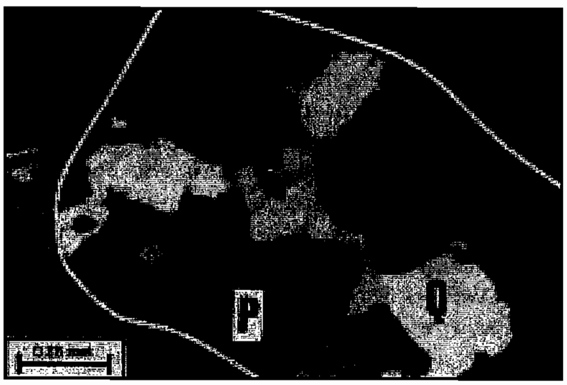

Figure 6B. *Photomicrograph of granitic rock fragment representative of igneous rock fragments throughout the Arkose Ridge Formation. Grain comprises plagioclase feldspar (P) and monocrystalline quartz (Q). Grain boundary is outlined by white line.*

Figure 6C. *Steeply dipping, boulder and cobble conglomerate deposits of succession 1. White line defines bedding. Note person for scale (arrow, upper right center).*

Figure 6D. *Sandstone and lava of succession 2. Exposure includes 20-m-thick lava unit that is outlined by arrows and is darker in color than the sandstone beds. Sandstones consist of highly amalgamated, broad, shallow channels. Exposure is approximately 250 m thick.*

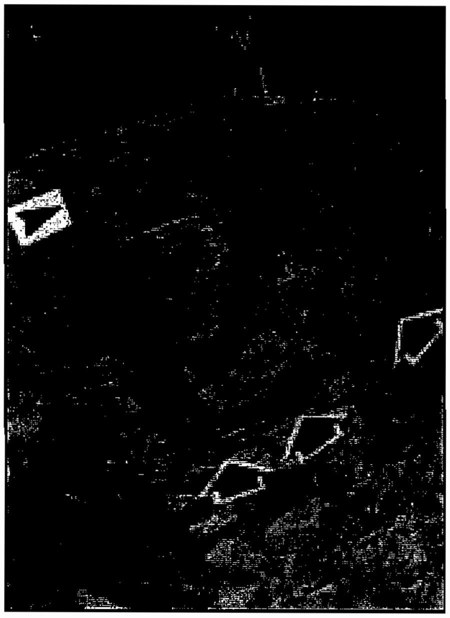

Figure 6E. *Amalgamated sandstone channels typical of succession 2. Large black arrows outline the erosional base of one channel. Top of channel is dominated by trough cross-stratification (arrowhead). Bedding dips to left. Person (upper center) for scale.*

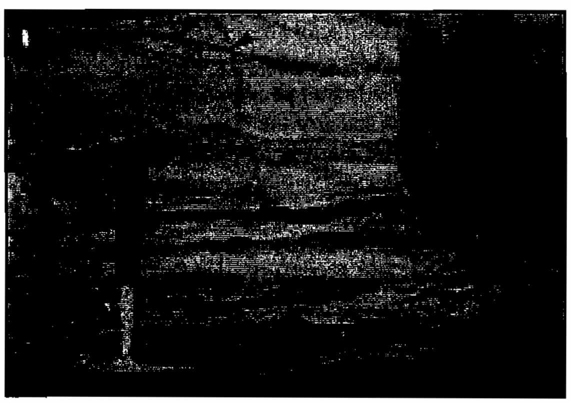

Figure 6F. *Ripple-laminated sandstone with clay drapes. Black arrows point toward a clay drape preserved on a ripple slip face. Note laminated sandstone and mudstone near hammer. Hammer (28 cm) for scale.*

massive to planar cross-stratified sandstones that grade upward into ripple-laminated, fine-grained sandstones which are capped by structureless to laminated mudstones with abundant plant fossil leaves. Mudstone beds are 0.2–10 m thick, structureless to laminated, and laterally persistent at the outcrop scale (10–50 m). Thin interbeds of carbonaceous shale and coal are also present.

Volcanic strata occur in the upper part of succession 2 and consist mostly of mafic lava flows (fig. 4). At Arkose Ridge, lava flows are 5–20 m thick, laterally continuous for 100–300 m, and interbedded with cross-stratified sandstone and mudstone (figs. 4, 6D). Although lava flows are common, pyroclastic volcanic rocks were not recognized at any of the three study sites.

INTERPRETATION OF SUCCESSION 2

Succession 2 is interpreted as being formed by streamflow and volcanic processes on an alluvial fan or braidplain. Evidence for fluvial deposition includes the presence of planar and trough cross-stratification, upward-fining packages, and lenticular bed geometries. The amalgamated sheetlike architecture of channel sandstones and the scale of individual sedimentary structures (25–50 cm high planar foresets) suggest that deposition occurred by migration of transverse and longitudinal sandbars in low-sinuosity braided streams generally less than 150 cm deep (Harms and others, 1982). The amalgamation of sandstone units is attributed to frequent switching of streams across an unconfined depositional surface whereas upward-fining cycles likely resulted from eventual abandonment of channels. Most mudstones were probably deposited by suspension fallout of fine-grained material during major flood events. The thickness and lateral continuity of interbedded volcanic rocks suggest that lava deposition occurred in both channel and interchannel regions of the alluvial fan or braidplain.

DESCRIPTION OF SUCCESSION 3

Succession 3 consists of channelized thin- to medium-bedded sandstone, laminated sandstone and shale, and massive carbonaceous shale. Large-scale, inclined heterolithic strata consisting of laminated siltstone and thin-bedded sandstone are preserved in succession 3. Clay-draped trough and ripple cross-stratification (fig. 6F), flaser bedding, wavy bedding, climbing ripples, and bioturbation are characteristic of succession 3. Plant megafossils are very abundant and exquisitely preserved, particularly in carbonaceous mudstones.

INTERPRETATION OF SUCCESSION 3

The intricate mixture of channelized sandstone and mudstone, in addition to the type, scale, and arrangement of sedimentary structures in succession 3 indicates deposition in a tidally influenced fluvial system (Clifton, 1982; Eisma, 1998), such as the upper reaches of an estuary. Sandstone deposition likely occurred by migration of tidal-fluvial point bars in upper estuary channels, whereas laterally continuous carbonaceous mudstones were deposited in nearby tidal-fluvial marshes and tidal flats. Flaser to wavy bedding and clay-draped sand ripples common throughout succession 3 suggest repeated fluctuations in current velocity, a depositional feature characteristic of tidal regimes (Eisma, 1998). Waxing and waning of current velocity and stand still of currents during high tide produce clay-draped ripples (Reineck and Singh, 1973). Inclined heterolithic strata are characteristic of deposits formed by sandy point bars in micro- to mesotidally influenced reaches of rivers (Smith, 1985; Thomas and others, 1987). Flow reversal indicators, such as herringbone cross-stratification, were not observed in the Arkose Ridge Formation. Almost all tidally influenced rivers, however, are ebb dominant (Barwis, 1978) and numerous workers have demonstrated that the preservation potential of flow reversal indicators in the more upstream reaches of tidally influenced rivers is low (for example, Dorjes and Howard, 1975). The relative abundance of preserved delicate plant-leaf fossils is probably a function of proximity to nearby vegetated terrestrial environments and high sedimentation rates in estuarine environments (Eisma, 1998).

PALEOGEOGRAPHY AND DEPOSITIONAL MODEL

New sedimentological and petrological data indicate that the Paleocene–Eocene Arkose Ridge Formation was deposited proximal to active volcanoes and uplifted plutonic segments of a Mesozoic magmatic arc along the northern margin of the Cook Inlet–Matanuska Valley forearc basin. Lithofacies, paleocurrent, and compositional data indicate that alluvial fan, fluvial, and estuarine depositional systems dispersed sediment southwestward, along the trend of the Paleocene–Eocene magmatic arc (fig. 7a). Three major lithofacies successions in the Arkose Ridge Formation record a transgressive sequence from gravel-rich alluvial fan and fluvial systems below to sandy, braided streams and tidally influenced, sinuous streams above (fig. 7a). The upsection change in depositional environments is attributed to a progressive relative rise in sea level during the Late Paleocene to Middle Eocene. Rising sea level prompted northward (arcward) onlap of finer-grained, tidally influenced deposystems across coarser-grained alluvial fan deposits and lava flows. The transgressive event recorded by the lithofacies of the Arkose Ridge Formation is coeval with global eustatic sea-level curves that illustrate first-order transgression during the Late Paleocene (60–55 Ma) and sea-level highstand during the Early Eocene (55–50 Ma; Haq and others, 1988). Additional extrinsic factors may have contributed to the relative rise in sea-level including variations in tectonic subsidence and sediment supply. A modern analog for our depositional model of the Arkose Ridge Formation is upper Cook Inlet (fig. 7b). Recent lava flows along the Aleutian arc are located within tens of kilometers of their eruptive centers and merge basinward with braided streams, tidally influenced streams, and tidal flats along the Cook Inlet estuary (Kienle and Nye, 1990; Magoon and others, 1976; fig. 7b).

CONCLUSIONS

Sandstone and conglomerate compositional data combined with southwestward-directed paleocurrent indicators suggest that detritus was derived mainly from local source terranes exposed directly north of the Castle Mountain fault system during deposition of the Paleocene–Eocene Arkose Ridge Formation. Compositional data reveal a lower petrofacies rich in metamorphic and granitic detritus and an upper petrofacies with higher proportions of volcanic detritus. Initially, metamorphic-rich detritus was eroded from the plutonic roots of an inactive Mesozoic magmatic arc, whereas erosion along an active Cenozoic magmatic arc provided detritus rich in volcanic lithic fragments during the later stages of sedimentation.

New sedimentological data demonstrate that alluvial fan, fluvial, and estuarine depositional systems deposited the Paleocene–Eocene Arkose Ridge Formation along the arcward margin of the Cook Inlet–Matanuska Valley forearc basin. Progressive upsection changes in sedimentary lithofacies reveal a transgressive

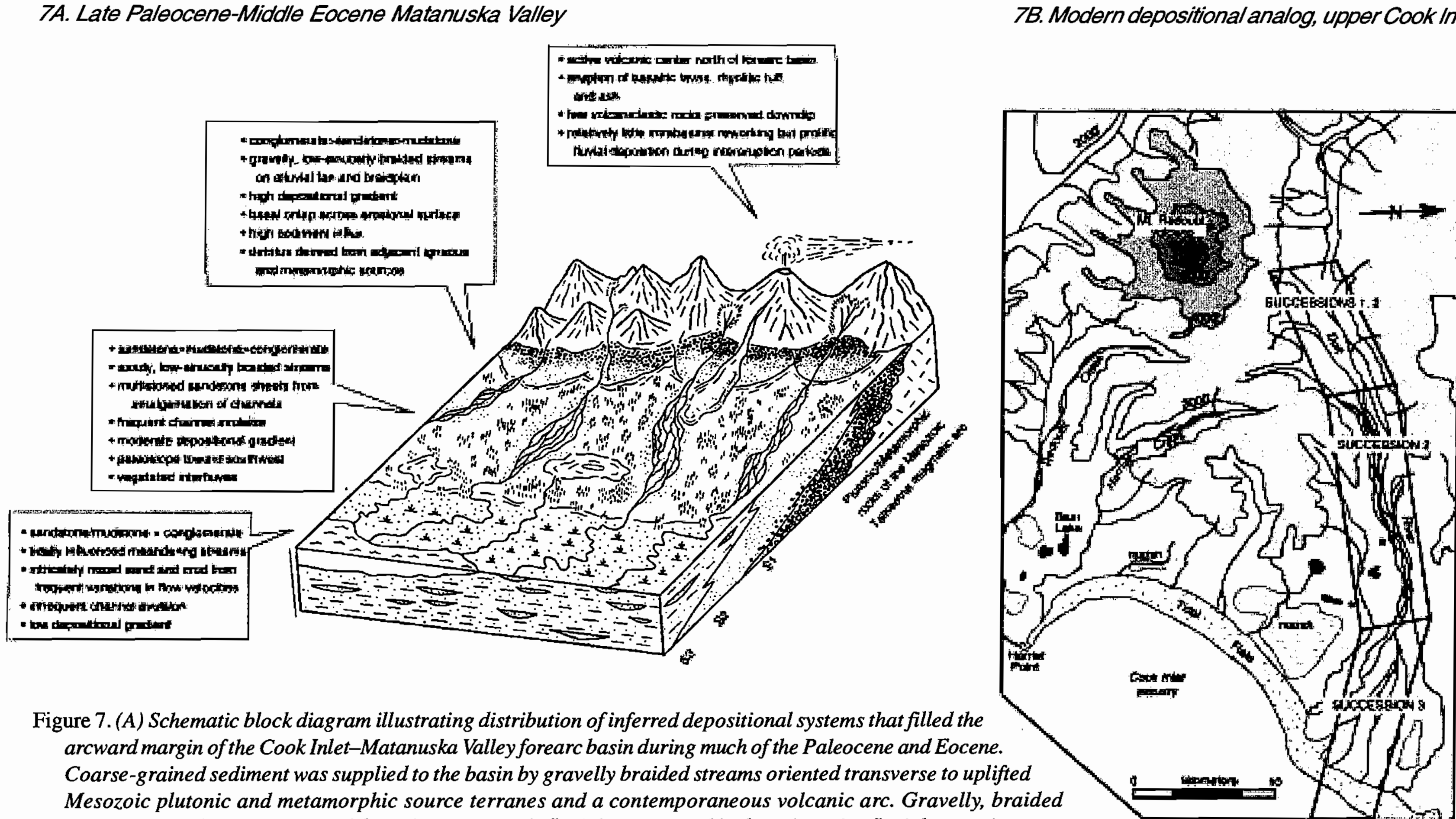

Figure 7. *(A) Schematic block diagram illustrating distribution of inferred depositional systems that filled the arcward margin of the Cook Inlet–Matanuska Valley forearc basin during much of the Paleocene and Eocene. Coarse-grained sediment was supplied to the basin by gravelly braided streams oriented transverse to uplifted Mesozoic plutonic and metamorphic source terranes and a contemporaneous volcanic arc. Gravelly, braided streams merged downstream with low-sinuosity, sandy fluvial systems and higher-sinuosity, fluvial-estuarine streams. An increase in relative sea level caused northward migration of distal deposystems, producing an overall retrogradational lithofacies succession. (B) Modified topographic map of the Kenai B-8 15-minute quadrangle showing modern depositional systems along the southeastern flank of Mt. Redoubt, an active volcano of the Aleutian magmatic arc. Location of map shown in figure 1. This modern setting may be analogous to the depositional environments of the Paleocene–Eocene Arkose Ridge Formation. Braided streams drain the flanks of the calc-alkaline basaltic stratovolcano and merge downstream into progressively finer-grained and more sinuous, tidally influenced streams adjacent to the Cook Inlet estuary. The inferred positions of major lithofacies successions documented in the Arkose Ridge Formation are outlined by rectangles representing succession 1 (S1), succession 2 (S2), and succession 3 (S3).*

depositional sequence from gravel-rich, alluvial fan systems to sandy, braided streams to tidally influenced, sinuous streams. An increase in relative sea level during the Late Paleocene to Middle Eocene resulted in northward onlap of tidally influenced deposystems toward the basin margin and increased preservation of fine-grained sediment. Interbedded volcanic flows in the upper part of the formation indicate relative proximity to active volcanic centers during deposition.

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REFERENCES

Barnes, F.F., 1962, Geologic map of the lower Matanuska Valley, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–359, scale 1:63,360.

Barwis, J.H., 1978, Sedimentology of some South Carolina tidal-creek point bars, and a comparison with their fluvial counterparts, *in* Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 129–160.

Boothroyd, J.C., and Ashley, G.M., 1975, Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska, *in* Jopling, A.V., and McDonald, B.C., eds., Glaciofluvial and Glaciolacustrine Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication 23, p. 193–222.

Busby-Spera, C.J., 1986, Sedimentation and subsidence styles in a Cretaceous forearc basin, southern Vizcaino Peninsula, Baja California, Mexico, *in* Abbott, P.L., ed., Cretaceous stratigraphy of western North America, Society of Economic Paleontologists and Mineralogists, Field Trip Guidebook 46, p. 79–90.

Clifton, H.E., 1982, Estuarine deposits, *in* Scholl, P.A., and Spearing, D.R., eds., Sandstone Depositional Environments: American Association of Petroleum Geologists, Memoir 31, p. 179–184.

Csejtey, Bela, Jr., Nelson, W.H., Jones, D.L., Silberling, N.J., Dean, R.M., Morris, M.S., Lanphere, M.A., Smith, J.G., and Silberman, M.L., 1978, Reconnaissance geologic map and geochronology, Talkeetna Mountains quadrangle, northern part of Anchorage quadrangle, and southwestern corner of Healy quadrangle, Alaska: U.S. Geological Survey Open-File Report 78–558-A, 62 p., 1 sheet, scale 1:250,000.

Dickinson, W.R., 1988, Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins, *in* Kleinspehn, K.L., and Paola, Chris, eds., New Perspectives in Basin Analysis: New York, Springer-Verlag, p. 3–25.

Dickinson, W.R., 1995, Forearc basins, in Busby, C.J., and Ingersoll, R.V., eds., Tectonics of Sedimentary Basins, Cambridge, Blackwell Science, p. 221–262.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America, Bulletin, v. 94, p. 222–235.

Dorjes, Jurgen, and Howard, J.D., 1975, Fluvial-marine transition indicators in an estuarine environment, Ogeechee River–Ossabaw Sound, *in* Estuaries of the Georgia coast, U.S.A., sedimentology and biology: Senckenbergiana Maritima 7, p. 137–179.

Eisma, D, 1998, Intertidal Deposits: River mouths, tidal flats, and coastal lagoons, with contributions by P.L. Boer, G.C. Cadee, K. Dikema, H. Ridderinkhof, and C. Philippart, CRC Press, Boca Raton, Florida, 525 p.

Engebretson, D.C., Cox, Allan, and Gordon, R.G., 1983, Relative motions between oceanic and continental plates in the Pacific basin, *in* Howell, D.G., Jones, D.L., Cox, A., and Nur, A.M., eds., Proceedings of the Circum-Pacific terrane conference, Stanford, California: Stanford University Publications, Geological Sciences, v. 18, p. 80–82.

Fisher, M.A., and Magoon, L.B., 1978, Geologic framework of lower Cook Inlet, Alaska: American Association of Petroleum Geologists Bulletin, v. 62, p. 373–402.

Fuchs, W.A., 1980, Tertiary tectonic history of the Castle Mountain–Caribou fault system in the Talkeetna Mountains, Alaska, Salt Lake City, Utah: University of Utah, Ph.D. thesis, 152 p.

Fulford, M.M., and Busby, C.J., 1993, Tectonic controls on non-marine sedimentation in a Cretaceous forearc basin, Baja California, Mexico, *in* Frostick, L.E, and Steel, R.J., eds., Tectonic controls and signatures in sedimentary successions, Special Publication of the International Association of Sedimentologists, v. 20, p. 301–333.

Grantz, Arthur, 1966, Strike-slip faults in Alaska: U.S. Geological Survey Open-File Report 66–53. 82 p.

Haq, B.U., Hardenbol, Jan, and Vail, P.R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, *in* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H.W., Van Wagoner, John, Ross, C.A., and Kendall, C.G. St. C., Sea-Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication No. 42, p. 78–108.

Harms, J.C., Southard, J.B., and Walker, R.G., 1982, Structure and sequences in clastic rocks: Society of Economic Paleontologists and Mineralogists, Short Course No. 9, p. 3-1-3-51.

Heller, P.L., and Dickinson, W.R., 1985, Submarine ramp facies model for delta-fed, sand-rich turbidite systems: American Association of Petroleum Geologists Bulletin, v. 69, p. 960–976.

Ingersoll, R.V., 1979, Evolution of the Late Cretaceous forearc basin, northern and central California: Geological Society of America Bulletin, v. 90, p. 813–826.

Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., and Sares, S.W., 1984, The effect of grain size on detrital modes: A test of the Gazzi-Dickinson point-counting method: Journal of Sedimentary Petrology, v. 54, p. 103–116.

Johnson, A.M., 1965, A model for debris flow: University Park, PA, Ph.D. thesis, Pennsylvania State University.

Kienle, Juergen, and Nye, C.J., 1990, Volcanoes of Alaska, *in* Wood, C.A., and Kienle, Juergen, eds., Volcanoes of North America: Cambridge, MA, p. 8–110.

Kirschner, C.E., and Lyon, C.A., 1973, Stratigraphic and tectonic development of Cook Inlet Petroleum Province, *in* Pitcher, M.G., ed., Arctic Geology: American Association of Petroleum Geologists, Memoir 19, p. 396–407.

Kuenzi, W.D., Horst, O.H., and McGehee, R.V., 1979, Effect of volcanic activity on fluvial-deltaic sedimentation in a modern arc-trench gap, southwestern Guatemala: Geological Society of America Bulletin, v. 90, p. 827–838.

Little, T.A., 1988, Tertiary tectonics of the Border Ranges fault system, north-central Chugach Mountains, Alaska—Sedimentation, deformation, and uplift along the inboard edge of a subduction complex: Stanford, CA, Stanford University, Ph.D. thesis, 565 p.

Little, T. A., 1990, Kinematics of wrench and divergent-wrench deformation along a central part of the Border Ranges fault system, northern Chugach Mountains, Alaska: Tectonics, v. 9, p. 585–611.

MacKevett, E.M., Jr., and Plafker, George, 1974, The Border Ranges fault in south-central Alaska: U.S. Geological Survey Journal of Research, v. 2, p. 323–329.

Madden-McGuire, D.J, Silberman, M.L., and Church, S.E., 1990, Geologic relationships, K-Ar ages, and isotopic data from the Willow Creek gold mining district, southern Alaska, *in* Keays, R.R., Ramsey, W.H.R., and Groves, D.I., eds., Geology of gold deposits—The prospective in 1988: Economic Geology, Monograph 6, p. 242–251.

Magoon, L.B., Adkison, W.L, and Egbert, R.M., 1976, Map showing geology, wildcat wells, Tertiary plant fossil localities, K-Ar age dates, and petroleum operations, Cook Inlet area, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I–1019, 3 sheets, scale 1:250,000.

Marsaglia, K.M., and Ingersoll, R.V., 1992, Compositional trends in arc-related, deep-marine sand and sandstone: A reassessment of magmatic-arc provenance: Geological Society of America Bulletin, v. 104, p. 1637–1649.

Martin, G.C., and Katz, F.J., 1912, Geology and coal fields of the lower Matanuska Valley, Alaska: U.S. Geological Survey Bulletin 500, 98 p.

Miall, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary, *in* Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 597–604.

Middleton, G.V., and Hampton, M.A., 1976, Subaqueous sediment transport and deposition by sediment gravity flows, *in* Stanley, D.J., and Swift, D.J.P., eds., Marine Sediment Transport and Environmental Management: New York, Wiley, p. 197–218.

Morris, W.R., and Busby-Spera, C.J., 1988, Sedimentologic evolution of a submarine canyon in a forearc basin, Upper Cretaceous Rosario Formation, San Carlos, Mexico: American Association of Petroleum Geologists Bulletin, v. 72, p. 717–737.

Morris, W.R., Smith, D.P., and Busby-Spera, C.J., 1989, Deep marine conglomerate facies and processes in Cretaceous forearc basins of Baja California, Mexico, *in* Colburn, I.P., Abbott, P.L., and Minch, John, eds., Conglomerates in basin analysis: A symposium dedicated to A.O. Woodford: Society of Economic Paleontologists and Mineralogists, Pacific Section, v. 62, p. 123–142.

Nemec, W., and Steel, R.J., 1984, Alluvial and coastal conglomerates: Their significant features and some comments on gravelly mass-flow deposits, *in* Koster, E.H., and Steel, R.J., eds., Sedimentology of gravels and conglomerates: Canadian Society of Petroleum Geologists, Memoir 10, p. 1–31.

Oil and Gas Journal, 1998, Independents lead resurgence of drilling in Alaska's Cook Inlet, v. 96, p. 27–29.

Pavlis, T.L., and Crouse, G.W., 1989, Late Mesozoic strike slip movement on the Border Ranges fault system in the eastern Chugach Mountains, southern Alaska, *in* Page, R.A., ed., Special section on northern Chugach Mountains–southern Copper River basin segment of the Alaskan Transect; Part I: Journal of Geophysical Research, B, Solid Earth and Planets, v. 94, p. 4321–4332.

Plafker, George, Jones, D.L, and Pessagno, E.A., Jr., 1977, A Cretaceous accretionary flysch and melange terrane along the Gulf of Alaska margin, *in* Blean, K.M, The United States Geological Survey in Alaska—Accomplishments during 1976: U.S. Geological Survey Circular 751-B, p. B41–B43.

Plafker, George, and Berg, H.C., 1994, Overview of the geology and tectonic evolution of Alaska, *in* Plafker, George, and Berg, H.G., The Geology of Alaska: The Geology of North America, v. G–1, p. 989–1021.

Reineck, H.E., and Singh, I.B., 1973, Depositional Sedimentary Environments, New York, Springer-Verlag, 439 p.

Rust, B.R., 1977, Depositional models for braided alluvium, *in* Miall, A.D., ed., Fluvial Sedimentology, Canadian Society of Petroleum Geologists Memoir 5, p. 605–625.

Silberman, M.L., and Grantz, Arthur, 1984, Paleogene volcanic rocks of the Matanuska Valley area and the displacement history of the Castle Mountain fault, *in* Coonrad, W.L., and Elliot, R.L., eds., The United States Geological Survey in Alaska - Accomplishments during 1981: U.S. Geological Survey Circular 868, p. 82–86.

Silberman, M.L., O'Leary, R.M., Csejtey, Bela, Jr., Smith, J.G., and Connor, C.L., 1978, Geochemical anomalies and isotopic ages in the Willow Creek mining district, southwestern Talkeetna Mountains, Alaska: U.S. Geological Survey Open-File Report 78–223, 33 p.

Smith, D.G., 1985, Modern analogs of the McMurray Formation channel deposits, sedimentology of mesotidal-influenced meandering point bars with inclined beds of alternating mud and sand: Alberta Oil Sands Technology and Research Authority, Final Report for Research Project No. 391, 78 p.

Thomas, R.G., Smith, D.G., Wood, J.M., Visser, J., Calverley-Range, E.A., and Koster, E.H., 1987, Inclined heterolithic stratification—terminology, description, interpretation, and significance: Sedimentary Geology, v. 53, p. 123–179.

Triplehorn, D.M., Turner, D.L., and Naeser, C.W., 1984, Radiometric age of the Chickaloon Formation of south-central Alaska—Location of the Paleocene–Eocene boundary: Geological Society of America Bulletin, v. 95, p. 740–742.

Vessel, R.K., and Davies, D.K., 1981, Nonmarine sedimentation in an active forearc basin: Special Publication of the Society of Economic Paleontologists and Mineralogists, no. 31, p. 31–45.

Winkler, G.R., 1978, Framework grain mineralogy and provenance of sandstones from the Arkose Ridge and Chickaloon Formations, Matanuska Valley, *in* Johnson, K.M., ed., The United States Geological Survey in Alaska - Accomplishments during 1977: U.S. Geological Survey Circular 772-B, p. B70–B73.

Winkler, G.R., 1992, Geologic map and summary geochronology of the Anchorage 1x3 degree quadrangle, southern Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I–2283, 1 sheet.

Wolfe, J.A., Hopkins, D.M., and Leopold, E.B., 1966, Tertiary stratigraphy and paleobotany of the Cook Inlet region, Alaska: U.S. Geological Survey Professional Paper 398-A, p. A1–A29.