**EVOLUTION OF MESOZOIC SANDSTONE COMPOSITIONS, SOUTHERN JUNGGAR, NORTHERN TARIM,**

**AND WESTERN TURPAN BASINS, NORTHWEST CHINA: A DETRITAL RECORD OF THE ANCESTRAL TIAN SHAN**

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**ABSTRACT: Sandstone compositional data can be a powerful tool in the interpretation of tectonic and climatologic influences on sedimentary basin fill, in addition to yielding important information about porosity in sandstone petroleum reservoirs. In order to explore these relationships, a modified Gazzi–Dickinson point-counting technique was used to analyze the composition of 143 Mesozoic sandstone samples from the southern Junggar, northern Tarim, and western Turpan basins of northwestern China. Results indicate that a Mesozoic, ancestral version of the Tian Shan physiographically separated the Junggar and Tarim basins and provided sand of very different composition to each basin. Mesozoic sandstone from the northern Tarim basin is diverse in composition and lithic-rich (Qm41F14L45**; **Qp42Lvm26Lsm32), is locally micaceous, and contains common radiolarian-chert grains and few dense accessory minerals. Inferred source rocks include upper Paleozoic alkali granite and metamorphic complexes, thick Silurian bedded-chert sequences, and lower Paleozoic strata of a passive continental margin. In contrast, sandstone from the southern Junggar and western Turpan basins is uniformly volcanic-rich (Qm21F21Lt58; Qp13Lvm68Lsm19), and contains abundant dense accessory minerals and only local radiolarian chert and mica. Inferred principal source rocks are Devonian–Carboniferous andesitic arc volcanics.**

**The effect of sampling scale on sandstone composition outweighs that of plate-tectonic setting. Samples were derived mostly from mediumand coarse-grained fluvial systems that likely drained only portions of the ancestral Tian Shan and hence preserve local source-rock signatures, rather than an integrated compositional signal that can be directly compared to plate-tectonic petrofacies models. In addition, though Mesozoic basins of western China were most akin to broken foreland basins, Mesozoic sandstone is considerably more compositionally diverse and lithic-rich than that of modern or ancient broken foreland basins because of the variety of accreted terranes constituting the ancestral Tian Shan.**

**Temporal changes in sandstone composition are consistent with episodes of Mesozoic deformation in the Tian Shan. Each deformational episode increased physiographic relief of the ancestral range, produced renewed downcutting and erosion of source rocks, and resulted in the deposition of compositionally very immature sandstone in adjacent basins. Although a regional early Mesozoic megamonsoon and an Early Cretaceous rain shadow cast across the northern Tarim basin are interpreted from regional facies and paleontologic data, neither paleoclimatic phenomenon appears to have significantly modified sandstone composition in the study area.**

**Calculations of intergranular volume (% porosity** 1 **% cement) indicate that porosity in sandstone from the Tarim and Junggar basin depocenters was reduced principally by burial compaction and that the rate of porosity reduction was highest for lithic-rich samples.**

# INTRODUCTION

Central and southern Asia is a mosaic of tectonic elements, including microcontinents and associated passive-margin sedimentary prisms, accreted magmatic arcs and their subduction complexes, ophiolite fragments, and igneous intrusions (Sengo¨r 1987; Coleman 1989; Sengo¨r et al. 1993). Most of this mosaic was assembled piecemeal during Phanerozoic time, as in-

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dividual tectonic elements were accreted onto the south Asian continental margin and deformed by succeeding collisions (Zhang et al. 1984; Watson et al. 1987). Situated in the midst of this large tectonic mosaic is the Chinese Tian Shan (‘‘Heavenly Mountains’’) and associated sedimentary basins, including the Junggar, Tarim, and Turpan basins.

The Tian Shan complex was assembled during middle and late Paleozoic time and contains several distinct tectonic elements, including two major sutures (Fig. 1). The oldest of these sutures corresponds to the Qinbulak– Qawabulak Fault (Fig. 1) which marks the boundary between the Ili microcontinental block (generally coincident with the ‘‘Ili basin’’ in Figure 1) and a north-facing sequence of passive-continental-margin strata formerly associated with the Tarim Block (Allen et al. 1993). The ocean basin separating the Tarim and Ili Blocks closed during Devonian time in a poorly understood collision that produced a major angular unconformity in the northern Tarim basin (Carroll et al. 1995). A younger suture, corresponding to the modern Borohoro–North Tian Shan fault system (Fig. 1), was formed by the Late Carboniferous–Permian accretion of the North Tian Shan–Bogda Shan arc system(s) to the northern side of the combined Ili/Tarim Blocks (Windley et al. 1990; Allen et al. 1993; Carroll et al. 1995). This accretion terminated arc magmatism in the region, produced late Paleozoic thrusting in the northern Tian Shan (Allen et al. 1993), and resulted in widespread erosional unroofing and cooling of rocks now exposed in the core of the Tian Shan (Zhou 1997; T.A. Dumitru, personal communication 1999). By Early Permian time, erosional detritus from the ancestral Tian Shan was shed into the southern Junggar and northern Tarim basins (Carroll et al. 1990; Carroll et al. 1995).

The idea of a Mesozoic Tian Shan has long been favored by Chinese geologists (e.g., Huang 1978), although this hypothesis has not been not universally accepted (e.g., Bally et al. 1986). Several lines of stratigraphic evidence suggest that the Junggar and Tarim basins continued to be physiographically separated by the ancestral Tian Shan during Mesozoic time and that several relatively minor episodes of Mesozoic contractile deformation occurred in the area (Hendrix et al. 1992). Isopach maps indicate that Mesozoic strata in the Junggar and Tarim basins thicken towards the range (Zhang et al. 1993; Gu 1994), suggesting that the ancestral Tian Shan was the source of sediment. Approximately 5600 m and 4700 m of Mesozoic nonmarine siliciclastic strata are exposed in the upturned flanks of the southern Junggar and northern Tarim basins, respectively, attesting to the importance of tectonic subsidence. Both the Ili and the Turpan intermontane basins (Fig. 1) contain Mesozoic stratal patterns indicating syndeformational ponding of sediment (Graham et al. 1994), and there are several intra-Mesozoic angular unconformities in the Turpan basin (Greene et al. 1997).

In addition to preserving a record of central Asian tectonism, Mesozoic nonmarine strata in basins of northwestern Chinese contain a remarkable record of both regional and local Mesozoic paleoclimate (Hendrix et al. 1992; Greene et al. 1997; Ritts 1998). Regional Lower through Middle Jurassic organic-rich strata record well-watered environments associated with a monsoonal circulation (Hendrix et al. 1992). In contrast, Upper Jurassic redbeds record a regional increase in aridity and cessation of monsoonal circulation (Parrish 1993). The presence of thick Lower Cretaceous redbeds in the northern Tarim basin and coeval regional lacustrine deposits in the southern Junggar basin was interpreted by Hendrix et al. (1992) to

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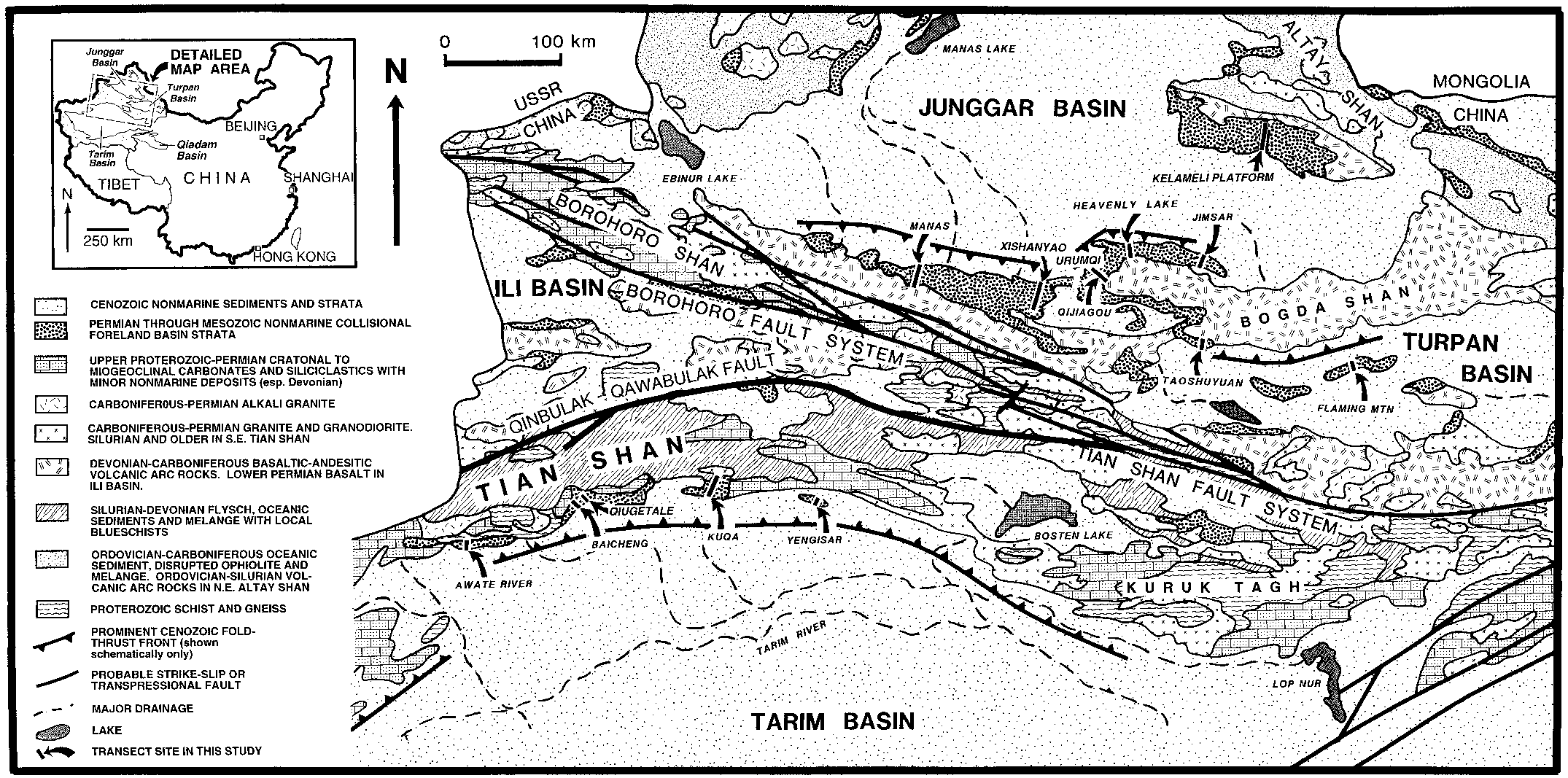


FIG. 1.—Location geologic map of the field area, showing the southern Junggar, northern Tarim, and western Turpan basins, as well as all locations where Mesozoic

sandstone was sampled.

reflect an Early Cretaceous rain shadow cast by the ancestral Mesozoic Tian Shan.

Although the Tian Shan now stands as one of the world’s great mountain ranges, with peaks locally exceeding 7400 m elevation, recent tectonic and paleogeographic analyses of northwestern China suggest that the major components of the Tian Shan complex have remained approximately in their present relative positions since their late Paleozoic assembly (e.g., Windley et al. 1990; Carroll et al. 1995) and that surprisingly little structural shortening and erosional unroofing have accompanied Cenozoic deformation. Estimates of the magnitude of Cenozoic shortening across the Tian Shan at 788 longitude include 80 km (Allen et al. 1994), 100 km (Molnar and Tapponnier 1975), 124 6 30 km (Avouac et al. 1993), and 330 6 760 km (Chen et al. 1991). Analyses of primary apatite from plutonic and metamorphic rocks and detrital apatite from sandstone in the Tian Shan indicate that most of the range has undergone less than ø3 km of total exhumation during Mesozoic and Cenozoic time (Zhou 1997; T.A. Dumitru, personal communication 1999). Similarly, Yin et al. (1998) concluded that most of the range has undergone less than 5 km of Cenozoic erosional unroofing, on the basis of reconnaissance 40Ar/39Ar dating.

The apparent structural integrity of the Tian Shan, the heterogeneity of accreted terranes that constitute it, and the well preserved records of tectonism and paleoclimate in Mesozoic strata of adjacent sedimentary basins provide ideal conditions for exploring relationships among sandstone composition, Mesozoic tectonism, depositional setting, and local and regional paleoclimate. In this paper, I compare coeval sandstone compositions between basins to further test the hypothesis that the Junggar and Tarim basins were physiographically separated throughout Mesozoic time, and I examine the possibility that the provenance of Mesozoic sandstone can be tied to specific source terranes in the Tian Shan complex (e.g., Graham et al. 1993; Carroll et al. 1995). I discuss the effect of sampling scale on sandstone composition, and I examine the composition of Mesozoic sandstone in the context of previously published interpretations of Mesozoic paleoclimate, tectonic setting, and tectonic history for the study area. Lastly, I describe relationships among porosity, burial depth, and sandstone composition in order to provide information about the petroleum reservoir quality of Mesozoic sandstone.

# METHODS

Sandstone samples were collected from Mesozoic strata exposed along the upturned flanks of the southern Junggar, northern Tarim, and western Turpan basins (Fig. 1). Most samples were collected from the Junggar and Tarim basin depocenters at Manas and Kuqa, respectively, where complete Mesozoic sections are exposed. In addition, samples were collected away from depocenter regions and across the western Turpan basin as exposure and access permitted.

A total of 143 sandstone samples were point-counted using a modified Gazzi (1966)–Dickinson (1970) method (Appendix 1, archived, see statement after text; Ingersoll et al. 1984). At least 500 individual grains were identified and tabulated per sample. Each slide was stained with a combination of alizarin-red and sodium cobaltinitrite to facilitate identification of feldspars. Specific point-counting procedures used in this study are explained in Hendrix (1992). Raw point-count data (Appendix 1) were recalculated into detrital modes following the methods of Ingersoll et al. (1984) (Appendix 2, archived) and plotted on Qm–F–Lt, Qp–Lvm–Lsm, and Qm–P–K ternary diagrams (Fig. 2).

The effects of diagenesis on sandstone (e.g. Dickinson 1970; Milliken et al. 1989; Harris 1990; Kairo and Basu 1991; McBride et al. 1996) were insufficient to render the original framework-grain composition unrecognizable or quantitatively irreproducible for samples analyzed in this study. Diagenetic alterations in the sample suite include grain compaction, partial replacement of feldspar by calcite or clay, and addition of calcite, clay, chlorite, and/or zeolite cements (see also Hu et al. 1990; Tang et al. 1997a, 1997b). Samples considered to be too diagenetically altered to produce reliable framework compositional data were deleted from the study.

Although dating of Mesozoic nonmarine strata in the study area is difficult because of a lack of interbedded, datable volcanic units and little reported magnetostratigraphic work (but see McFadden et al. 1988a,

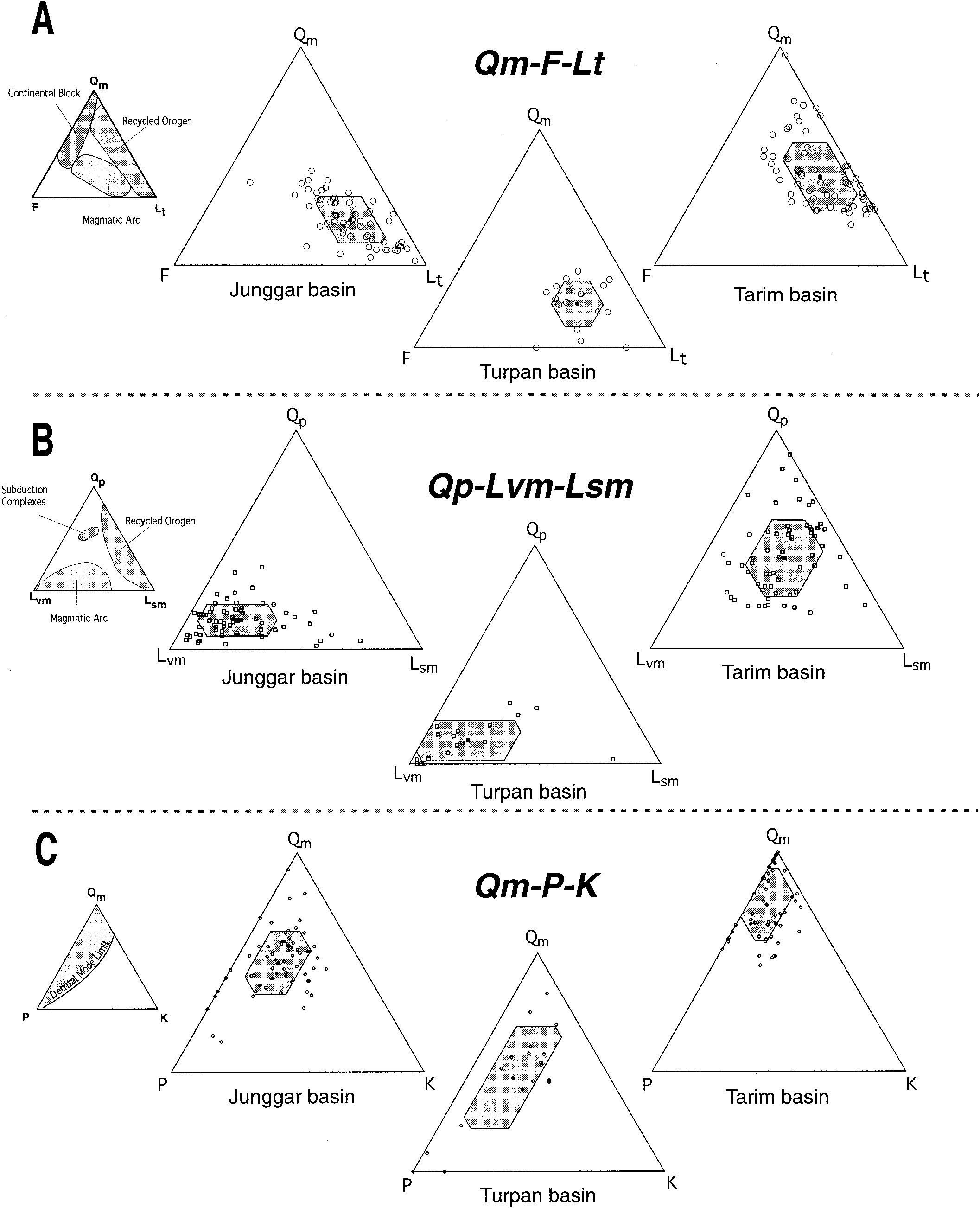


FIG. 2.—Mesozoic sandstone compositional data, means, and 1s standard deviations for the southern Junggar, northern Tarim, and western Turpan basin plotted on **A)** QmFLt, **B)** QpLvmLsm, and **C)** QmPK ternary diagrams. Qm 5 monocrystalline quartz; F 5 total feldspar; Lt 5 total lithic framework fraction; Qp 5 polycrystalline quartz; Lvm 5 lithic volcanic plus metavolcanic grains; Lsm 5 lithic sedimentary plus metamorphic grains; P 5 plagioclase; K 5 potassium feldspar. Tectonic fields of Dickinson and Suczek (1979) are included on unfilled triangles for comparison.

1988b), age control to the epoch level is possible because of a large body of paleontologic literature (e.g., Saidov 1956; Sze 1956; Yang and Sun 1982; Zhang 1983; Wu and Zhou 1986; Wei 1989; Liu 1990; Wu 1990; Zhang and Li 1990; Shen and Mateer 1992). Along with biostratigraphic and lithostratigraphic summaries of Mesozoic strata in western China (Zhang 1981; Chen 1985b), these paleontologic results form the basis for age control in this study.

# SANDSTONE COMPOSITIONAL TRENDS AT THE BASIN SCALE

## Possible Controls on Sandstone Composition

The composition of sand-size detritus in ancient sedimentary rocks may be influenced by numerous possible variables, including the composition of source terrane(s) (e.g., Cavazza et al. 1993; Marsaglia 1993; Ridgway and DeCelles 1993), source-rock texture (Heins 1993), drainage-basin size and variety of included source rocks (e.g., Soreghan and Cohen 1993), intensity of chemical weathering (e.g., Suttner and Dutta 1986; Dutta and Wheat 1993), rigor and time spent in transport (Johnsson and Meade 1990; Osborne et al. 1993), depositional environment (Garzanti 1986; Kairo et al. 1993; Soreghan and Cohen 1993), and modification by diagenesis (Milliken et al. 1989). For a thorough review of the system of controls on sandstone composition, the reader is referred to Johnsson (1993).

In tectonically active settings such as that inferred for the study area during Mesozoic time (Wang et al. 1990; Hendrix et al. 1992; Hendrix et al. 1995; Greene et al. 1997), the influence of weathering on sandstone composition may be less important than that of source-rock composition. In such settings, residence time of sediment in lowland soil profiles is short, rate of introduction of ‘‘fresh’’ erosional detritus to sediment dispersal systems is high, and burial rate of sediment is rapid, all serving to minimize the effects of weathering and transport on sandstone composition (e.g., Cavazza et al. 1993; Devaney and Ingersoll 1993; Ridgway and DeCelles 1993). As demonstrated below for this study suite, the broad inter-basinal trends in sandstone composition as well as changes in sandstone composition through time are most easily explained as a function of the distribution of source rocks in the Tian Shan complex and episodic unroofing of those source terranes.

## Regional Observations

Mesozoic sandstone from the Junggar, Tarim, and Turpan basins is characterized by several broad similarities as well as some marked differences, which provide the basis for interpretations regarding the relative influence of paleoclimate, depositional setting, and tectonic history on sandstone composition.

**Lithic Grains.**—Sandstone from all three basins is lithic-rich (Tarim Qm41F14L45; Junggar Qm20F20L60; Turpan Qm20F25L55; Fig. 2), although the types of lithic grains in the Tarim basin are very different that those of the Junggar and Turpan basins (Fig. 2B). With few exceptions, samples from both the Junggar and Turpan basins are dominated by volcanic detritus (Junggar Qp13Lvm67Lsm20; Turpan Qp11Lvm71Lsm18). In fact, sandstone compositions for the southern Junggar and Turpan basins are statistically indistinguishable at the 1s level for all major framework components (Appendix 2; Fig. 2B). Chert and lithic sedimentary debris is a common constituent of some samples from the Junggar and Turpan basins. In contrast, Mesozoic samples from Tarim have diverse lithic compositions and are dominated by Qp (including chert), Ls, and Lm, and contain subordinate amounts of volcanic rock fragments (Tarim Qp42Lvm26Lsm32). The standard deviation (1s) for modal Qp, Lvm, and Lsm in Tarim basin samples is outside that of samples from both the Junggar and Turpan basins (Appendix 2; Fig. 2B).

**Monomineralic Grains.**—The occurrence of monomineralic framework grains (Qm, P, K) in Tarim samples also is significantly different than that of either the Junggar or Turpan basins. Tarim samples contain notably higher QmPK%Qm than either Junggar or Turpan samples (Tarim Qm76P16K8; Junggar Qm50P33K17; Turpan Qm43P39K18). Monocrystalline quartz in Tarim is diverse in character. Most grains contain mild undulatory extinction and common inclusions and appear to be plutonic (Basu et al. 1975). Highly strained metamorphic quartz also is present. Inclusion-free quartz with uniform extinction, interpreted to be volcanic in origin, is uncommon in Tarim sandstone. In contrast, monomineralic framework grains in Junggar and Turpan samples are dominated by plagioclase, and much of the monocrystalline quartz is clear and inclusion-free, and locally contains embayed crystal margins suggestive of a volcanic origin (Fig. 3A).

## Evidence for a Mesozoic Ancestral Tian Shan—Regional Distribution of Source Rocks and Specific Provenance Indicators

Variations in Mesozoic sandstone composition among basins of western China provides strong evidence for an ancestral, Mesozoic version of the Tian Shan. Many of the observed variations in sandstone composition are most easily explained through the erosion of source terranes that occur in the Tian Shan complex. The higher modal percentages of Qp, Ls, and Lm in Tarim samples (Fig. 2B) resulted from erosion of Precambrian and upper Paleozoic granite, lower Paleozoic passive-continental-margin strata, and high-grade metamorphic rock assemblages. The scatter in lithic data is consistent with the diverse source-rock types interpreted for the northern Tarim basin. These rock types are inferred to have cropped out on the southern flanks of the Mesozoic Tian Shan but to have been largely lacking on the northern flanks (Fig. 1). In contrast, the consistently Lv-rich character of sandstone from the Turpan and Junggar basins resulted from erosion of Devonian through Carboniferous arc volcanics that cropped out along the northern flank of the Mesozoic Tian Shan and the entire Mesozoic Bogda Shan, a distribution similar to that of today (Fig. 1). Devonian–Carboniferous arc volcanics are interpreted to have cropped out only locally on the southern flanks of the Mesozoic Tian Shan, and hence were a comparatively minor source of clastic debris shed into the northern Tarim basin during Mesozoic time.

**Specific Source-Rock Indicators.**—Several distinct grain types in the study suite can be used as specific provenance indicators for the Mesozoic Tian Shan. Unusually abundant potassium feldspar is found in Paleozoic sandstone (Carroll et al. 1995), Mesozoic sandstone (this study), and modern sands (Graham et al. 1993) from basins of northwestern China. Potassium feldspar was likely derived from a suite of Permian alkali granite and rhyolite containing potassium feldspar phenocrysts that are widespread in the southern Tian Shan (Fig. 1; Chen 1985a; Coleman 1989; Carroll et al. 1995). Granitic rock fragments (Fig. 3B) are common in the sample suite, and the occurrence of potassium feldspar commonly parallels that of granitic rock fragments (Figs. 4, 5). For example, both potassium feldspar and granitic rock fragments are negligible, if present, in Triassic strata of the Kuqa section. Both grain types first appear in significant quantities in Lower Jurassic strata and are present throughout the younger Mesozoic section. Although highly potassium-feldspar-rich sandstone is not common in the rock record, Ingersoll and Cavazza (1991) described potassium-feldsparrich sandstone from local stream systems draining a rhyolitic volcanic center in the Rio Grande Rift. Graham et al. (1993) speculated that regional deposition of potassium-feldspar-rich ancient sandstone may be a common feature of collisional orogenic systems that are widely intruded by latestage, alkalic plutons (cf. Coleman 1989).

Detrital radiolarian chert (Fig. 3C) in the study suite also can be traced to particular stratigraphic units in the Tian Shan (Figs. 1, 4, 5; Appendix 1). Thick bedded chert, probably in part structurally telescoped, occurs in the Silurian section of the south Tian Shan (Zhang 1981; Chen 1985a; Zhou 1997). In the present study, detrital radiolarian chert was identified in sandstone from each section in the northern Tarim basin except the Awate River locality (Fig. 1). Detrital chert is particularly abundant in the Kuqa section (Figs. 1, 3C). Chert in Mesozoic sandstone from northern

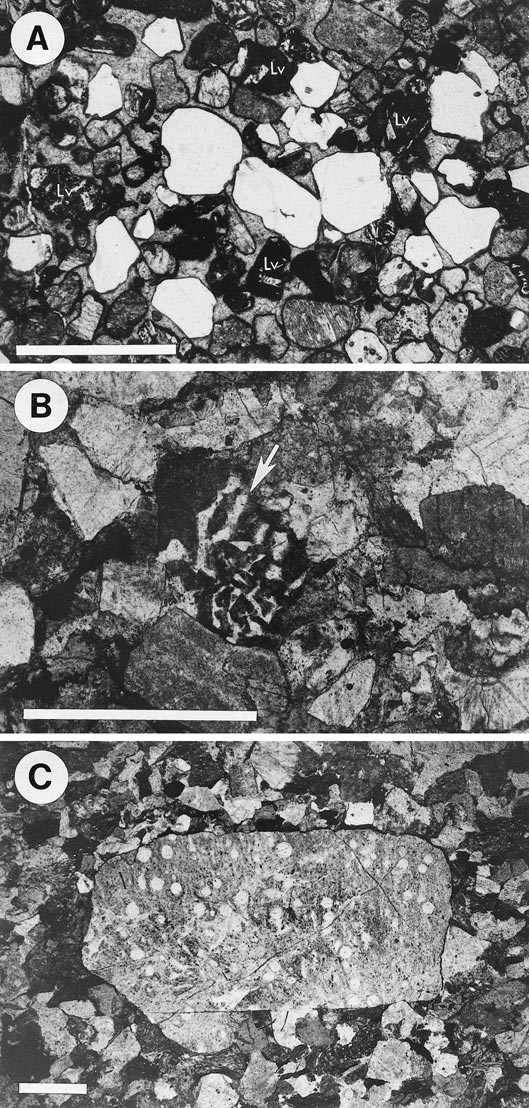


FIG. 3.—Photomicrographs of grain types inferred to be specific source-rock indicators in Mesozoic sandstone from the study area. Scale bar in each photomicrograph is 1 mm long. **A)** Optically clear, euhedral quartz grains interpreted to be volcanic in origin (88-T-105), Taoshuyuan section, western Turpan basin. Much of the quartz in samples from the Turpan and Junggar basins is similar and is interpreted to be derived from volcanic sources. In contrast, quartz from the Tarim basin

is commonly more strained and polycrystalline and is interpreted to have been derived mostly from plutonic and metamorphic sources. Note also the abundance of lithic volcanic grains (Lv) in this photomicrograph. **B)** Graphic granite fragment (highlighted by arrow) in Middle Jurassic sandstone (89-M-18), Manas section, southern Junggar basin. These grains are interpreted to have been derived from Permian alkali granites in the ancestral Tian Shan. Their occurrence parallels that of potassium feldspar in samples from the northern Tarim and southern Junggar

Tarim is inferred to have been eroded from Silurian chert in the southern flank of the Mesozoic Tian Shan. In contrast, radiolarian chert is uncommon and occurs inconsistently in sections from the southern Junggar and Turpan basins, suggesting that Mesozoic streams draining the northern flank of the Tian Shan did not have access to the widespread Silurian chert sequences in the southern Tian Shan. Rather, radiolarian chert in the Junggar and Turpan basins was likely derived from structural slivers of Devonian ophiolite that are present throughout much of the Tian Shan (Chen 1985a; Wang et al. 1990). Chert in the Jimsar, Qijiagou, and Taoshuyuan sections may have been eroded from small, intra-arc basins in the Bogda Shan (e.g., Pollack 1987).

Particularly high percentages of detrital mica in the northwestern Tarim basin and the abundance of dense minerals across the study area also may be related to specific source terranes in the Mesozoic Tian Shan. Percentages of mica in the Awate River and Baicheng sections average 5.9% and 3.2%, respectively (Appendix 1). Although diverse potential source rocks (e.g., late Paleozoic alkali feldspar-rich granite and adamellite; Lower Proterozoic plagiogranite and adamellite; Chen et al. 1985a) could have supplied the mica to these two localities, the most likely source is a belt of Proterozoic greenschist and local blueschist that occurs north and northeast of Aksu and Baicheng (Fig. 1; Chen 1985a; Jia 1996; Zhou 1997). Detrital dense minerals, particularly epidote, are generally more abundant in the southern Junggar and Turpan basins (combined average 5 0.4% of all framework grains) than sandstone from the northern Tarim basin (average 5 0.2%). These accessory minerals were probably derived principally from Carboniferous arc-related andesite that occurs widely in the northern parts of the Tian Shan and Kuruk Tagh and in the entire Bogda Shan, but only sporadically in the southern Tian Shan (Fig. 1).

**Additional Support for a Mesozoic Tian Shan.**—Three additional lines of independent evidence support the existence of a Mesozoic ancestral Tian Shan. First, directional paleocurrent measurements from Mesozoic strata in the northern Tarim and southern Junggar basins (Hendrix et al. 1992) demonstrate the presence of a Mesozoic positive physiographic feature separating these two basins. Second, much of the Mesozoic section in the Tarim and Junggar basins is composed of conglomerate that could not have traveled far from its source. Third, Mesozoic unroofing of the Tian Shan is strongly suggested by Mesozoic detrital-apatite fission-track cooling ages reported by Zhou (1997) for samples collected in the core of the Tian Shan and by Sobel and Dumitru (1997) for samples collected from the northwestern Tarim basin. The existence of a Mesozoic ancestral Tian Shan also is consistent with evidence of local contractile Mesozoic deformation in the northwestern Junggar basin (Chang 1980; Lin 1984; Xie et al. 1984), in the southeastern Junggar basin (Li and Jiang 1987), and in the subsurface of the Tarim basin (Hendrix et al. 1996).

# TEMPORAL CHANGES IN FRAMEWORK-GRAIN COMPOSITION AT JUNGGAR AND TARIM BASIN DEPOCENTERS

Variations in the composition of framework grains through time yield considerable information regarding the history of the Mesozoic Tian Shan. In this study, analysis is focused on the thickest and most continuously exposed stratigraphic sections available in the southern Junggar basin (Manas section; Figs. 1, 4) and northern Tarim basin (Kuqa section; Figs. 1, 5). Documentation of stratigraphy, sedimentology, and organic geochemistry for these sections is presented in Hendrix et al. (1992) and Hendrix et al. (1995) and is not repeated here.

basins. **C)** Detrital radiolarian chert grain in a Lower Jurassic sandstone (98-K-31A) from the Kuqa section, northern Tarim basin. Radiolarian chert grains are a common component of samples from the Kuqa section, where they are interpreted to have been derived from a thick sequence of Silurian bedded chert exposed in the ancestral southern Tian Shan.

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| FIG. 4.—Summary of facies and sandstone compositional data for Mesozoic samples of the southern Junggar depocenter section at Manas. Qt 5 total quartz fraction; M 5 mica; D 5 dense accessory minerals; Gr 5 granitic rock fragments; Cht 5 radiolarian chert. Lithologic abbreviations: sh 5 shale; slt 5 siltstone; m 5 mediumgrained sandstone; c 5 coarse-grained sandstone; gr 5 granule-bearing sandstone; cngl 5 conglomerate. |

## Junggar Basin Depocenter (Manas)

Mesozoic sandstone samples from the Manas section display several major temporal changes in the relative proportions of quartz, feldspar, and lithic grains (Fig. 4). Triassic and Lower Jurassic sandstone is particularly rich in lithic detritus. Middle Jurassic sandstone is more quartzofeldspathic, but uppermost Jurassic sandstone is lithic-rich. Lowermost Cretaceous samples are quartzofeldspathic, and Upper Cretaceous samples are dominated by labile, lithic components (Fig. 4).

Significant temporal variation within the lithic fraction also is observed in sandstone from the Manas section. Triassic samples at Manas are very volcaniclastic, similar to Permian samples downsection (Fig. 4; Carroll et al. 1995). Lower, Middle, and Upper Jurassic samples are successively more enriched in lithic sedimentary and metamorphic detritus and contain somewhat lower percentages of volcanic grains (Fig. 4). Samples of lowermost Cretaceous strata are more Lvm-rich and Lsm-poor, but samples of Upper Cretaceous (K2d) strata display an increase in Lsm and a slight decrease in modal Lvm.

## Tarim Basin Depocenter (Kuqa)

Compositional changes in the relative proportions of quartz, feldspar, and lithic grains also are present in the Kuqa section (Fig. 5). Triassic sandstone contains high percentages of total quartz and undifferentiated lithic fragments. Overlying Lower and Middle Jurassic samples contain the lowest stratigraphic occurrence of significant potassium feldspar, are relatively enriched in total feldspar, and include a lower percentage of undifferentiated lithic grains. However, uppermost Jurassic samples (;3500 m mark in Figure 5) are enriched in lithic components and contain considerably less Qm and total feldspar than samples farther downsection. Relative to the composition of uppermost Jurassic samples, Lower Cretaceous sandstone is somewhat more quartzofeldspathic.

Mesozoic sandstone from Kuqa also displays considerable temporal variation within the lithic fraction (Fig. 5; Appendix 2). Permian–Triassic samples from Kuqa are dominated by Qp, chert, and Lm. Lower and Middle Jurassic sandstone is considerably enriched in volcanic components (Fig. 5). Upper Jurassic samples are dominated by Qp and Ls. Lower Cretaceous samples are enriched in Lv, and Upper Cretaceous samples are rich in Ls.

# INTERPRETATION OF SANDSTONE COMPOSITIONAL TRENDS

## Influence of Depositional Setting and Climate

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| FIG. 5.—Summary of facies and sandstone compositional data for Mesozoic samples of the northern Tarim depocenter section at Kuqa. M 5 mica; D 5 dense accessory minerals; Gr 5 granitic rock fragments; Cht 5 radiolarian chert. Lithologic abbreviations the same as in Fig. 4. |

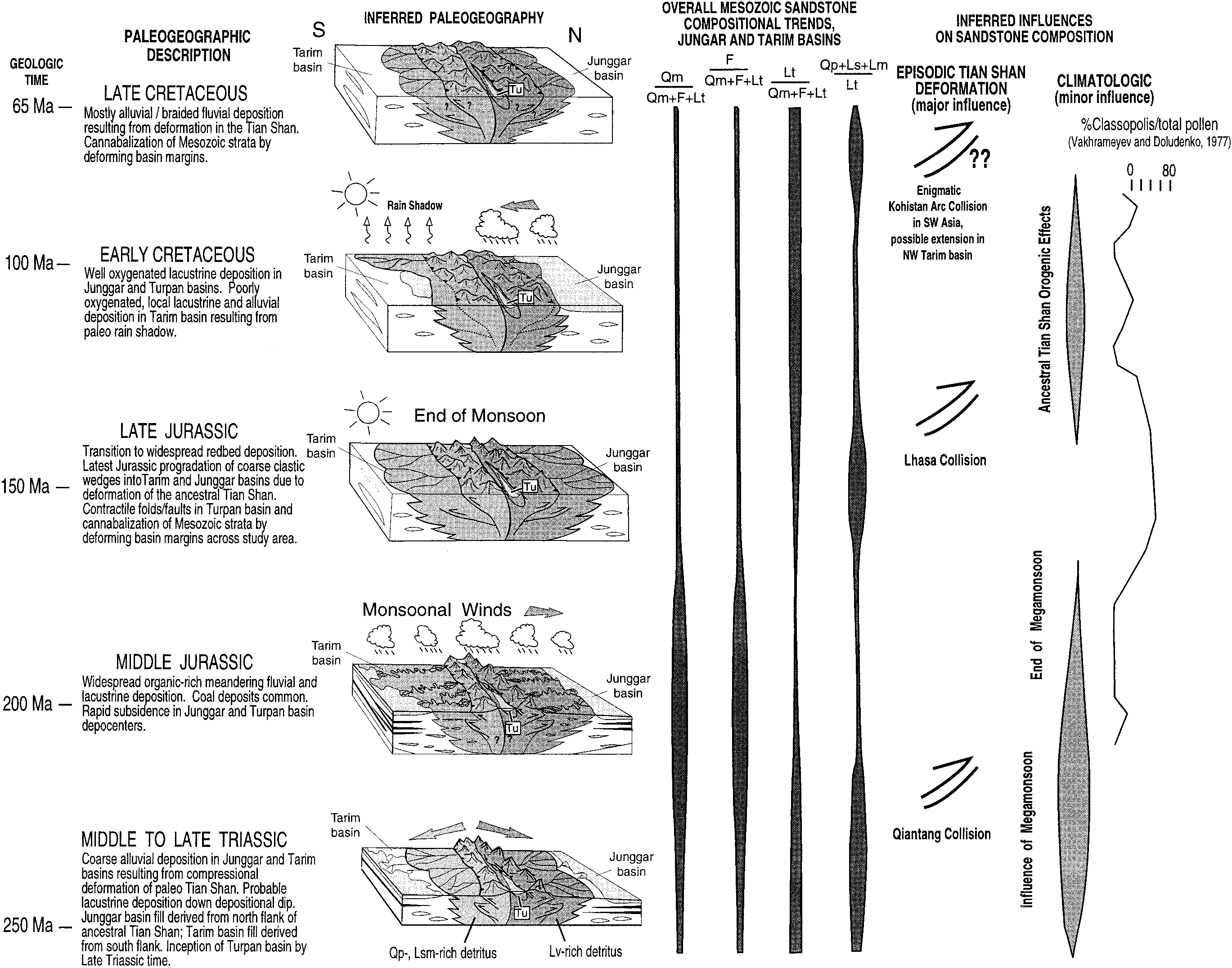
Significant changes in Mesozoic depositional setting across the study area, pollen data, and global climate models of central Asian basins all suggest the establishment of an early Mesozoic megamonsoonal circulation system across central Asia and the ending of that monsoonal circulation by latest Jurassic time (Hendrix et al. 1992; Parrish 1993). Lower and Middle Jurassic coal-bearing meandering-fluvial and lacustrine facies are ubiquitous in central Asian basins and are interpreted to record monsoon-derived moisture (e.g., Hendrix et al. 1992; Hendrix et al. 1995; Ritts and Biffi 2000). Regionally, these organic-rich strata are overlain by Upper Jurassic fine-grained redbeds that were deposited after the monsoonal climatic period (Vakhrameyev and Doludenko 1977; Hendrix et al. 1992; Ritts and Biffi 2000). Supporting this interpretation is a marked Late Jurassic increase in the relative abundance of *Classopolis* sp. pollen derived from drought-tolerant Cheiralipidiaceaen conifers (Vakhrameyev 1982; Fig. 6). Global climate models also predict an early Mesozoic megamonsoonal circulation pattern over central Asia (Kutzbach and Gallimore 1989; Parrish 1993) that ended by Early Cretaceous time (Parrish and Curtis 1982; Parrish 1985).

Temporal changes in sandstone composition may be, in part, attributable to parallel changes in depositional setting and the intensity of chemical weathering resulting from establishment and ending of the megamonsoon, but it does not appear that these changes were the main factors influencing sandstone composition. At Manas, Lt-rich, Qt-poor Triassic sandstone deposited by gravelly braided rivers is overlain by Lower and Middle Jurassic meandering-fluvial and lacustrine sandstone containing appreciably greater percentages of Qt and total F and less Lt (Fig. 4). Overlying Upper Jurassic sandstone collected from braided-fluvial redbeds is enriched in Lt and relatively depleted in Qt and F. Numerous studies have concluded that firstcycle sand transported in a humid climate tends to be depleted in feldspar and rock fragments and enriched in quartz because of the intensity of chemical weathering (e.g., Basu 1976; Suttner and Dutta 1986; Johnsson et al. 1988; Johnsson and Meade 1990; Johnsson 1990; Johnsson et al. 1991; Dutta and Wheat 1993). Whereas increased Qt and decreased Lt in Lower and Middle Jurassic sandstone is consistent with higher rates of chemical weathering during the monsoon, increased total F during this period is not, suggesting that sandstone composition was most influenced by factors other than climate.

Broad compositional differences between Lower Cretaceous sandstone from the southern Junggar basin and the northern Tarim basin also suggest

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FIG. 6.—Summary of tectonic and paleoclimatologic factors interpreted to be important influences on the composition of Mesozoic sandstone from the Junggar, Tarim, and Turpan basins. Facies information is derived principally from Hendrix et al. (1992). Tu 5 Turpan basin.



that depositional environment and climate were not major influences on sandstone composition. Hendrix et al. (1992) interpreted that, during Early Cretaceous time, prevalent northerly winds cooled adiabatically as they were forced over the ancestral Tian Shan. Most of the precipitation from northerly weather systems was shed north of the range in the Junggar basin, producing a regional system of well-oxygenated, oligotrophic lakes (‘‘overfilled lake basins’’ of Carroll and Bohacs 1999). In contrast, a paleo–rain shadow was cast across the northern Tarim basin, producing mainly finegrained terrestrial redbeds and local anoxic lacustrine deposits (‘‘underfilled lake basins’’ of Carroll and Bohacs 1999; Fig. 6). (See Ritts and Biffi 2000, for a similar interpretation for the Qaidam basin, south of the study area; Fig. 1). If depositional setting and climate had been major controls on sandstone composition, Lower Cretaceous sandstone on the windward side of the ancestral Tian Shan (Manas) should be enriched in stable components (particularly Qm) and depleted in less stable grains (Lvm, Lsm) as a result of chemical weathering (Suttner and Dutta 1986). Sandstone on the leeward side of the ancestral Tian Shan (Tarim) should be enriched in labile grains as a result of decreased chemical weathering associated with the rain shadow. Neither scenario is the case. Lower Cretaceous sandstone from the southern Junggar basin contains notably more QmFLt%Lt and less QmFLt%Qm than equivalent sandstone from the northern Tarim basin (Junggar 5 Qm24F23Lt51; Tarim Qm42F25Lt35; Appendix 1). Rather than reflecting differences in climate and the degree of chemical weathering associated with different depositional environments across the study area, Lower Cretaceous sandstone compositions likely record the distribution of source rocks flanking the northern and southern sides of the ancestral Tian Shan during Early Cretaceous time, as discussed above.

## Influence of Sampling Scale and Plate-Tectonic Setting

Observed correlations between sand/sandstone composition and platetectonic setting have led to the establishment of petrological models for provenance interpretation (e.g., Dickinson and Suczek 1979; Dickinson 1985, 1988). Ingersoll et al. (1993), however, concluded that petrofacies models linking plate-tectonic setting and sandstone composition are dependent on the scale at which source rocks are sampled by drainage systems that produce the sandstones (e.g., Critelli et al. 1997). Plate-tectonic petrofacies models (e.g., Dickinson and Suczek 1979) apply best to sand or sandstone from large rivers or marine systems (third-order drainage systems of Ingersoll 1990), whereas samples from small tributaries and rivers draining mountain ranges (first-order and second-order, respectively) may produce ambiguous or incorrect plate-tectonic interpretations. The study suite was collected from strata deposited on alluvial fans, in braided and meandering rivers, and in lakes (Hendrix et al. 1992; Hendrix et al. 1995) and likely representing mostly local drainages and drainages that integrated only limited portions of the ancestral Tian Shan. Mesozoic strata deposited in marine environments are not present in the study area, and deposition by large streams draining the entire Tian Shan (third-order drainages) are unlikely, given the coarseness of sediment and their proximal character (Hendrix et al 1992). In order to test the hypothesis that the effect of sampling scale on sandstone composition outweighs that of plate-tectonic setting for sandstones from first-order and second-order drainages, the relationships between actual sandstone composition and that predicted from plate-tectonic petrofacies models (Dickinson and Suczek 1979) are explored below.

Mesozoic basins of western China were perhaps most analogous to the broken foreland basins of the Cordilleran Laramide Orogeny (e.g., Dickinson and Snyder 1978) or the modern Sierras Pampeanas of Argentina (e.g., Jordan et al. 1983). Mesozoic basins of western China were situated in a retroarc position relative to active arcs on the south Asian continental margin (Dietrich et al. 1983; Zhang et al. 1984; Watson et al. 1987), and contractile deformation of Mesozoic age (e.g., Li and Jiang 1987; Zhang et al. 1993; Hendrix et al. 1996) suggests that these basins were a product of load-induced subsidence along basin flanks.

Despite structural similarities to modern broken foreland basins, the composition of Mesozoic sandstone is dissimilar to that reported from other modern and ancient broken foreland basins. Sandstone from broken foreland basins of North America (Dickinson and Suczek 1979; Dickinson et al. 1986; Ingersoll 1990) is mostly quartzofeldspathic, because of erosion of granitic basement-cored uplifts, and plots in the ‘‘continental block’’ provenance field of Dickinson and Suczek (1979). Few Mesozoic samples from western China are quartzofeldspathic. Rather, samples from the Junggar and Turpan basins are lithic-rich and plot in the magmatic-arc and recycled-orogen provenance fields on Qm–F–Lt ternary diagrams (Fig. 2). Samples from the Junggar and Turpan basin plot in the magmatic-arc provenance field on a Qp–Lvm–Lsm ternary diagram. Samples from the Tarim basin are also lithic-rich and plot mostly in the recycled-orogen provenance field of Dickinson and Suczek (1979). Tarim samples plot mainly in the recycled-orogen provenance field on a Qp–Lvm–Lsm ternary diagram, although many samples also fall in the magmatic-arc field.

In this study, sandstone compositions reflect the diversity of basement rocks in the ancestral Tian Shan and the localized source-rock signatures produced by first-order and second-order drainages, rather than the Mesozoic plate-tectonic setting. For example, the magmatic-arc signature of samples from the Junggar and Turpan basins (Fig. 2) resulted from erosion of the extinct Devonian–Carboniferous arc system in the northern Tian Shan. Similarly, temporal changes in the composition of Mesozoic sandstone (e.g., alternation between magmatic-arc and recycled-orogen signatures for the Junggar and Tarim basins; Hendrix 1992) probably do not signify major changes in plate-tectonic setting of the study area because there exists no evidence for such tectonic changes. Rather, these changes likely resulted from variations in the supply of detritus from specific source rocks to each basin.

Other compositional studies support the conclusion that plate-tectonic petrofacies models do not adequately predict the composition of sand/sandstone from locally drained heterogeneous accreted terranes because the local sampling scale provides insufficient homogenization and stabilization of source-rock detritus. These include analysis of Cretaceous sandstone from a strike-slip basin in Alaska (Trop and Ridgway 1997), Cenozoic and modern sand/sandstone from southern California (Link 1982; Critelli et al. 1997; Rumelhart and Ingersoll 1997) and studies of modern sands from basins of western China (Graham et al. 1993).

## Influence of Episodic Mesozoic Deformation in the Tian Shan

Sandstone samples collected from coarse clastic strata at Manas and Kuqa show compositional shifts consistent with episodes of Mesozoic deformation in the Tian Shan (Hendrix et al. 1992). For example, Triassic sandstone from Kuqa is rich in metamorphic Qp and chert and poor in F and Lvm (Appendix 1). Samples from overlying Lower and Middle Jurassic strata contain notably less Qp and markedly more F and Lvm (Fig. 5; Appendix 1). These trends are best explained by a change from local Triassic drainage systems that tapped high-grade metamorphic rocks and Silurian chert sequences to better integrated Early and Middle Jurassic drainage systems that included Paleozoic volcanic rocks and lower Paleozoic passive-continental-margin strata (Fig. 6). The sedimentary style and inferred paleoenvironments for Triassic through Middle Jurassic strata support these interpretations. Triassic strata consist of coarse-grained alluvial and braided-fluvial rocks deposited by high-gradient streams in presumably localized catchment basins. Lower and Middle Jurassic strata consist of coal-bearing meandering-fluvial and lacustrine deposits that record lower stream gradients and more fully developed, integrated drainage systems (Fig. 6).

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| FIG. 7.—Plots of intergranular volume (% pore space 1 % cement) vs. inferred maximum burial depth for samples from the southern Junggar basin depocenter (Manas) and the northern Tarim basin depocenter (Kuqa). Maximum burial depth estimates are derived from Hendrix (1992). Best-reservoir limit refers to the likely maximum realizable porosity at a given depth, exclusive of secondary porosity. |

Compositional trends associated with uppermost Jurassic and Upper Cretaceous coarse alluvial strata at Kuqa and Manas also are consistent with the interpretation of Mesozoic deformation in the Tian Shan. At Manas, uppermost Jurassic sandstone is markedly enriched in Ls, relative to Lvdominated sandstone stratigraphically above and below (Fig. 4; Appendix 1 1). Upper Cretaceous strata in each section also is more Ls-rich than strata immediately downsection (Figs. 4, 5; Appendix 1). The Ls-rich character of these coarse, alluvial and braided-fluvial deposits probably resulted from cannibalization of thick, fine-grained sedimentary strata immediately downsection (Figs. 4, 5). This interpretation is supported by the presence of an angular unconformity in uppermost Jurassic strata in the southern Turpan basin and unpublished seismic reflection profiles from the Turpan that show uppermost Jurassic strata to be regionally folded and overlain by relatively undeformed Lower Cretaceous strata (T. Greene, written communication, 1997).

Considerable independent evidence suggests that the Tian Shan underwent multiple episodes of deformation during Mesozoic time. Direct structural evidence of Mesozoic deformation in basins of western China has been reported by Li and Jiang (1987), Zhang et al. (1993), and Hendrix et al. (1996). Hendrix et al. (1992) documented synorogenic, coarse-grained alluvial and braided-fluvial deposits from the Junggar and Tarim basin during Late Triassic, latest Jurassic, and Late Cretaceous time and interpreted them to have resulted from deformation associated with the accretion of tectonic terranes onto the south Asian continental margin. The timing of coarse clastic deposition and coeval shifts toward lithic compositions reported here is similar to the timing of Mesozoic structural deformation reported for the Tian Shan and surrounding parts of central Asia during Late Triassic (Hendrix et al. 1996), latest Jurassic (Zheng et al. 1991; Zheng et al. 1996; Zheng et al., pers. comm. 2000; Zou et al. 1992; Davis et al. 1998a; Davis et al. 1998b; Zhu 1997) and Late Cretaceous time (Searle et al. 1987).

## Relationships among Sandstone Composition, Burial Depth, and Reduction of Intergranular Volume

Mesozoic sandstones are important reservoirs for petroleum in the northern Tarim, southern Junggar, and Turpan basin (Huang et al. 1991; Kang et al. 1992; Zhang et al. 1993; Gu 1994). Hence, the relationships among porosity, burial depth, and sandstone composition are of practical interest to petroleum explorationists and developers. In this area, latestage calcite cement associated with weathering occludes original intergranular pore space, so inferred minimum values for porosity were determined through calculations of ‘‘intergranular volume’’, following the methods of Houseknecht (1987). Intergranular volume is the sum of the areal percentages of remnant porosity and cement, as determined from point-count data.

The total percentage of intergranular volume is moderate for samples from all three basins. The average value for all Tarim samples is 11.1% (*n* 5 60; s5 4.7%), for Junggar samples is 11.8% (*n* 5 64; s5 5.1%), and for Turpan samples is 15.2% (*n* 5 19; s 5 7.0%). These results are somewhat lower than published direct porosity measurements for Mesozoic sandstone from the southeastern Junggar basin (Tang et al. 1997b) and the Manas area (Hu et al. 1990), almost certainly because secondary porosity is not included in the calculation of intergranular volume. In addition, porosity destruction related to compaction likely was greater in samples collected at Manas and Kuqa because of thick overburden associated with each basin depocenter. Indeed, the larger average intergranular volume for Turpan samples is consistent with thinner Mesozoic and Cenozoic sequences in that basin (Hendrix et al. 1992).

Maximum burial depths are estimated to be accurate to within 1–2 km and were derived from GENEXt burial/uplift modeling software (IFP 1996), which incorporates stratigraphic thickness, organic maturity, and apatite fission-track data for these sections (Hendrix 1992). A negative correlation exists between intergranular volume and maximum burial depth for each depocenter section (Fig. 7), suggesting that compaction was the principal means by which porosity was lost. Upper Triassic and uppermost Jurassic sandstone samples from the Manas section deviate from the overall trend, however, containing less intergranular porosity than expected (Fig. 7). These anomalously low intergranular volumes are interpreted to be a direct result of the lithic-rich composition of these sandstones (Fig. 4; Appendix 1) and the susceptibility of lithic grains to deform under compaction, relative to more quartzofeldspathic samples at comparable burial depths.

# CONCLUSIONS

1. Broad differences in Mesozoic sandstone compositions between the northern Tarim and southern Junggar basins strongly suggest that the two basins were physiographically separated throughout Mesozoic time by an ancestral version of the Tian Shan. Sandstone from the northern Tarim basin is quartzolithic and contains high percentages of Qp, Lm, and Ls. Tarim sandstone was derived from diverse Precambrian and Paleozoic metamorphic complexes, deformed lower Paleozoic radiolarian-chert sequences, upper Paleozoic alkali granite, and volcanic-arc rocks that cropped out on the southern flanks of the Mesozoic Tian Shan. In contrast, sandstone from the southern Junggar and Turpan basins is dominated by volcaniclastic detritus, reflecting the erosion of Devonian through Carboniferous arc volcanics that cropped out on the northern flank of the ancestral Tian Shan.
2. Mesozoic paleoclimate was not a dominant influence in shaping framework-grain compositions of the study suite, and overall trends in framework-grain compositions predicted from facies distributions and the likely degree of chemical weathering associated with specific paleoenvironments were not observed. Neither the signature of a megamonsoonal climate, interpreted for central Asia during the early Mesozoic, nor the signature of an Early Cretaceous rain shadow in the northern Tarim basin (Hendrix et al. 1992) were distinguishable in sandstone compositional data.
3. Application of petrofacies models linking plate-tectonic setting and sandstone composition do not directly apply to the sample suite because most samples were deposited by local tributaries and drainages tapping parts of the ancestral Tian Shan; in contrast, petrofacies models were developed using samples from large rivers and marine environments representing more integrated drainage systems. Mesozoic basins of western China were probably most analogous to broken foreland basins, but sandstone compositions are lithic-rich and reflect diverse source rocks in accreted terranes of the ancestral Tian Shan, rather than derivation from granitic basement, as in modern and Tertiary broken foreland settings.
4. A signature of episodic Mesozoic deformation of the ancestral Tian Shan is preserved in Mesozoic sandstone compositions. Upper Triassic, uppermost Jurassic, and Upper Cretaceous sandstone collected from coarse, synorogenic alluvial and braided-fluvial strata is particularly lithic-rich because of the establishment of local drainage systems that tapped specific source terranes and the short residence times for sand in the evolving ancestral Tian Shan orogen. Abundant Ls in coarse uppermost Jurassic and Upper Cretaceous strata likely reflects cannibalization of fine-grained sedimentary strata immediately downsection.
5. Calculations of intergranular volume (% pore space 1 % cement) indicate that sandstones from the Junggar and Tarim basins could be good petroleum reservoirs, provided that burial has not been excessive. Intergranular volume decreases predictably with burial depth for basin depocenter sections, except for very lithic-rich samples in the Junggar basin, which have anomalously low values of intergranular volume because of porosity occlusion by deformed lithic grains.

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The two appendices cited in this paper have been archived, and are available in digital form, at the World Data Center–A for Marine Geology and Geophysics, NOAA/NGDC, 325 Broadway, Boulder, CO 80303, U.S.A.; telephone 303-4976339; fax 303-497-6513; e-mail: wdcamgg@ngdc.noaa.gov; URL http:// www.ngdc.noaa.gov/mgg/sepm/jsr/

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