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Compositional trends within a clastic wedge adjacent to a fold-thrust belt: Indianola Group, central Utah, U.S.A.

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ABSTRACT

The Indianola Group, a coarse-grained clastic wedge at the western margin of the Cretaceous Cordilleran foreland basin in central Utah, was derived from the unroofing of the Sevier orogenic belt lying to the west. Compositional trends in Indianola Group conglomerates and sandstones confirm that the clastic detritus was eroded from an uplifted miogeoclinal and cratonal section of Precambrian to Jurassic age. The miogeoclinal prism consists of Precambrian to Cambrian quartzite and argillite units and middle to late Palaeozoic carbonate strata, while the Mesozoic cratonal section is dominated by sandstone. Thrusting and uplift of the section resulted in deposition of carbonate-rich detritus eroded from the Palaeozoic section in the lower part of the Indianola Group and quartzose detritus from the Precambrian and Cambrian section in the upper part. The upsection enrichment in quartz is reflected in both conglomerate-clast populations and detrital modes of sandstones. Chert grains are an important derivative of the carbonate provenance and provide durable evidence of a carbonate source even in rocks lacking detrital carbonate grains.

The combination of compositional trends and Indianola depositional patterns suggest that influxes of contrasting detritus may be tied to major ramp uplift on two thrust systems. Deposition of the initial carbonate-rich wedge occurred during ramping and uplift of the Canyon Range thrust in late Albian time. Deposition of alluvial-fan deposits in the overlying quartzose wedge resulted from uplift during ramping of the Pavant thrust. Almost all of the Indianola detritus, however, was derived from the Canyon Range plate, first during uplift above the active Canyon Range thrust and second as the plate rose passively above the younger Pavant system in late Santonian to Campanian time. Frontal structures developed during late Campanian thrusting folded the Indianola Group and terminated subsidence along the basin margin.

INTRODUCTION

The Cretaceous Indianola Group forms the proximal part of a synorogenic clastic wedge within the central Utah part of the Cordilleran foreland basin. The presence of thick sequences of conglomerate in the Indianola Group led Spieker (1946) to postulate the presence of an orogenic terrane to the west. Documented ages within the section range from late Albian to late Campanian and indicate that deposition of the Indianola Group occurred during emplacement of thrust allochthons in the Sevier orogenic belt (Armstrong, 1968a). An upsection decrease in the relative abundance of limestone cobbles in Indianola conglomerates of the Gunnison Plateau (Spieker, 1949) was interpreted by Armstrong (1968a) to represent an unroofing sequence created as upper Palaeozoic carbonate clasts were initially stripped from uplifted thrust plates before lower Palaeozoic and upper Precambrian quartzites could be eroded. Similar inverted stratigraphies have been reported from the northern Utah–Wyoming–Idaho thrust belt (Armstrong & Oriel, 1965; Royse, Warner & Reese, 1975) and the Alberta foreland basin (Price & Mountjoy, 1970).

This paper presents compositional data from Indianola conglomerates and sandstones which document a secular trend in detrital modes within the stratigraphic section. The compositional trend is interpreted to have resulted from the unroofing of a single thrust plate in two episodes. The first period of erosion occurred as the thrust plate initially ramped upward from deeper structural levels, while the second episode occurred when the allochthon rose during ramping of a younger, structurally deeper thrust.

Geological setting

Indianola Group rocks crop out in a region which lies immediately east of ramp-style thrust faults but west of undeformed strata within the foreland basin (Fig. 1). Outcrops generally have homoclinal moderate to steep dips both to the east and west, although most major panels dip east. This deformation resulted from uplift of the section over the easternmost interpreted thrust ramp immediately west of the Gunnison Plateau, as well as from folding and faulting above a triangle zone west of the line indicating easternmost thrust deformation in Fig. 1 (Lawton, 1985). At the westernmost exposure of the Indianola Group, the Canyon Range thrust plate overlies a thick conglomeratic section called the Canyon Range fanglomerate by Armstrong (1968a).

Ramp-style thrust faults which lie to the west of Indianola outcrops occur in a Precambrian and Palaeozoic miogeoclinal section and a Triassic through Jurassic cratonal section. The miogeoclinal section west of the Gunnison Plateau consists of Precambrian and lower Cambrian quartzite and argillite overlain by a Cambrian to Mississippian carbonate-dominated section (Armstrong, 1968b). A thin Pennsylvanian to Permian section thickens dramatically northward within the area of Fig. 1 and in the Wasatch Mountains consists of 7925 m of

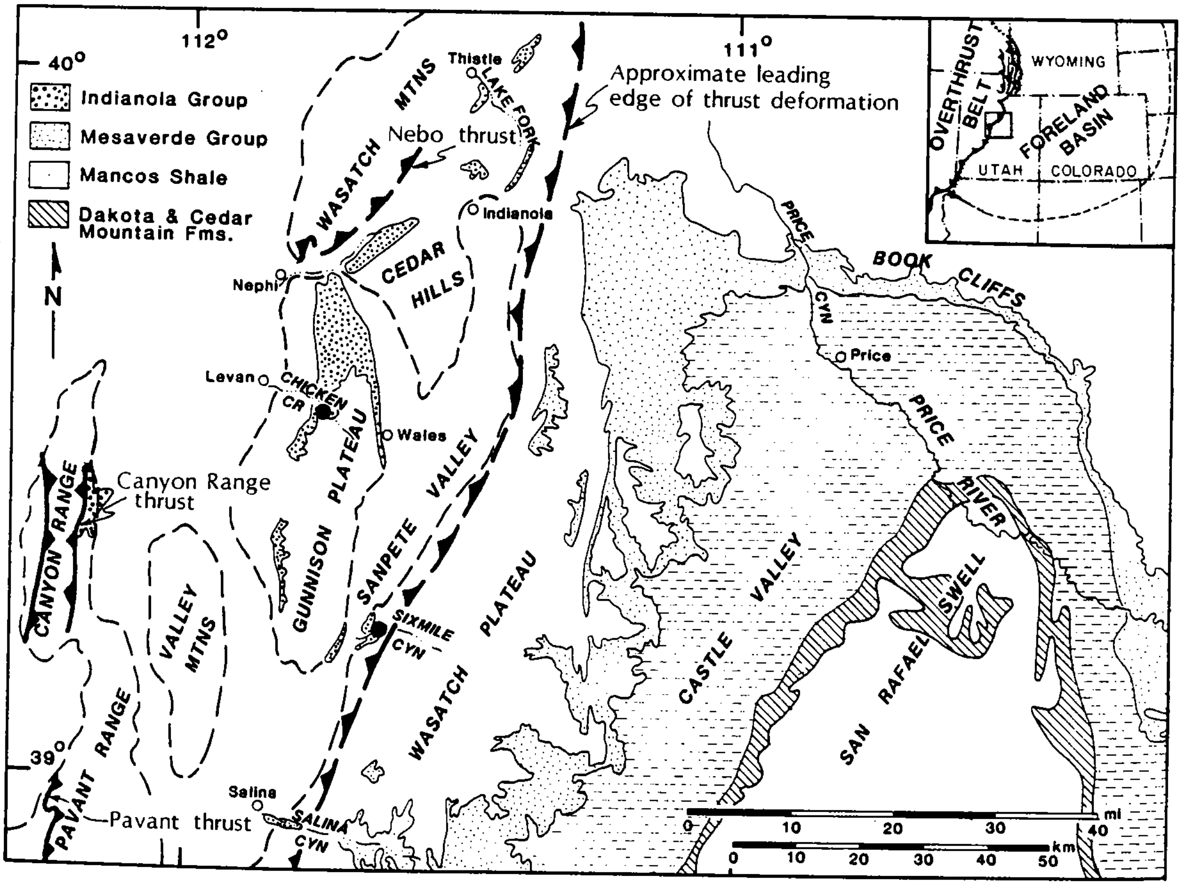

Fig. 1. Map of study area in central Utah and geographical names used in this report. Indianola outcrops occur within the Sevier orogenic belt, the eastern extent of which is indicated by the dashed line. Other units indicated, the Cedar Mountain and Dakota formations, the Mancos Shale, and the Mesaverde Group, are distal equivalents of the Indianola Group in the foreland basin. Solid dots indicate locations of sections studied for this report.

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quartzite and carbonate strata in the upper plate of the Nebo thrust (Baker, 1947). The Mesozoic section consists of sandstone, shale and subordinate limestone.

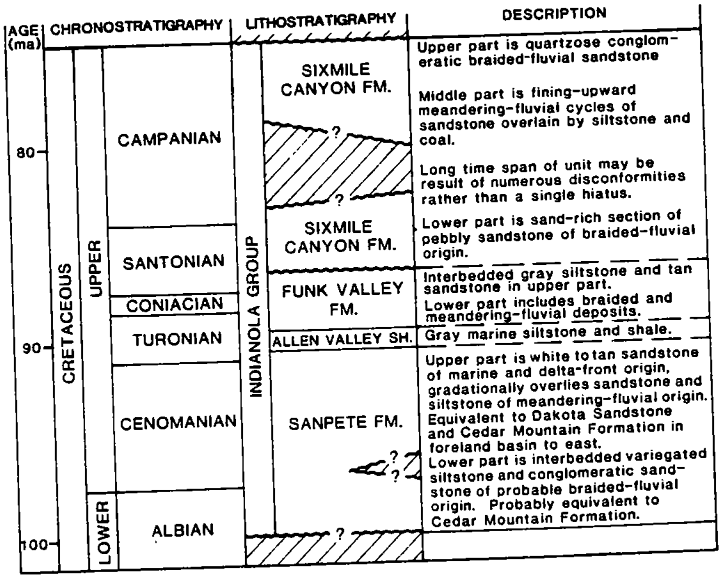
Two thrust plates, the Canyon Range and Pavant allochthons, have been identified west of the Gunnison Plateau (Burchfiel & Hickcox, 1972). The structurally higher Canyon Range thrust emplaced Precambrian quartzite and argillite on Cambrian to Devonian carbonate strata. The lower Pavant thrust emplaced the entire Palaeozoic section on strata as young as Jurassic. The Canyon Range plate has been extensively stripped away by erosion and forms a large klippe of Precambrian strata resting on the Pavant plate (Christiansen, 1952).

Indianola Group stratigraphy

Upper Cretaceous rocks which crop out in the thrust belt region of central Utah west of the Wasatch Plateau (Fig. 1) were assigned to the Indianola Group by Spieker (1946). The most complete Indianola section in the Cedar Hills is approximately 4000 m thick (Jefferson, 1982). The equivalent but thinner section within the little-deformed foreland basin to the east includes the Cedar Mountain and Dakota Formations, the Mancos Shale, and the Mesaverde Group. This distal sequence is dominated by marine shale and interbedded delta-front sandstones, but contains fluvial sandstone and siltstone in the Cedar Mountain Formation and upper part of the Mesaverde Group (Fisher, Erdman & Reeside, 1960).

The Indianola Group was divided into four formations by Spieker (1946), with lithotypes in the Sixmile Canyon area. These formations in ascending order are the Sanpete Formation, Allen Valley Shale, Funk Valley Formation, and Sixmile Canyon Formation (Fig. 2). The lower three units were provisionally recognized in other parts of the Wasatch Plateau by Spieker (1946). Correlation of formations within the Indianola Group in the Gunnison Plateau and Cedar Hills using new fossil data and physical stratigraphy has subsequently confirmed Spieker's stratigraphy (Jefferson, 1982; Lawton, 1982).

Deposition of the Indianola Group ranged from late Albian to late Campanian (Fig. 2). Fluvial rocks near the base of the unit are difficult to date, but palynomorphs collected 600 m above the base of the Indianola Group on the Gunnison Plateau are late Albian (Aspen Shale equivalent) in age (Standlee, 1982). Cenomanian fission-track ages (96·2 ± 5·0 Ma; 90·6 ± 4·8 Ma; 90·3 ± 4·8 Ma; Willis, 1986) on zircon grains have been acquired from claystone beds in a conglomeratic section overlying known Middle Jurassic (Callovian) strata in Salina Canyon. These dates appear to corroborate the palynomorph data. The marine upper part of the Sanpete Formation, the Allen Valley Shale and the Funk Valley Formation



Upper part is quartzose conglomeratic braided-fluvial sandstone

Middle part is fining-upward meandering-fluvial cycles of sandstone overlain by siltstone and coal.

Long time span of unit may be result of numerous disconformities rather than a single hiatus.

Lower part is sand-rich section of pebbly sandstone of braided-fluvial origin.

Interbedded gray siltstone and tan sandstone in upper part.

Lower part includes braided and meandering-fluvial deposits.

Gray marine siltstone and shale.

Upper part is white to tan sandstone of marine and delta-front origin, gradationally overlies sandstone and siltstone of meandering-fluvial origin. Equivalent to Dakota Sandstone and Cedar Mountain Formation in foreland basin to east.

Lower part is interbedded variegated siltstone and conglomeratic sandstone of probable braided-fluvial origin. Probably equivalent to Cedar Mountain Formation.

Fig. 2. Stratigraphy and age of the Indianola Group.

are well dated by marine fossils (Fouch *et al.*, 1983). Palynomorphs collected from the upper part of the fluvial Sixmile Canyon Formation have yielded a late Campanian age (Fouch *et al.*, 1983).

The recent age determinations from fluvial rocks of probable Indianola affinity but very low in the section have raised a nomenclature problem. These ages indicate the presence of approximately a 60 Myr disconformable hiatus between Middle Jurassic strata and Cretaceous strata. However, Spieker (1946) tentatively assigned these Albian to Cenomanian beds to the Morrison(?) Formation of Late Jurassic age based on stratigraphic position and lithologic similarity to Morrison beds elsewhere. These beds have been more recently called Cedar Mountain Formation after the time-equivalent unit on the Colorado Plateau (Standlee, 1982; Lawton & Willis, 1986), but this practice mixes nomenclature from the thrust belt and foreland basin. In this paper, I provisionally include the Albian strata in the Sanpete Formation pending further studies and consider them to represent the initial molasse deposit of the foreland basin.

Depositional trends

The Indianola Group generally comprises an upward-coarsening megasequence at all localities where significant sections are exposed. The trend appears to have resulted from an interaction of eustatic and tectonic factors which affected the western margin of the foreland basin. The following overview of Indianola depositional environments summarizes more complete descriptions and interpretations from previously published work (Lawton, 1982).

The lower half of the Indianola section, encompassing the Sanpete Formation, Allen Valley Shale and Funk Valley Formation, consists of interfingering deposits of non-marine and marine origin. The lower part of the Sanpete Formation is characterized by a 2300 m thick section of conglomeratic sandstone and conglomerate beds 5–25 m thick, interbedded with thick variegated shale and siltstone beds. The cross-bedded conglomerate and sandstone beds are composed of individual and stacked channelform units. Each channel unit fines upward and is truncated by the overlying channel or grades to siltstone. At localities in the Wasatch Plateau these channelform beds of fluvial origin decrease in average grain size upsection. In addition, shale content of the section increases. Coal is present in some shale sequences and oyster-bearing lenticular beds of burrowed sandstone underlie fossiliferous upward-coarsening shoreface sequences at the top of the Sanpete Formation. The overlying Allen Valley shale consists of 150–200 m of grey thin-bedded siltstone, mudstone and sandstone. These prodelta or marine-shelf deposits represent a maximum transgression of marine conditions in mid-Turonian time.

The thickness and environmental diversity of the Sanpete Formation varies considerably along strike. In the northern part of Fig. 1 along Lake Fork and in the Cedar Hills, the Sanpete Formation consists of fluvial conglomerate and sandstone overlain by a few metres of transgressive marine sandstone, in contrast to the thick deltaic and marginal marine deposits described above and found in Salina and Sixmile Canyons. This variability is interpreted to be a result of valley backfilling during transgression. Weimer (1984) has described similar fluvial and deltaic rocks of late Albian age deposited in river valleys that were backfilled as transgression proceeded. Although located 500 km to the NE in the foreland basin, the valley-fill deposits described by Weimer appear to match the sequence of the lower part of the Indianola section, which was deposited at the culmination of the same transgression. Thus, although the Indianola sediments were deposited within 80 km of the thrust front, sea-level change appears to have had a strong effect on patterns of deposition.

The overlying Funk Valley Formation is characterized by a lower 350 m sequence of sandstone and siltstone deposited in shoreface, delta-plain, and fluvial environments and an upper 600 m marine sequence of prograding shoreface deposits. In northern locations, cobble conglomerates were deposited above strata of possible lagoonal origin in the lower part of the Sanpete Formation suggesting the possibility of fan-delta development east of the thrust front.

The upper half of the Indianola section in Sixmile Canyon, included in the Sixmile Canyon Formation, is composed of 1350 m of sandstone, pebbly sandstone, and conglomerate deposited in meandering-fluvial and braided-fluvial environments. In more western outcrops, strata equivalent to the Sixmile Canyon Formation are composed of cobble and boulder conglomerates deposited in an alluvial-fan environment. The Sixmile Canyon Formation, while containing significant grain-size and environmental variability, represents an overall coarsening of grain size within the section as depositional environments proximal to the orogenic terrane migrated eastward ahead of the thrust front. Thus, orogenic processes appear to have dominated sedimentation within the upper part of the Indianola section.

PETROGRAPHY OF THE INDIANOLA GROUP

Methods

Compositional data were collected from two Indianola sections, one at Chicken Creek in the Gunnison Plateau and the other at Sixmile Canyon in the Wasatch Plateau (Fig. 1). The Chicken Creek section is dominated by conglomerate, while the Sixmile Canyon section, located farther from the major thrust plates, is dominated by sandstone. Clast data were obtained by counting all pebble and cobble-sized clasts within a delineated rectangle on conglomeratic outcrop faces and recording each lithic type, usually to yield a minimum population of 300 clasts. The data thus obtained are frequency, rather than volumetric, counts. Sandstone samples were thin sectioned, and a minimum of 400 framework grains counted for each sample on a 0·6 × 0·6 mm grid. A total count of 400 modal points ensures a two-sigma confidence range of 5% or less of the whole rock for any calculated modal percentage (Van der Plas & Tobi, 1965). Standard QtFL (Dickinson, 1970) and QmFLt (Graham, Ingersoll & Dickinson, 1976) triangular diagrams were plotted to illustrate compositional characteristics of Indianola Group sandstones. Data from both thin-section and conglomerate counts were plotted stratigraphically to determine compositional trends within the stratigraphic section.

Definition of grain types

Clast and grain types for conglomerates and sandstones were defined operationally at the outset of the study to insure counting consistency. Brief descriptions of the lithologic groupings are outlined in Table 1 for conglomerates and Table 2 for sandstones. Clast-count data and point-count results are shown in Tables 3 and 4, respectively.

Table 1. Lithic types discriminated in clast counts of Indianola Group conglomerates, and calculated conglomerate parameters plotted in Fig. 5

- (a) Clast types
  - (1) Quartzite (Qz)
    - (a) Red, pink and purple quartzite (Qzrp)
    - (b) Quartzite of other colours (Qzo)
  - (2) Carbonate (CO_3)
    - (a) Limestone (Ls)
    - (b) Dolomite (Dol)
  - (3) Chert (Ch)
  - (4) Other clastic
    - (a) Sandstone (Ss)
    - (b) Mudstone, siltstone (Ms)
  - (5) Miscellaneous
    - (a) Vein quartz
    - (b) Silicified bone and plant fragments
- (b) Calculated conglomerate parameters
  - (1) $Qz = Qzrp + Qzo$ = total percentage quartzite
  - (2) $CC = CO_3 + Ch$ = percentage (carbonate + chert)

Table 2. Sandstone grain categories used in calculating QtFL and QmFLt plots

- (1) Qt: Total framework quartz ($Qt = Qm + Qp$)
  - (a) Qm: Monocrystalline quartz
  - (b) Qp: Polycrystalline quartz
    - (1) Chert
    - (2) Polycrystalline quartz of sedimentary, igneous, metamorphic origin
    - (3) Aggregate quartz of indeterminate origin
- (2) F: Total framework feldspar ($F = K + P$)
  - (a) K: Potassium feldspar
  - (b) P: Plagioclase feldspar
- (3) L: Framework lithic fragments (for QtFL plot; $L = Ls + Lv$)
  - (a) Ls: Sedimentary lithic fragments
    - (1) Argillite—shale
    - (2) Very fine grained feldspathic sandstone
    - (3) Detrital carbonate
  - (b) Lv: Volcanic and hypabyssal lithic fragments
- (4) Lt: Total framework lithic fragments (for QmFLt plot: $Lt = L + Qp$)

Conglomerate clast types

The following clast types were distinguished during clast counts at conglomeratic outcrops:

(1) Quartzite. Quartzite clasts are compositional quartz arenites with quartz cement. Plain and banded, red, pink and purple quartzites were discriminated from white, tan and grey quartzites because the red, pink and purple clasts may be tied to a specific source lithology, the Upper Precambrian Mutual Formation presently exposed in the upper plate of the Canyon Range thrust to the west (Christie-Blick, 1982; Sprinkel & Baer, 1982).

(2) Carbonate. Carbonate clasts consist of a wide range of colours and textures. They are most commonly grey and tan, and range from micritic limestone to coarse saccharoidal dolomite. Limestone and dolomite were discriminated during counts using a stain prepared with alizarin red-S solution (Dickson, 1966). The carbonate category includes clasts partly replaced by chert (Fig. 3).

Table 3. Conglomerate clast data, Chicken Creek, Gunnison Plateau, with counts listed in stratigraphic order above the base of the Indianola Group shown in Fig. 5. Clast size is listed in centimetres for maximum and average long-axis measurements. Clast type fractions are listed as percentages of the total count (*n*). Grain parameters are as listed in Table 1

Interval	Clast size (cm)		Quartzite		Carbonate		Chert	Other clastic		Misc	*n*
(m)	Max	Average	Qzrp	Qzo	Ls	Dol		Ss	Ms		
2220	40	3·0–4·0	12·1	79·6	0	0	1·5	6·8	0	0	264
2010	15	1·5–2·0	8·6	70·7	0	0	7·7	11·9	0·8	0·3	362
1775	30	4·0–6·0	10·6	72·1	0	0	5·0	10·6	1·8	0	283
1655	100	2·5–4·0	12·3	72·2	0	0	1·4	11·6	2·5	0	277
1595	15	2·0–3·0	5·2	37·2	33·6	3·3	8·8	10·0	1·8	0	330
1380	10	1·0	12·6	43·5	21·4	12·2	0·7	2·2	7·4	0	271
1380	10	1·5–2·0	9·5	53·1	18·7	8·2	3·9	6·2	0·3	0	305
1320	5	1·0	0	5·4	0·5	89·7	0·9	3·6	0	0	223
1275	10	1·5–3·0	4·7	20·4	60·4	10·2	1·8	1·8	0·7	0	275
1080	10	0·8–1·0	0·3	19·9	43·4	8·3	16·2	1·8	10·1	0	327
1005	26	8·0	5·1	66·7	0	1·1	3·7	11·4	11·7	0·3	351
730	45	5·0	1·7	16·4	32·8	45·6	2·6	0·6	0·3	0	353
610	60	5·0	1·2	7·6	23·9	62·4	2·3	1·8	0·6	0·3	343
525	60	2·5–4·0	1·7	5·4	18·6	72·3	1·0	1·0	0	0	296
370	27	n.d.	3·9	18·9	12·8	60·2	0·9	1·6	1·6	0	312
315	12	n.d.	4·8	3·3	2·7	86·9	2·1	0·3	0	0	335
180	15	n.d.	3·0	51·2	35·6	2·6	1·7	5·6	0	0·3	303
120	n.d.	n.d.	2·4	37·3	39·7	15·5	2·1	0·9	0	2·1	330
75	25	n.d.	0·3	41·3	41·7	9·7	1·3	1·3	0	4·3	300

Table 4. Mean modal compositions of Indianola Group sandstones. Numbers in parentheses are standard deviations

Unit	*n*	Qt	F	L	Qm	Lt	K	P	Qp	Ls	Lv	Detrital Co_3
Indianola Group Undifferentiated	8	74·7 (19·4)	0·3 (0·3)	25·0 (19·6)	71·5 (19·8)	28·2 (20·0)	0·3 (0·3)	0·1 (0·1)	3·2 (1·5)	25·0 (19·6)	0	20·7 (22·9)
Sanpete Formation	5	77·1 (10·3)	2·8 (1·6)	20·2 (11·8)	75·5 (9·2)	21·7 (10·7)	2·7 (1·5)	0·1 (0·2)	1·5 (1·4)	20·1 (11·8)	0	17·4 (11·5)
Funk Valley Formation	10	71·3 (8·4)	3·4 (3·7)	25·3 (11·1)	69·0 (8·7)	27·6 (10·3)	3·4 (3·7)	0	2·3 (2·0)	25·2 (11·1)	0	24·7 (11·5)
Sixmile Canyon Formation	9	84·9 (15·7)	0·1 (0·2)	15·0 (15·6)	80·3 (14·2)	19·6 (14·1)	0·1 (0·2)	0	4·6 (4·7)	15·0 (15·6)	0	13·9 (16·5)

(3) Chert. This category includes cryptocrystalline siliceous pebbles that are tan, grey, white, red, and rarely, black. The chert occasionally contains thin laminations or silicified invertebrate fossils, indicating an origin by replacement of limestone or dolomite rather than deep-basin deposition.

(4) Other clastic. The clastic category includes a wide range of detrital rock types including red to tan feldspathic and sublitharenitic sandstone and white, brown, and grey mudstone and siltstone.

Miscellaneous categories include white vein or bull quartz, silicified wood fragments, and bone material.

Sandstone grain types

Grain parameters discriminated in point counts are summarized in Table 2. Lithic grain types are in general defined following the descriptions of Graham *et al.* (1976). However, there are some differences in the classification used here; hence, a brief description of the dominant grain types follows:

(1) Argillite-shale: murky, fine-grained siliceous or argillaceous fragments, many containing silt-sized quartz and feldspar grains.

(2) Chert: microcrystalline aggregates of equant silica grains, with most domains less than 0·03 mm.

(3) Detrital carbonate: limeclasts of variable texture, ranging from micrite through mosaic microspar and pseudospar to coarse-grained or monocrystalline spar.

(4) Volcanic-hypabyssal: fine-grained felsitic fragments with aphanitic to microporphyritic or mosaic textures and rare microlitic and flow-banded siliceous grains.

(5) Aggregate quartz: fine-grained polycrystalline

Fig. 3. Laminated dolomite clast partly replaced by chert, Indianola Group, Chicken Creek. Marks on staff are 10 cm long.

quartz, including chalcedony, probably chiefly of vein origin.

(6) Feldspathic sandstone: detrital quartzofeldspathic aggregates of silt to very fine sand grains.

Discrimination of the above lithic types is sometimes difficult and in some rocks occasionally subjective. Extraformational argillite grains cannot always be discriminated texturally from intraformational mudstone clasts, which rarely exceed 1% in the samples counted and must be recognized by their anomalously large grain sizes. Fine-grained argillites and chert compose end members of a range of siliceous mudstones with variable amounts of included argillaceous and opaque material. Most, if not all, chert originated by diagenetic replacement of limestone and dolomite prior to erosion of the clastic grains. The replacement of micrite frequently resulted in the inclusion in impure chert grains of very fine detrital material, including occasional silt grains, generally quartz but rarely feldspar, and aphanitic material that imparts a dark grey smoky texture to the chert. Moreover, silicified invertebrate fossils are common in chert grains. In general, grains containing more than 10% argillaceous or opaque inclusions were counted as argillite, although pebbles of the same material in conglomerates would undoubtedly be counted as chert. In general, high confidence is attributed to the relative proportions of the major grain types, (Qm, Qp, F, Ls, and Lv) the subcategories of which are listed in Table 2. The potentially greatest source of inconsistency rests in the discrimination of chert and argillite, which may affect the relative proportions of Qp and Ls, respectively.

Detrital mineralogy of Indianola Group

Indianola sandstones are compositional litharenites, sublitharenites, and quartz arenites, using the classification system and nomenclature proposed by McBride (1963). QtFL and QmFLt compositions are plotted in Fig. 4. The dominant lithic grain type in Indianola sandstones is detrital carbonate, which ranges in abundance from 0 to 52%, with a mean of 19·5% (Table 4). Argillite-shale grains are next in abundance, ranging from 0 to 16%, with a mean of 2·5%. Chert grains range from 0 to 13%, with a mean of 2%.

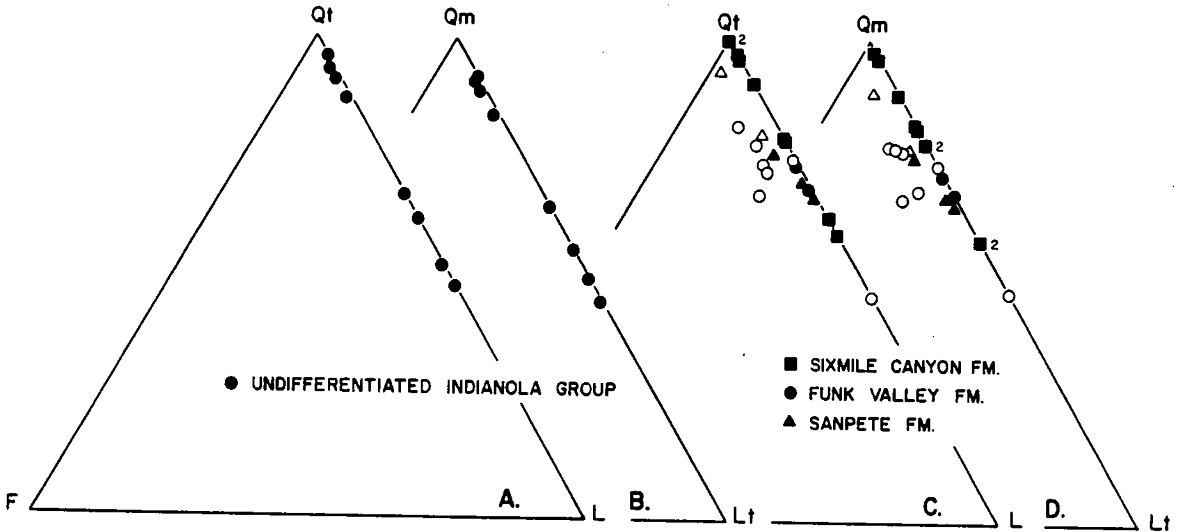


Fig. 4. QtFL and QmFLt plots for Indianola Group sandstones from Chicken Creek (triangles A, B) and Sixmile Canyon (triangles C, D). Open symbols indicate samples from marine facies. Numerals adjacent to symbols indicate multiple coincident observations.

Diagenetic effects

The major diagenetic effect noted in Indianola sandstones is development of sparry calcite cement and the recrystallization of detrital carbonate grains to form coarse mosaic spar. Consequently, detrital carbonate grains often occur as relicts, recognizable by the presence of impurities in tracts of sparry calcite. In sandstone samples that do not contain detrital carbonate grains, calcite cement is not present. The observed relationships suggest that calcite cement in the Indianola sandstones was formed in part from dissolution of detrital carbonate grains. In addition, sandstones of the Indianola section at Chicken Creek contain an average of 5·4% less total carbonate (cement plus grains) than the conglomerates, suggesting that loss of carbonate occurs during grain-size reduction and diagenesis. Thin rims of haematite cement often occur on detrital carbonate grains, but are poorly developed to absent on siliciclastic grains.

Compositional trends

For comparison of conglomerate and sandstone compositional trends through the Indianola section, frequency data are plotted with respect to stratigraphic position at both Chicken Creek (Fig. 5) and Sixmile Canyon (Fig. 6). Parameters plotted for conglomerates include pink and purple quartzite (Qzrp), total quartzite (Qz), and carbonate plus chert (CC). Sandstone grain parameters plotted are Qm (in place of Qz), carbonate plus chert (CC), and total feldspar (F) at Sixmile Canyon only. The textural evidence in both conglomerate clasts and sandstone grains for formation of chert through carbonate silicification indicates that a single compositional parameter of combined chert and carbonate should be a sensitive indicator of the Palaeozoic carbonate sequence in the thrust terrane. The combined parameter has the additional advantage in the sandstone analyses of recording the presence of mechanically and chemically durable chert grains even when carbonate grains were lost through transport and dissolution. Thus, the carbonate provenance may be interpreted even in the absence of detrital carbonate grains.

Least squares curves fitted to the data indicate important compositional trends in both conglomerates and sandstones for several parameters:

(1) Quartzite (Qz) and monocrystalline quartz (Qm). The monocrystalline quartz and quartzite content clearly increases upsection in both the Chicken Creek and Sixmile Canyon sections. A dramatic increase in quartz content occurs at the top of the Chicken Creek section in the proximal alluvial-fan deposits.

(2) Pink and purple quartzite (Qzrp). Banded quartzite clasts derived from the Precambrian Mutual Formation increase in frequency upsection. A small popula-

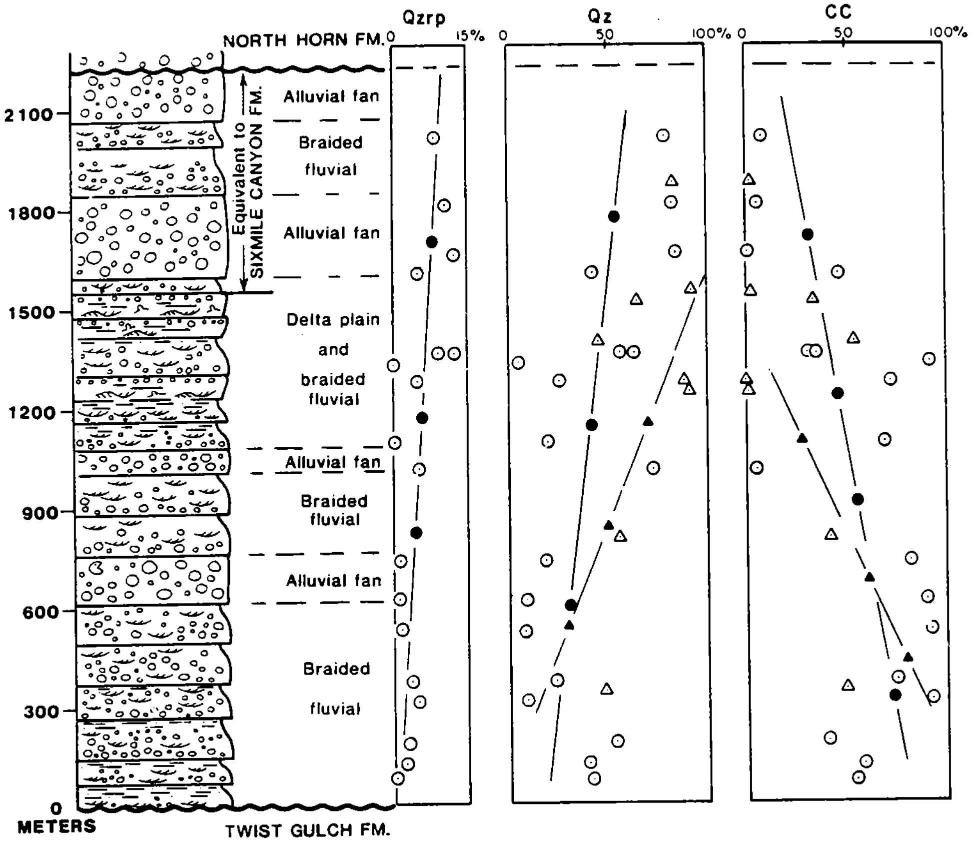


Fig. 5. Stratigraphic compositional trends for the Indianola Group at Chicken Creek, Gunnison Plateau, Utah. Column headings refer to clast and grain types described in Tables 1 and 2, with Qm substituting for Qz in sandstone samples. Key to symbols: circles, conglomerate clast data; triangles, sandstone modal data. Solid symbols indicate best-fit curves for each data category.

tion of distinctive red and purple quartzite clasts is present in the stratigraphically lowest conglomerate beds.

(3) Carbonate and chert (CC). Clast and grain types derived from carbonate source rocks decrease in frequency upsection. A rapid decrease in the percentage of carbonate and chert clasts occurs at metre 1325 of the Chicken Creek section (Fig. 5), coincident with the base of boulder and cobble conglomerates equivalent to the Sixmile Canyon Foundation in Sixmile Canyon.

(4) Feldspar (F). The total feldspar frequency in the Sixmile Canyon section does not display a characteristic stratigraphic trend. Measurable feldspar percentages are restricted to marine units of the Sanpete and Funk Valley Formations. The marine sandstones tend to be very fine grained, while associated non-marine sandstones range from fine grained to coarse-grained (Lawton, 1982).

DISCUSSION

Interpretation of compositional data

The compositional data from Indianola sandstones and conglomerates provide insight into the structural evolution and palaeogeography of the thrust belt. Sandstone modal plots and clast compositions simply corroborate the assumption that the thrust belt served as a source of Indianola clastic debris. Indianola sandstones plot within the field for recycled orogenic provinces (Dickinson & Suczek, 1979) on the QtFL and QmFLt triangular plots of Fig. 4. The almost exclusive presence of sedimentary lithic grains indicates that the detritus was derived from the thrusted sedimentary strata of the Sevier orogenic belt. This observation is further substantiated by the presence of only sedimentary lithic clasts in Indianola conglomerates.

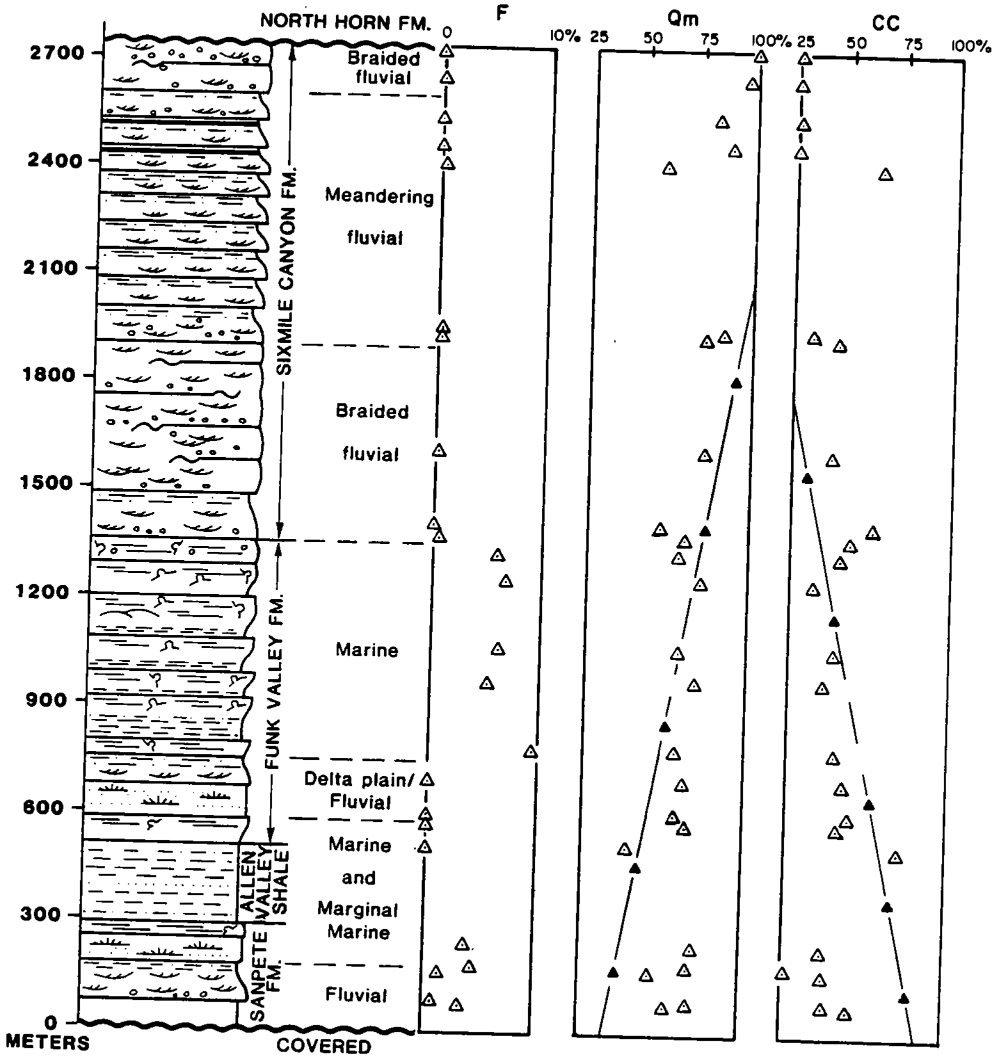


Fig. 6. Stratigraphic compositional trends for sandstones of the Indianola Group at Sixmile Canyon, Wasatch Plateau, central Utah. Column headings refer to grain types described in Table 2. Triangles represent sandstone modal data. Solid symbols indicate best-fit curves for data.

However, the stratigraphic compositional trends of Figs 5 and 6 permit more detailed interpretation of the nature of the source terrane than do the standard compositional plots. Several aspects of the trends pertain to detailed structural development within the thrust belt. Stratigraphic plots for both sandstones and conglomerates indicate a secular evolution from carbonate-rich compositions to quartzose compositions. Thus, the Indianola section does contain a simple record of unroofing of the miogeoclinal sequence to the west as suggested by Armstrong (1968a). Moreover, although significant scatter exists in the stratigraphic plots, it appears that the carbonate to quartzite cycle occurs only once in the Gunnison Plateau area. Thus, apparently only one miogeoclinal section was stripped by erosion, indicating that the section was not repeated several times by numerous thrust faults. The mapped relations of the Pavant and Canyon Ranges (Christiansen, 1952; Burchfiel & Hickcox, 1972) support this interpretation. The Canyon Range plate, eroded to Precambrian rocks, rests on the Pavant plate which carries an uneroded section ranging in age from presumed Precambrian to Jurassic.

Although an inverted clast stratigraphy is present in Indianola conglomerates, clasts from the Precambrian Mutual Formation (Qzrp category of Table 1) occur in the lowermost part of the section. This indicates that drainage systems in the thrust terrane had early access to strata low in the miogeoclinal section. This may have occurred by rapid downcutting of canyons transverse to what was probably a strike-dominated drainage network within the thrust belt. Alternatively, early exposure of Precambrian strata may have occurred at positions of along-strike structural relief formed by tear faults or lateral ramps. Such a feature, the Leamington Canyon Fault, exists immediately north of the Canyon Range (Sprinkel & Baer, 1982), but it is unclear if clasts shed from that area would have been deposited as far south as Chicken Creek. In either case, the early appearance of Precambrian clasts suggests that structural relief sufficient to expose Precambrian strata to erosion was developed synchronously with uplift. Because folds with several kilometres of amplitude are absent in the area, I suggest that both structural and erosional relief were developed by ramping and duplexing of the exposed thrust plates. This is probably the most common uplift mechanism associated with thrust-fault tectonics (Boyer & Elliott, 1982).

Interaction of basin-margin tectonics and basin fill

A comparison of regional stratigraphic and structural relations with the compositional data discussed earlier indicates that the structural geology of the thrust belt may be tied to depositional and compositional trends in the basin to form a unified tectonic scenario for basin development. The basin may be considered to consist of two major compositional wedges, a lower carbonate-rich wedge and an upper quartzose wedge (Fig. 7). The quartzose wedge is displaced eastwards with respect to the carbonate-rich wedge, and is overlain in turn by a smaller, more eastern clastic wedge (Price River Formation).

The lower carbonate-rich wedge encompasses the 'Canyon Range fanglomerate' of Armstrong (1968a), and the Sanpete, Allen Valley and Funk Valley

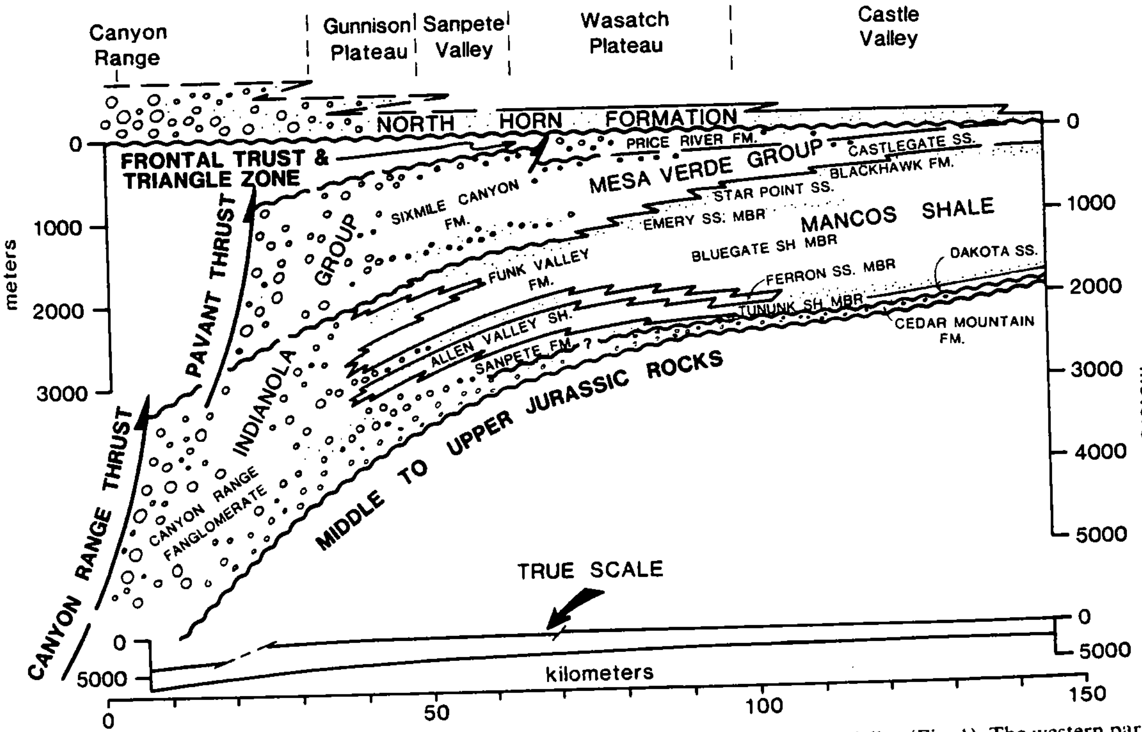


Fig. 7. Reconstructed east–west basin cross-section from the Canyon Range to the Castle Valley (Fig. 1). The western part of the foreland basin forms three offlapping wedges, each tied westward to the major thrust event which provided a source for the clastic detritus. The lowermost wedge is rich in detrital carbonate in the conglomerate and sandstone fractions. The middle wedge (indicated by light stipple) is dominated by quartzite-clast conglomerate and quartzarenite. The upper wedge (Price River Formation), not discussed in this paper, consists of litharenite and sublitharenite (Lawton, 1983).

Formations and their equivalents. The most distal deposits of the lower wedge in Utah are dominated by the Mancos Shale. Because thrust deformation and basin subsidence were only incipiently developed in the west, possibly coupled with rising sea-level beginning in late Albian time (Vail, Mitchum & Thompson, 1977), the depositional systems were strongly influenced by fluctuating shoreline conditions. The lower wedge is structurally bounded on the west by the Canyon Range thrust, from which the clastic material was derived and which ultimately overrode the basin margin. The juxtaposition of thrust plate and conglomerates suggests that the late thrust deformation occurred close to, or at, the synorogenic erosion surface.

The upper quartzose wedge encompasses the Sixmile Canyon Formation and its more proximal equivalents in the Gunnison Plateau. The upper wedge grades eastward into quartzarenites of the Castlegate Sandstone (Lawton, 1983) which extend 200 km from the thrust front before pinching out into marine siltstone (Van de Graaff, 1972). The quartzose wedge is not bounded by a thrust fault on the west in present exposures, but deposition occurred prior to thrust ramping which folded the Indianola outcrops concomitant with the development of easternmost thrust structures (Lawton, 1985). I suggest that the uplift which provided the source of the quartzose detritus was created by ramping of the Pavant thrust beneath the Canyon Range plate. The Canyon Range plate was then eroded more deeply and removed over most of the area. The appearance of large numbers of sandstone clasts (other clastic category, Table 3) contemporaneously with the flood of quartzose detritus indicates that the Mesozoic sandstone units beneath the Canyon Range thrust also contributed clastic material. The abrupt shift from pebbly braided-fluvial deposits to cobble and boulder conglomerates of alluvial-fan origin in the Chicken Creek section coincides with the base of the quartzose wedge and further documents the proximal uplift related to ramping of the Pavant thrust.

The third clastic wedge, although not discussed here, consists of the Price River Formation (Fig. 7). This clastic wedge is displaced eastward with respect to the quartzose wedge and consists of litharenites higher in sedimentary lithic fragments than the quartzose wedge. It was probably deposited during the formation of the easternmost structures of the thrust terrane (Lawton, 1985).

In the Cedar Hills, north of the sections studied for this report, the Indianola Group does not show an increased quartz content upsection (Jefferson, 1982). Instead, quartzite clasts are abundant throughout the section. This contrast with the results reported here is interpreted to reflect a difference in the stratigraphic section of the source area. As mentioned earlier, the Pennsylvanian to Permian section thickens dramatically northward and contains abundant quartzite (Baker, 1947). Detritus shed from the initial uplift would thus have been rich in upper Palaeozoic quartzite, and a trend reflecting later contributions of Precambrian quartzite would be masked. Jefferson's data do not include a separate red quartzite category to allow interpretation of possible trends in clast types derived from known Precambrian strata.

CONCLUSIONS

The Indianola Group forms a coarsening-upward megasequence whose detrital compositions record unroofing of the Sevier orogenic belt immediately to the west. The sequence consists of two offlapping clastic wedges, the lower one relatively enriched in detrital carbonate in both conglomeratic and sandy facies, the upper one relatively rich in quartzite clasts and quartzose sandstone. Each clastic wedge is interpreted to have resulted from major uplift related to thrust ramping. Although the two major ramping episodes may be attributed to two different thrust systems, the Canyon Range and Pavant thrusts, the dominant source of basin clastics was the Canyon Range plate, first as it actively ramped upsection and second as it underwent passive uplift above the Pavant thrust system. Ages of the synorogenic wedge indicate that uplift above the Canyon Range thrust occurred in late Albian time, followed by major uplift above the Pavant thrust probably in early Santonian time. Indianola deposition terminated in late Campanian time as thrust deformation affected the foreland basin margin, folding Indianola strata above a triangle zone at the eastern limit of thrusting. The record of this late-stage deformation is found in the Price River Formation, which lies immediately east of the frontal structural belt.

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