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RECONSTRUCTION OF THE ORIGINAL EXTENT OF THE TERTIARY PRE-VOLCANIC GRAVELS IN THE NORTHERN SIERRA NEVADA (CA): IMPLICATIONS FOR THE RANGE'S PALEOTOPOGRAPHY

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ABSTRACT. The ancient auriferous gravels that helped spawn the California Gold Rush have figured prominently in investigations of the Cenozoic history of the Sierra Nevada. These fluvial sediments, scattered throughout the northern half of the range, are the remnants of much larger deposits that accumulated throughout the Eocene and Early Oligocene. In this study, we present a reconstruction of the original extent of the gravels developed according to a few simple rules. This reconstruction suggests that large swaths of the northern Sierra Nevada were once buried under broad alluvial plains, a result consistent with previous work. The reconstruction also supports the hypothesis that the gravels accumulated behind high ridges along the Sierra Nevada foothills, with the Yuba River providing an important outlet. Moreover, gravel deposits on two high peaks indicate that the gravels may have buried the Feather River watershed up to the modern crest of the range. Finally, on the basis of our reconstruction, we estimate that the total volume of the gravels was, at a minimum, $\sim 200 \text{ km}^3$.

Key words: Sierra Nevada, Tertiary gravels, Gold Rush, auriferous gravels

INTRODUCTION

The discovery of gold within remnant patches of Eocene – Early Oligocene river gravels in the northern Sierra Nevada mountains helped fuel California's Gold Rush in the 19th century (fig. 1). Because of their economic importance, these ancient deposits were investigated in great detail, most notably by Whitney (1880) and Lindgren (1911). However, the gravels have not only been exploited for monetary gain but also for the clues they might provide about the geological evolution of the range. Indeed, these two early studies form the foundation for our understanding of the geological history of the Sierra Nevada during the Cenozoic, and the value of these ancient fluvial sediments in deciphering the history of the range has continued into the present (for example, Cassel and Graham, 2011).

The ancient fluvial sediments found in the Sierra are typically referred to as the 'Tertiary gravels,' a term that includes the Eocene – Early Oligocene gravels and those that accumulated during the subsequent volcanic periods (Lindgren, 1911). In this study, we focus on the pre-volcanic gravels, which can be distinguished from the inter-volcanic gravels because the latter include rhyolitic and andesitic clasts. Paleobotanical evidence suggests that, by the Early Eocene, aggradation of the gravels had already begun in the northern Sierra Nevada (MacGinitie, 1941; Wolfe, 1994; Fricke and Wing, 2004). Deposition appears to have begun in the foothills of the Sierra Nevada, with the locus of deposition appearing to have migrated up the range through time (Cassel and Graham, 2011; Cassel and others, 2012b). The remnant patches of the pre-volcanic gravels are located along the western flank of the northern Sierra, with the largest deposits

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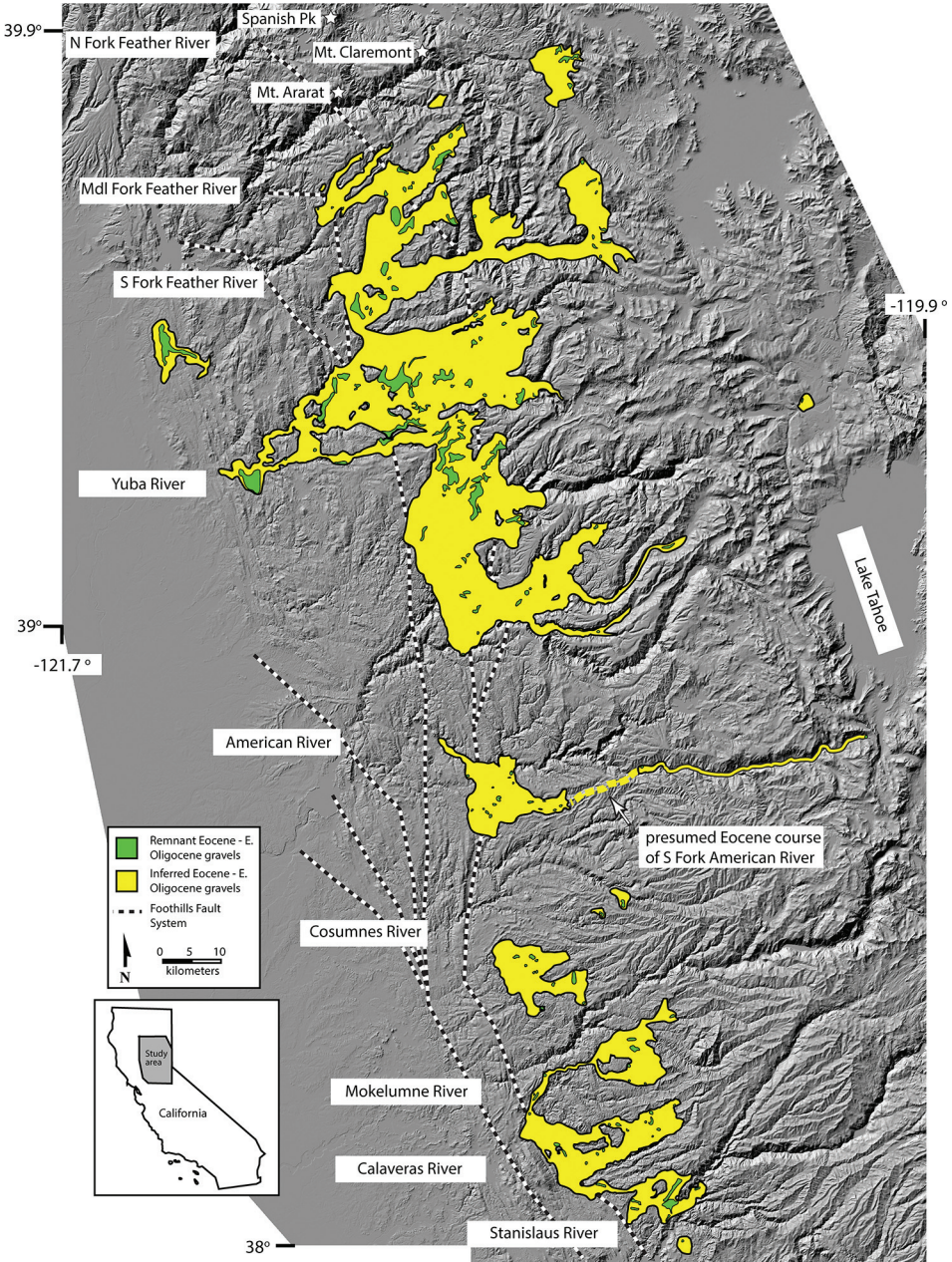


Fig. 1. Remnant and inferred gravels of the northern Sierra Nevada mapped onto a shaded relief 30-m DEM. This reconstruction suggests that large swaths of the northern Sierra were buried by fluvial gravels in the Eocene – Early Oligocene. Trace of Foothills Fault System from Clark (1960). Inset map shows the location of the study area.

in the north and the size and extent of the remnants gradually tapering to the south (fig. 1). Although Cassel and Graham (2011) provide detailed stratigraphic divisions of the deposits, the gravels have been historically divided into upper and lower units based on their stratigraphic composition and overall texture (for example, Whitney, 1880;

Lindgren, 1911; Yeend, 1974), and we follow that simplified nomenclature here. The lower unit, which contains higher concentrations of gold than the upper unit, is typically found on the beds of bedrock paleochannels and is commonly composed of rounded metavolcanic and metasedimentary clasts (Cassel and Graham, 2011) and deeply weathered plutonic rocks (Yeend, 1974). In addition, this unit is imbricated, poorly sorted, moderately indurated, and coarse-grained, with some boulders measuring several meters in diameter (for example, Whitney, 1880; Lindgren, 1911). The coarse texture of these deposits suggests the material was transported by energetic rivers (Cassel and Graham, 2011); indeed, Yeend (1974) estimated that one 3-m boulder had traveled at least 13 km. The upper unit, in contrast, is typically more fine-grained, with some units composed of pebbles, sand, and silt (Cassel and Graham, 2011); in addition, the upper unit contains a greater percentage of quartz clasts (Yeend, 1974). In the deposits examined by Cassel and Graham (2011), the stratigraphic architecture of the upper unit is consistent with a braided stream system and contains multiple upward-fining sequences; moreover, they detected an overall decrease in particle size through time, which they interpreted as a response to either a local decrease in gradient or a reduction in discharge. A change in source area may have also been responsible for the decrease in particle size.

Aggradation of the gravels continued at least into the Early Oligocene when they were overlain, both conformably and unconformably, by the rhyolitic Valley Springs Formation (Cassel and others, 2012a; Cassel and others, 2012b). Deposition of the rhyolitic volcanic rocks continued until the Early Miocene and left deposits that were up to ~250-m thick (Slemmons, 1966). The rhyolitic deposits were followed by the andesitic Mehrten Formation, which had accumulations as thick as ~1000 m (Slemmons, 1966). Although most of these Cenozoic deposits were eroded over time, their remnants provide important clues about the geological history of the range. In this contribution, we present a reconstruction of the original extent of the Eocene-Oligocene gravels based on stratigraphic and geometric principles. We use the reconstruction to re-create the paleotopography of the region during the Eocene – Early Oligocene and to estimate the volume of the gravels. According to our reconstruction, large swaths of the northern Sierra Nevada were buried by river deposits during this time period.

MATERIALS AND METHODS

Reconstructing the Original Extent of the Tertiary Gravels

We used a compilation of geologic maps and studies (Lindgren, 1911; Peterson and others, 1968; Yeend, 1974; Hietanen, 1976; Wagner and others, 1981; Saucedo and Wagner, 1992; Garside and others, 2005; Cassel and Graham, 2011) to locate extant Tertiary gravel deposits and to outline their extent on modern topographic maps. In addition, we used descriptions from Lindgren (1911) and Hudson (1955) to identify other deposits which are too small to show on geologic maps or were buried by later volcanic rocks and, thus, would not appear on a map of surficial deposits. An initial examination of the extant gravels revealed that there were sufficient deposits between the South Fork of the Feather River and the Stanislaus River to permit a reconstruction of the original extent of the deposits. Based on the locations of important gravel deposits (fig. 1), twenty-two topographic cross-sections parallel to the crest of the northern Sierran Nevada were extracted from 30-m digital elevation models (DEMs) in ArcGIS (fig. 2), and the pre-volcanic gravels and the later volcanic rocks were drawn onto the cross-sections (Appendix).

The original extent of the gravel deposits was inferred from the locations and elevations of the remnant patches according to the guidelines described below; these guidelines should ensure conservative estimates of the original gravel extent and volume. The first four rules apply to the reconstruction of deposits along the cross-

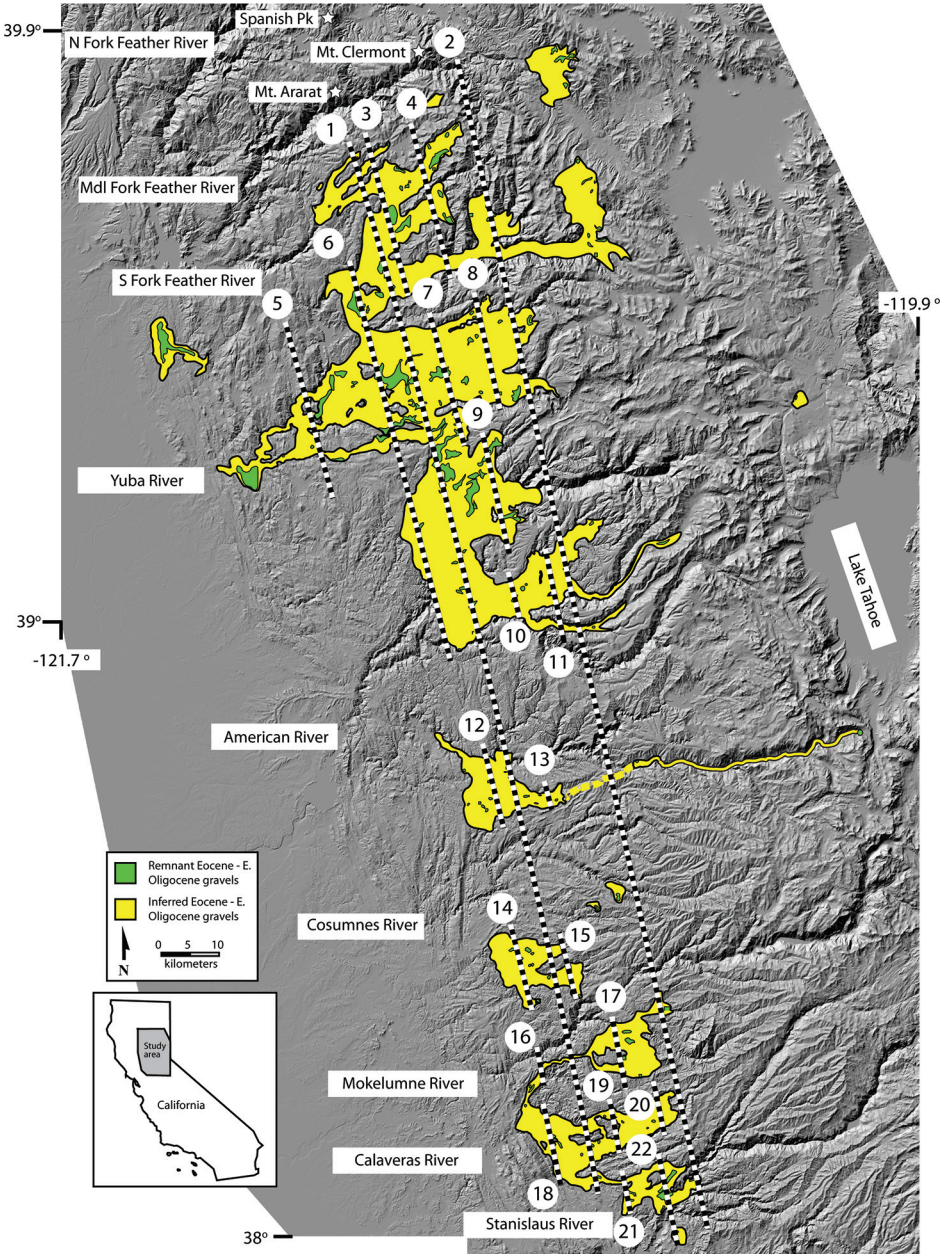


Fig. 2. Locations of the cross-sections for estimating the total volume of the gravel deposits. Average end-area analysis between the cross-sections was used to calculate the volume.

sections (that is, parallel to the range-crest); the final rule applies to the reconstruction between cross-sections (that is, perpendicular to the range-crest).

(1) Existing deposits mapped along one side of a valley were assumed to have extended across the valley at identical elevations (fig. 3A). Inferred deposits were never placed higher than the highest mapped deposit in the immediate vicinity or as encountered in a nearby mine. Similarly, inferred deposits were not placed at

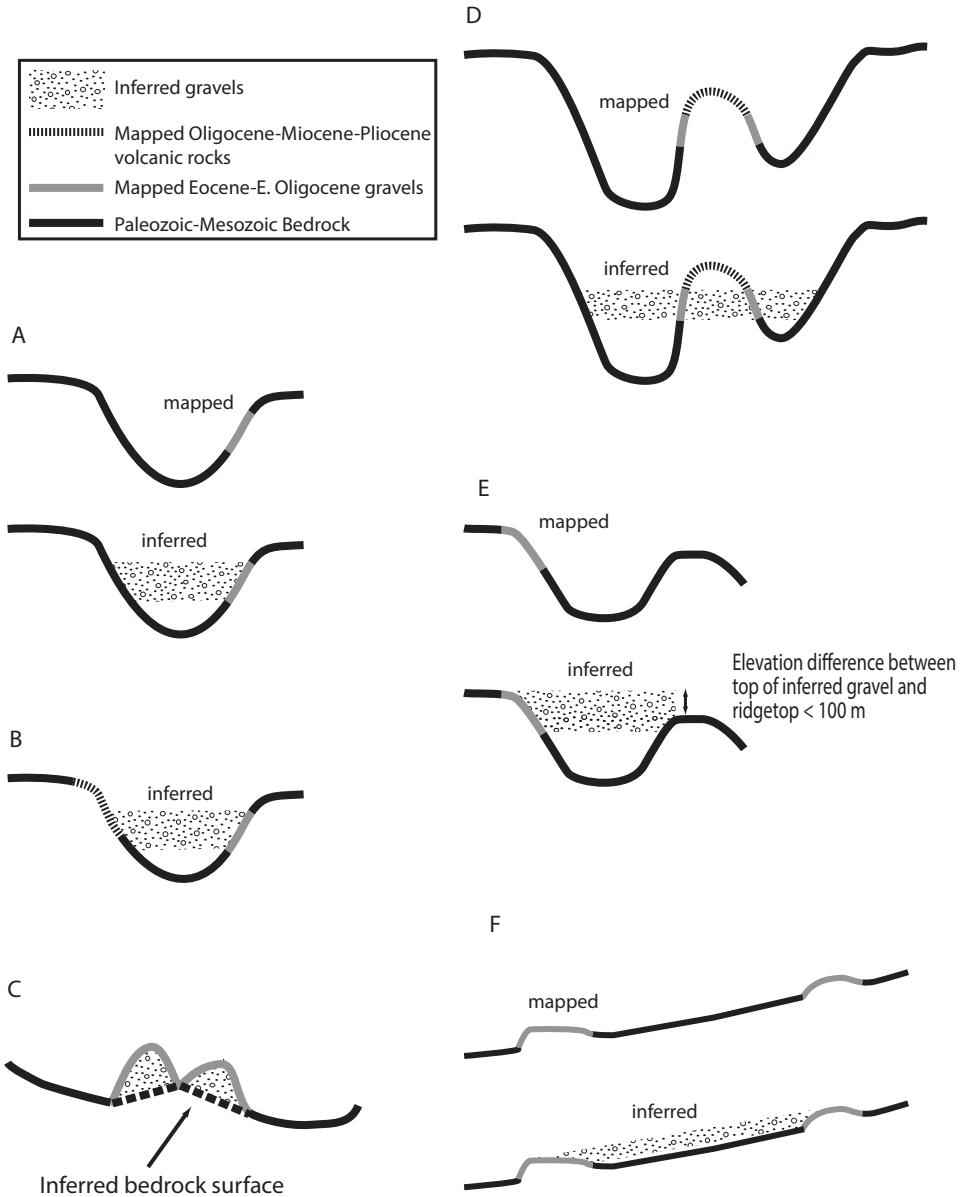


Fig. 3. Illustration of the guidelines used to reconstruct the original extent of the auriferous gravels. (A) Gravels mapped along one side of a valley are inferred to have extended across the valley at identical elevations. (B) The rule in (A) may place older gravels over younger volcanic deposits that have been partially eroded. (C) Where gravel thicknesses are not reported, the bedrock surface is assumed to be at the lowest point in the gravel deposit. (D) Gravel deposits on ridges capped by volcanic rock are assumed to extend through the ridge if the gravel outcrops are at similar elevations on both sides of the ridge and if the presence of gravels in the ridge is confirmed by observations. (E) To provide a conservative volume estimate, inferred gravels were not extended across ridges (in the range-parallel direction) where the top of the deposit was within 100 m of the ridge crest. (F) Reconstructed deposits along the dip of the range were assumed to have been continuous and with a uniform gradient.

elevations lower than the lowest nearby mapped deposit. According to the Law of Superposition, Eocene-Oligocene gravels should be stratigraphically above Paleozoic- and Mesozoic-aged bedrock and below the younger volcanic rocks. However, because the gravels were partially eroded prior to the deposition of the volcanic rocks, the implementation of this guideline results in instances where gravels on the cross-sections appear to extend above the younger volcanic rocks (fig. 3B).

(2) The bedrock surface beneath each gravel remnant was typically delineated based on reports of gravel thicknesses (Whitney, 1880; Lindgren, 1911). Where these were unavailable, the surface was approximated by linking together the lowest points of each deposit with a straight line (fig. 3C).

(3) Deposits found at similar elevations on each side of a ridge capped by volcanic rocks are assumed to extend through the ridge beneath the volcanic rocks (fig. 3D). This guideline is supported by exploratory boreholes, shafts, and quarries advanced through the ridges during the Gold Rush that often encountered auriferous gravels (for example, Whitney, 1880; Lindgren, 1911; Peterson and others, 1968). Note that, although figure 1 does not show the gravel deposits under ridges capped by volcanic rock, the buried gravels were included in the volume calculations where there was sufficient information regarding their thicknesses.

(4) In some instances, low bedrock ridges were overtopped by inferred gravels when extending their upper boundary laterally or downslope. To provide a conservative reconstruction and to account for possible interfluvial erosion since the Eocene, the extents of inferred deposits were terminated where they reached a ridge that had an elevation within 100 m of the top of the gravels (fig. 3E). This assumption implies that bedrock erosion of the interfluvial areas has been less than 100 m since the deposition of the gravels. Although Cecil and others (2006) estimated regional Cenozoic exhumation rates of ~ 0.03 mm/yr, which implies ~ 1000 m of erosion since the Eocene, the presence of pre-volcanic gravels draped over interfluvial areas throughout the northern Sierra Nevada demonstrates that these bedrock surfaces have changed little over the latter half of the Cenozoic.

(5) When interpolating deposits along the dip of the range, the surfaces of the original deposits were assumed to have been continuous and with a uniform gradient; therefore, deposits at higher elevations were extended to the top of deposits located downslope (fig. 3F). Similarly, the basal boundaries of the gravels were extended down-valley to the deposit located at the lowest elevation.

Volume Calculations

The cross-sections were used to calculate the total volume of the gravels using average end-area analysis. The cross-sectional area of the gravel deposits from each cross-section (for example, fig. 4) was averaged with the area of the deposits from the nearest adjacent section line; this average was then multiplied by the distance between the sections to provide a gravel volume between the two cross-sections. The volumes from each slice were summed to yield the total volume of gravels deposited during the Eocene – Early Oligocene. A patch of inferred gravels near the headwaters of the Middle Fork of the Feather River and another at the margin of the Central Valley, between the Feather and Yuba rivers, were not included in the volume calculation because of insufficient data regarding gravel thicknesses.

Note that post-depositional normal or reverse faults could have created vertical offsets of the gravel deposits, particularly in the northern section of the study area (Whitney, 1880; Wakabayashi and Sawyer, 2000). These faults typically trend in a direction approximately parallel to the range-crest and, thus, do not intersect the cross-sections. Because any offset would have occurred between adjacent cross-sections, vertical motion would have changed the elevation of the gravels, but not their

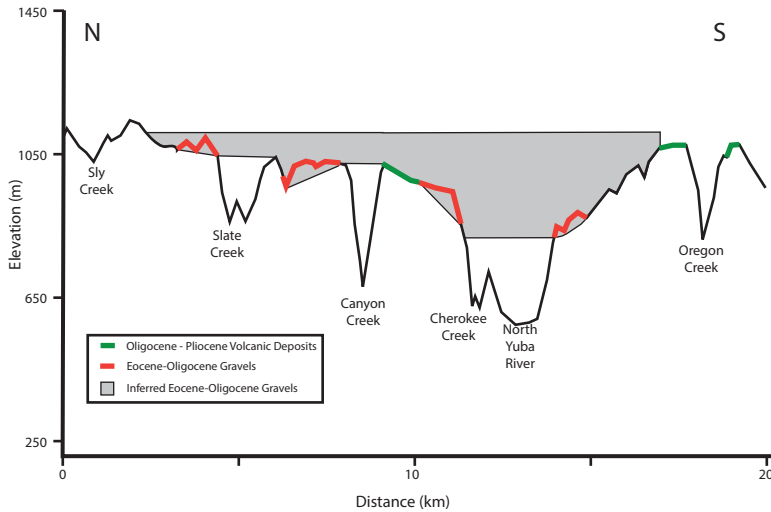


Fig. 4. Segment A of Cross-section 1 with the mapped Cenozoic deposits and the upper and lower boundaries of the inferred gravel. Note how the southern extent of the gravels is terminated at the ridge along Oregon Creek (see fig. 3E).

calculated cross-sectional area. As a result, the gravel volume calculation is insensitive to vertical displacements along faults.

Caveats

There are several caveats to our approach for reconstructing the original extent of the gravels. First, we were constrained by the limited number of extant deposits. Natural processes eroded much of the material since their deposition in the Eocene-Oligocene, and hydraulic mining during the Gold Rush removed some fraction as well. By the time comprehensive mapping of the deposits had begun, hydraulic mining had already destroyed many of them (Whitney, 1880; Lindgren, 1911); indeed, Lindgren began his investigations in 1886, two years after large-scale hydraulic mining had been effectively outlawed (James, 1994). Therefore, our reconstruction most likely underestimates the original extent of the deposits. The second caveat is that our reconstruction is not necessarily representative of the gravel distribution at any particular point in time. According to Cassel and Graham (2011), deposition of the gravels began along the western edge of the Sierra Nevada and then moved eastward, up the range. Given the wide span of ages for the deposits (Eocene to Early Oligocene) and their broad distribution, there were likely multiple episodes of sediment deposition and incision (Cassel and Graham, 2011). Therefore, the extent of the gravels in figure 1 does not necessarily represent contemporaneous deposits. Moreover, our volume calculation does not account for these multiple episodes of incision and aggradation and, thus, underestimates the actual total volume of sediment that accumulated. Third, our volume calculations do not account for fine-grained material flushed out of the Sierra Nevada foothills. Indeed, some of the bedrock units were so weak (for example, slates) that the only clasts they produced were from their quartz veins (Whitney, 1880, p. 323). Fourth, our reconstructions of the upper and lower boundaries of the gravel deposits were limited by the extent of extant gravels, thereby likely contributing to an underestimate of the volume. Finally, when estimating the volumes of gravel, we did not account for the isolated gravels found in mines because of insufficient information about their thicknesses and extents. These deposits at the bottoms

of paleovalleys were bounded by bedrock rims and capped by volcanic rocks and, thus, are not exposed at the surface (Whitney, 1880; Lindgren, 1911). Importantly, the volumes of these deposits are small relative to the overall volume (see later).

RESULTS

According to our reconstruction, the gravels buried at least 22% of the northern Sierra landscape (fig. 1). North of the American River, where the majority of the extant gravels are found, gravels covered at least 45% of the range. A segment of one of the cross-sections emphasizes the broad extent of gravel deposition as well as the thickness of the deposits (fig. 4). Note, also, how terminating inferred gravels where they passed within 100 m of adjacent ridge-tops likely underestimates their original extent (fig. 4).

Although the remnant gravels in the Feather River watershed were insufficient to reconstruct their original extent, a topographic profile suggests that this area of the northern Sierra was buried by gravels up to the present-day Sierran crest (fig. 5): Tertiary gravels can be found at the top of two of the tallest mountains in the Feather River watershed, Spanish Peak and Mount Claremont (fig. 1). Due to the positions and elevations of these mountain-top gravels, their sources were likely east of the range-crest. Unfortunately, these deposits are no longer accessible and their descriptions are limited (Whitney, 1880, p. 216–217) otherwise their sources could potentially be constrained based on their lithology.

From the volume calculations, a minimum of 199 km³ of gold-bearing gravels was deposited during the Eocene-Oligocene epochs. For comparison, volume estimates of the *remnant* gravels range from 0.1 to 0.7 km³ (Lindgren, 1911; Jarman, 1927; Peterson and others, 1968; Yeend, 1974). A potential limitation to the average end-area analysis is that it assumes that the straight-line distance between two cross-sections represents the actual distance. As a result, the volume of deposits within a tightly meandering canyon would be underestimated. However, the vast majority of the inferred gravels are in the uplands and within broad depressions (for example, fig. 4), where the linear-distance assumption may be reasonable, particularly since cross-sections are closely spaced in critical areas; for instance, the cross-sections in the Yuba River area are separated, on average, by only ~7 km (fig. 2).

To test our volume calculation determined with the average end-area analysis, we used the cut/fill analysis in ARCGIS with an elevation layer of our gravel reconstruction and a digital elevation model (10-m posting) of the modern landscape. This technique yielded a volume of 242 km³, which is greater than our estimate with the average end-area analysis because it assumes that the gravels filled the modern valleys; nevertheless, it provides support for our results.

DISCUSSION

Spatial Distribution of Reconstructed Gravels

Our reconstruction of the original extent of the gravels in the northern Sierra supports Cassel and Graham's (2011) conclusion that the upper unit was deposited by rivers flowing across broad floodplains (fig. 1). Moreover, according to our reconstruction, large swaths of the northern Sierra Nevada range were buried under fluvial sediments during the Eocene – Early Oligocene. After extensive field observations, early California geologists had come to a similar conclusion: the gravels had filled in valleys and overtopped ridges to spill into neighboring watersheds (Whitney, 1880; Lindgren, 1911). Moreover, whereas the maximum gravel thickness had previously been estimated to be ~160 m (Lindgren, 1911), we find that, along the North Yuba River, the deposits may have been at least 213-m thick (fig. 6).

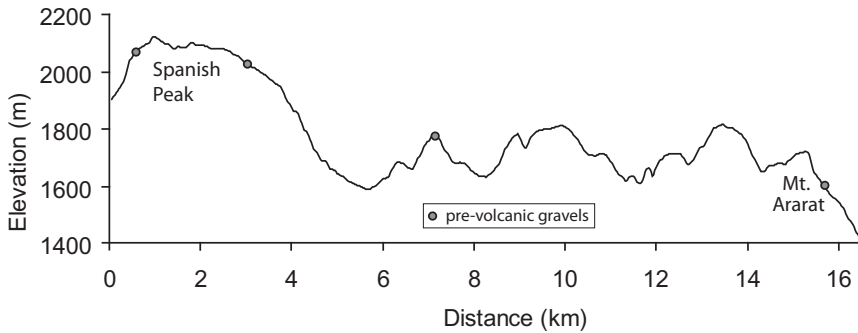


Fig. 5. Gravel deposits in the Feather River watershed along a topographic transect (see fig. 1 for locations of Spanish Peak and Mt. Ararat). Gravel remnants are capped by andesitic deposits (not shown). The gravel deposits on Spanish Peak indicate that the gravel surface in this region extended up to the crest of the range.

The reconstruction also provides clues about the conditions that led to the widespread aggradation of the gravels. In the northern portion of the study area, branches of the three main river systems (the Feather, Yuba, and American networks) presently meet in the Sierran foothills and likely did as well in the Eocene when the gravels began to aggrade (Lindgren, 1911; Gabet and Miggins, 2020). The initiation of deposition in the foothills (Cassel and Graham, 2011) suggests that the convergence of sediment loads, amplified by accelerated erosion (DeGraaff-Surplus and others, 2002), at these network junctions overwhelmed the transport capacity of the downstream reaches (Lindgren, 1911; Matthes, 1930; Matthes, 1960). In addition, the generally abrupt and linear western edge of the inferred deposits (fig. 1) supports the conclusion that the gravels backfilled behind northwest-trending ridges in the Sierra Nevada foothills (Cassel and Graham, 2011; Cassel and others, 2012b). Where the rivers flowed through the ridges (for example, the Yuba River), the gravels were deposited further west. The foothills along the northern half of the Sierra are composed of alternating bands of resistant and erodible metamorphic bedrock such that low-gradient valleys are found upstream of narrow canyons cut into more resistant rock (Gabet, 2020). Therefore, the narrow canyons may have hindered the passage of sediment supplied by the wave of incision sweeping up the range (DeGraaff-Surplus and others, 2002), while the low-gradient valleys upstream of these chokepoints promoted deposition (Lindgren, 1911; Cassel and Graham, 2011). Indeed, in his report, Lindgren (1911, p. 34) remarked that the gravels in the Yuba River watershed appeared to have been “held back as if by a dam by the narrow canyon of the lower, transverse river course.” In addition, Cassel and Graham (2011) proposed that sediment transport through the Sierra Nevada foothills may have been impeded by a ridge rising along a thrust fault in the Foothills fault system (fig. 1). Six geological cross-sections from Whitney’s 1880 report (Plates S and V) show thrust faults offsetting gravels resting on bedrock, with minimum displacements ranging from 4 to 18 m (fig. 7). At two of the sites, Whitney confirmed that the faulting had occurred during the deposition of the gravels, thereby providing evidence for active compression in the region at that time. Finally, sea level rise in the early Eocene could have also induced aggradation in the Sierran foothills (Cassel and Graham, 2011 and references therein). Note that these four explanations for widespread aggradation (fluvial network organization, alternating bands of weak and resistant rocks, thrust faults, and sea level rise) are not mutually exclusive.

Past studies have remarked on the difference in the spatial distribution of the Tertiary gravels, and the later volcanic rocks, between the northern and southern

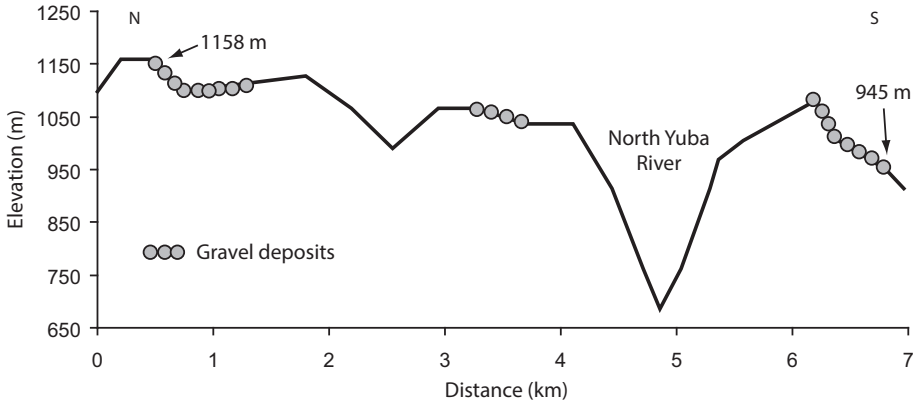


Fig. 6. Profile across the North Yuba River. The gravel deposits here were at least 213-m thick. Topographic and lithologic data from Hietanen (1976). Profile crosses the river at 39.516860° N, 121.012717° W. View looking upstream. The gravels at the southern edge of the profile are along the slopes of a tributary valley to the North Yuba River, evidence that incision of the North Yuba River canyon had already begun when the gravels were deposited in the Eocene – Early Oligocene.

Sierra (Bateman and Wahrhaftig, 1966; Cassel and Graham, 2011). This latitudinal difference is also reflected in the inferred gravels, which are greater in the northern part of the study area and gradually decrease southward, with the deposits essentially ending at $\sim 38^\circ$ N (fig. 1). There are at least two possible explanations for this geographic difference. First, the southern half of the range may have also had extensive gravel deposits in the Cenozoic, but they have since eroded away. Although there is conflicting evidence regarding Late Cenozoic uplift of the southern Sierra (Gabet, 2014), Martel and others (2014) suggest that normal faulting along the range's eastern escarpment could have led to 100's of meters of uplift by westward tilting. This uplift could have been sufficient to accelerate erosion (Stock and others, 2004) and completely remove the gravels. The second explanation is that gravels never accumulated in the southern Sierra to any significant degree. The alternating bands of weak and resistant metamorphic rocks mentioned above end abruptly at about 38.5° N, where plutonic rocks become dominant (Strand, 1967) and the conditions for deposition (that is, topographic constrictions downstream of gentle reaches with low sediment transport capacity) may have been less pervasive. Indeed, there are no widespread gravel deposits south of the metamorphic belt.

Northern Sierra Nevada: Late Cretaceous to the Early Oligocene

The analysis of the pre-volcanic gravels presented here, as well as previously published work, suggests the following sequence of events in the northern Sierra Nevada. In the Cretaceous, the region appears to have been characterized by rolling hills and a drainage system organized into an Appalachian-style trellis network cut into bands of alternating weak and strong rocks: long, broad, and gently sloping north-south oriented valleys were excavated into less resistant rock and along fault zones while short, steep, and narrow east-west oriented canyons were cut into more resistant rock (Lindgren, 1911; Matthes, 1930; Matthes, 1960; Yeend, 1974). In the Late Cretaceous and Early Cenozoic, this landscape was transformed as it became the western ramp of a high altitude plateau extending across Nevada and into Utah (for example, Wolfe and others, 1998; DeCelles, 2004; Best and others, 2009; Cassel and others, 2012b; Chamberlain and others, 2012). Knickpoints migrating eastward from the coast (the present-day eastern margin of the Central Valley) began cutting across watershed divides, capturing transverse channel reaches of the trellis network and integrating

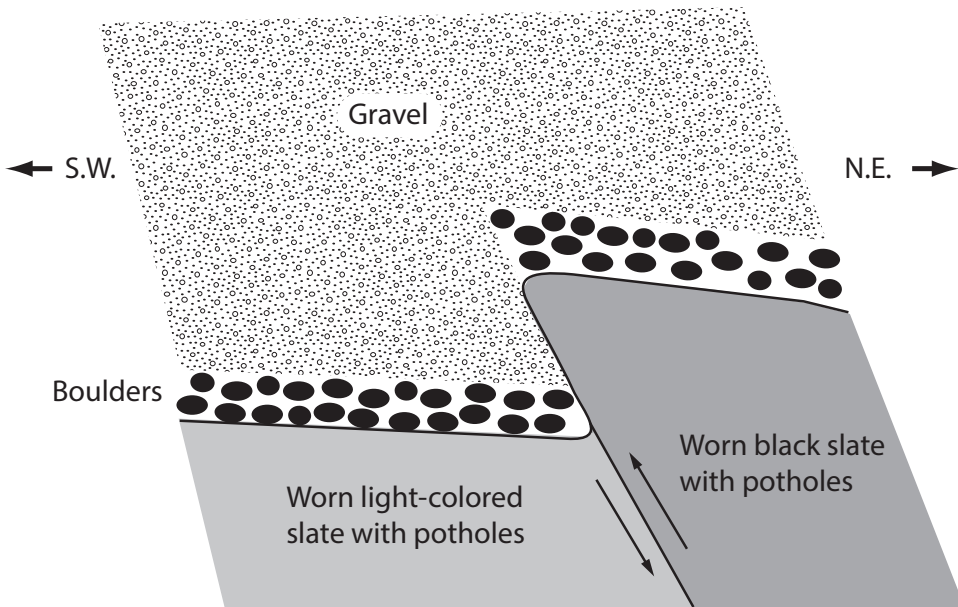


Fig. 7. Thrust fault striking NW – SE with ~ 4 m of offset (39.5378° N, 121.0252° W). Adapted from Whitney (1880, Pl. V-1); note, however, that the figure was mislabeled in the original publication. According to Whitney's observations of the deposits (1880, p. 462), this fault was active during the deposition of the gravels, indicating that the region was subjected to compressive stresses at the time.

them into an east-west drainage system (Lindgren, 1911; Matthes, 1930; Matthes, 1960; DeGraaff-Surpless and others, 2002). Indeed, Cecil and others (2006) infer rapid regional exhumation rates between 90 and 60 Ma. By the Late Eocene, this new fluvial network had reached into central Nevada (Garside and others, 2005; Henry and Faulds, 2010; Cassel and others, 2012b; Henry and others, 2012). Pre-volcanic Tertiary gravels deep within the modern canyons and within paleo-valleys buried by later volcanic deposits demonstrate that the bedrock beds of many of the trunk streams draining the range during the Eocene – Early Oligocene were already within 150 – 300 m of their modern elevations (Gabet and Miggins, 2020).

Erosion, of course, was not limited to the fluvial network; as the valleys deepened, their hillslopes would have steepened, leading to an increase in sediment delivered to the rivers. Some fraction of the sediment became trapped along the Sierra Nevada foothills and the bedrock channels, overwhelmed with coarse sediment, became braided rivers as the valley bottoms aggraded (Cassel and Graham, 2011). As valleys filled, sediment spilled over drainage divides and into neighboring catchments, eventually burying much of the topography (Whitney, 1880; Lindgren, 1911) (fig. 1). In addition, aggradation of the valleys would have buried migrating knickpoints, thereby halting the advance of the incision wave. Indeed, there is strong evidence that the Sierran rivers were steep, energetic, and actively downcutting when they became buried by the gravels. For example, large well-rounded boulders have been found on the bedrock beds of the paleochannels, underneath thick sequences of fluvial sediments that progressively fine upwards (Whitney, 1880; Lindgren, 1911; Yeend, 1974; Cassel and Graham, 2011). In addition, in their examinations of the paleochannels, both Whitney (1880) and Lindgren (1911) describe deep and narrow bedrock “gutters” excavated along some valley bottoms. These were likely channels that were in the process of incising deeply into their bedrock valley floors before being buried by

sediment (for example, Bender and others, 2016). Moreover, Cassel and Graham (2011) used the size of sediment particles within the auriferous gravels to estimate the gradients of the paleochannels and concluded that their slopes were indistinguishable, within uncertainties, from the steep modern rivers. Although Wakabayashi (2013) criticized this result by claiming that their approach failed to take into account the dependence of channel gradient on discharge, their technique is based on the well-known concept of shear stress, whereby the mobility of bed sediment is dependent on channel slope and flow depth (Paola and Mohrig, 1996). Because flow depth is proportional to discharge (Leopold and others, 1964), the approach followed by Cassel and Graham does, therefore, account for this important variable.

A pause in incision due to aggradation of fluvial sediment would have been further compounded by the rhyolitic eruptions in Nevada that deposited up to 250 m of volcanic rocks in the Sierra Nevada and contributed to the filling of paleocanyons (for example, Slemmons, 1966; Cassel and others, 2014). An abrupt change to a cooler climate at the Eocene – Oligocene transition (Zachos and others, 2001) may have also played a role in bringing about the end of the gravel era. While the warm and humid climate of the Eocene stimulated rapid weathering rates and the conversion of bedrock to more easily eroded material (Gibson and others, 2000), rapid cooling in North America ~33.5 Ma (Zanazzi and others, 2007) would have slowed weathering rates, thereby limiting the supply of sediment to the rivers.

The rhyolitic eruptions in the Oligocene and Early Miocene were followed by andesitic eruptions that continued into the Pliocene and left behind deposits that were up to ~1000-m thick. The Sierra, therefore, has undergone three long episodes of aggradation, and each was interrupted by periods of river incision (for example, Whitney, 1880; Lindgren, 1911; Cassel and Graham, 2011). Although post-Eocene episodes of incision have been interpreted as a response to tectonic uplift (for example, Busby and others, 2008; Wakabayashi, 2013), they are more simply explained as a response to a decrease in sediment supply (Gabet and Miggins, 2020). Like tectonic uplift, the accumulation of material within a river valley raises the elevation of a channel above its baselevel such that, when the supply of sediment drops below the river's transport capacity, the channel will resume incision; indeed, this type of river response has been documented after the deposition of river gravels (Gilbert, 1917) and volcanic rocks (Whipple and others, 2000). In the northern Sierra, the trunk streams re-excavated their original canyons in some cases and, in others, they cut new canyons (Gabet and Miggins, 2020). Moreover, these rivers have resumed the downcutting initially interrupted in the Eocene and Late Oligocene by the aggradation of fluvial deposits and have incised below their paleothalwegs, albeit perhaps at a slower pace because of the drier climate and the beheading of their headwaters (Schweickert, 2009).

Implications for Lindgren's Paleochannel Reconstructions

As hypothesized above, migration of the knickpoints into the upper reaches of the watersheds produced sediment that progressively buried their rejuvenated lower reaches; in addition, continued aggradation overtopped drainage divides and filled in adjacent valleys that had not yet been reached by the wave of the incision, perhaps owing to smaller drainage areas and weaker streams. These two types of buried valleys, incised and unincised, are described in Whitney (1880) and Lindgren (1911). For the former, as noted earlier, both authors refer to deep and narrow bedrock "gutters" excavated along some valley bottoms. In contrast, other gravel-filled valleys lack any defined bedrock channel walls; for example, Whitney (1880, p. 387) refers to a buried valley floor where "the bed-rock is nearly level for a width of 900 feet." This latter situation likely describes a valley filled by sediment spilling over a drainage divide; the gravels are resting on bedrock because soils on the valley bottom would have been initially stripped away by the

flow (Whitney, 1880). Although these two types of buried valleys and their fills are genetically different, the term *channel* was applied to both (Whitney, 1880), perhaps leading to some confusion about the courses of the Eocene – Early Oligocene rivers.

Because gold was not distributed uniformly within the gravels but, rather, tended to be concentrated in *leads* that followed the bottoms of bedrock channels (Whitney, 1880; Lindgren, 1911), miners and geologists placed great importance on trying to recreate the courses of the Sierra's Tertiary channels. The patchy nature of the deposits (fig. 1) rendered the task of retracing the channels' paths difficult and open to multiple plausible reconstructions (Whitney, 1880; Lindgren, 1892; Lindgren, 1911; Durrell, 1966; Yeend, 1974). The most well-known of these was presented by Lindgren (1911), who based his reconstructions on exhaustive observations of the gravel deposits during field visits from 1886 to 1892. Lindgren and others have used these reconstructions to argue for Late Cenozoic tilting and uplift of the northern Sierra Nevada on the basis of the gradients of these presumed paleochannels (Hudson, 1955; Christensen, 1966; Yeend, 1974; Jones and others, 2004). Recent work, however, has shown Lindgren's assumptions and reconstructions to be flawed. Some of his Tertiary channels are physically impossible, with reaches implying that water flowed uphill over high ~ 200-m ridges (Gabet, 2014). Moreover, inherent in these analyses is the assumption that Lindgren's reconstructions represent single and contemporaneous steady-state channels. However, the gravels are hypothesized to have backfilled from west to east, indicating non-steady-state conditions in which some reaches of channels were aggrading while others were incising (Cassel and Graham, 2011; Cassel and others, 2012b). Whitney, (1880) also concluded that the paleochannel remnants represented different generations of rivers. In addition, petrologic and zircon analyses demonstrate that Lindgren was connecting paleochannel remnants of unrelated age and provenance to create his Tertiary channels (Durrell, 1966; Cassel and others, 2012b). Therefore, the imprecise use of the term *channel* by miners and geologists to describe different contexts in which the fluvial gravels were found may have led Lindgren to incorrectly connect the paleochannel remnants.

CONCLUSION STATEMENT

With a few simple rules as guidelines, we inferred the original extent of Eocene – Early Oligocene gravel deposition from the remnants of these deposits in the northern Sierra Nevada. Our reconstruction suggests that large swaths of the bedrock landscape were buried under broad sheets of fluvial deposits. In addition, we present evidence that in the northern section of the study area, the gravels reached up to some of the highest peaks along the modern crest of the range. The extent of the reconstructed deposits is consistent with the presence of braided rivers sweeping over broad alluvial plains during the Eocene – Early Oligocene. Moreover, our reconstruction is consistent with the hypothesis that the gravels backfilled behind a topographic high in the Sierran foothills, with the Yuba River serving as an important outlet to the base of the range.

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APPENDIX

CROSS SECTION 1

Each of these plots is part of a continuous north-to-south cross-section. See figure 2 for locations.

Figure A1 is section 1.

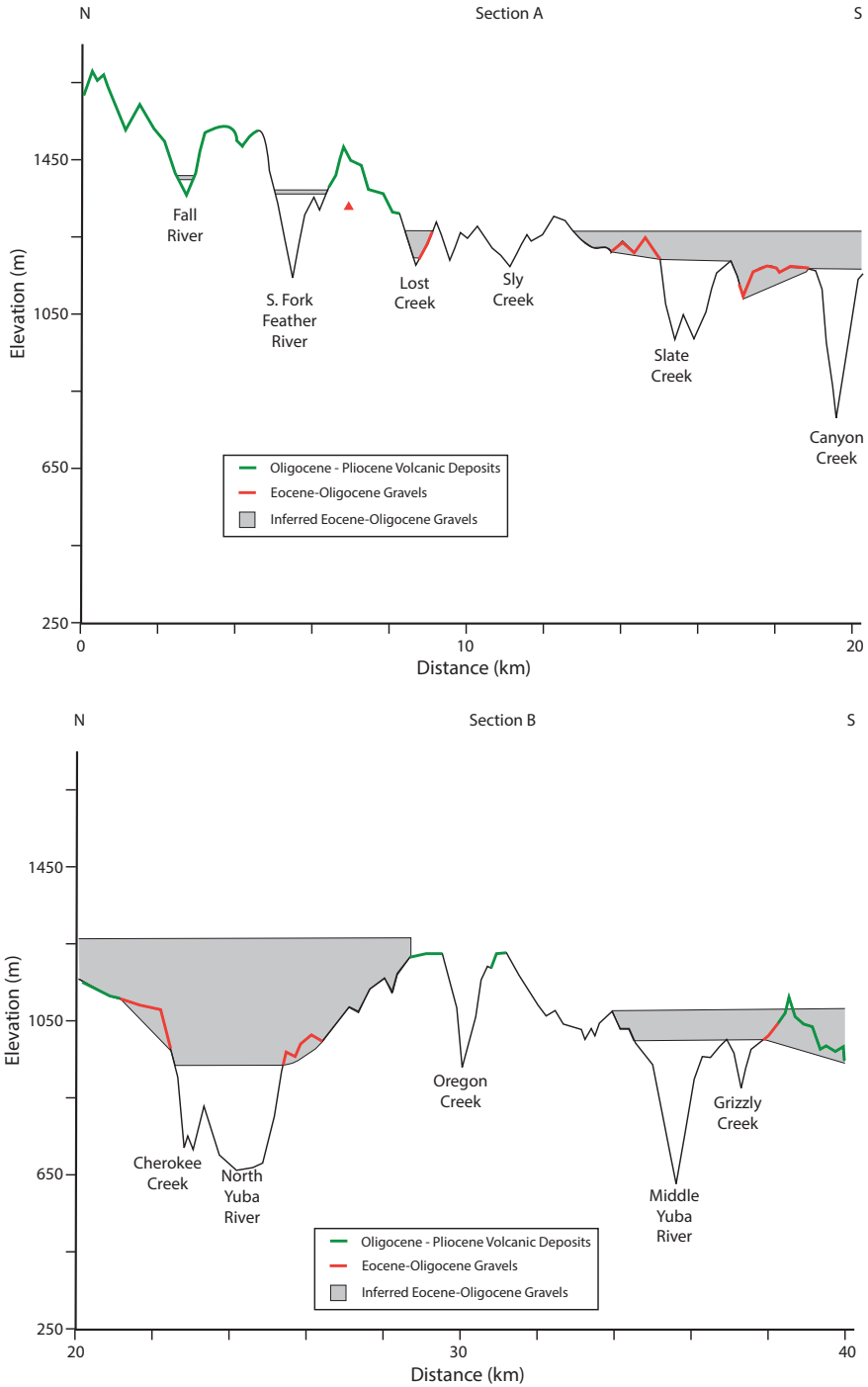


Fig. A1. Cross-section 1. Each of these plots is part of a continuous north-to-south cross-section. See figure 2 for location.

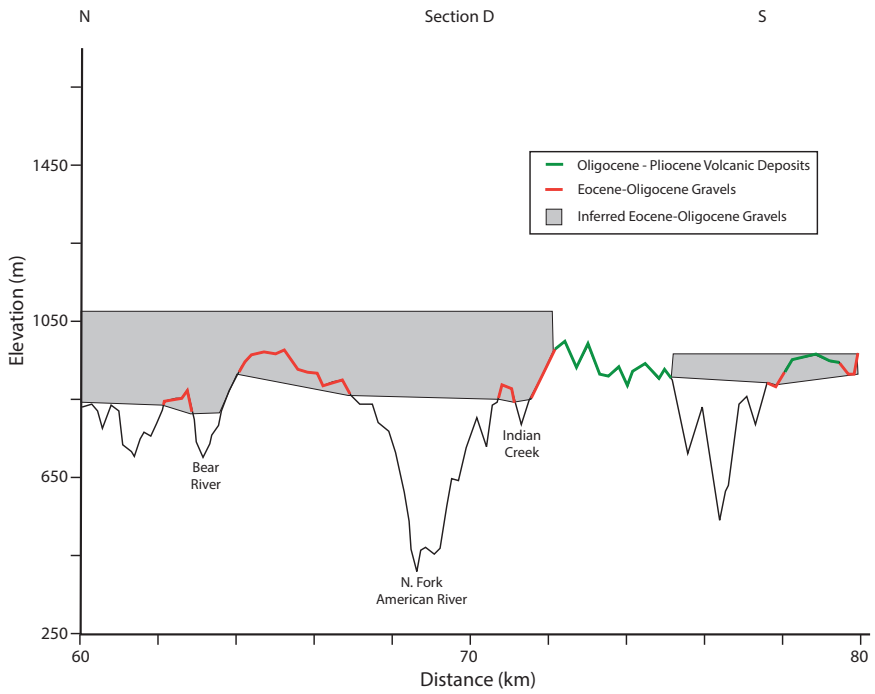
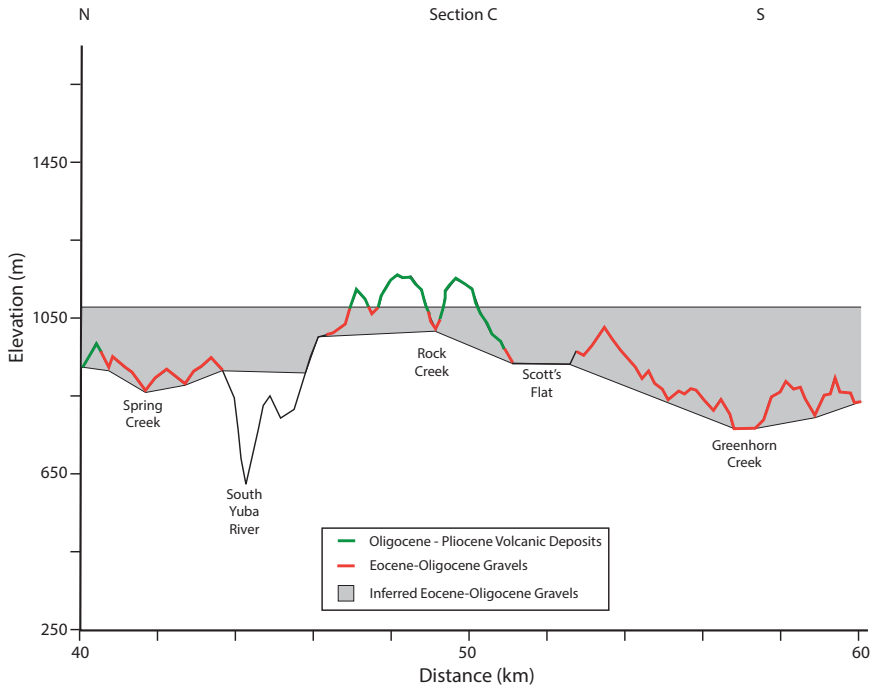


Fig. A1. Continued

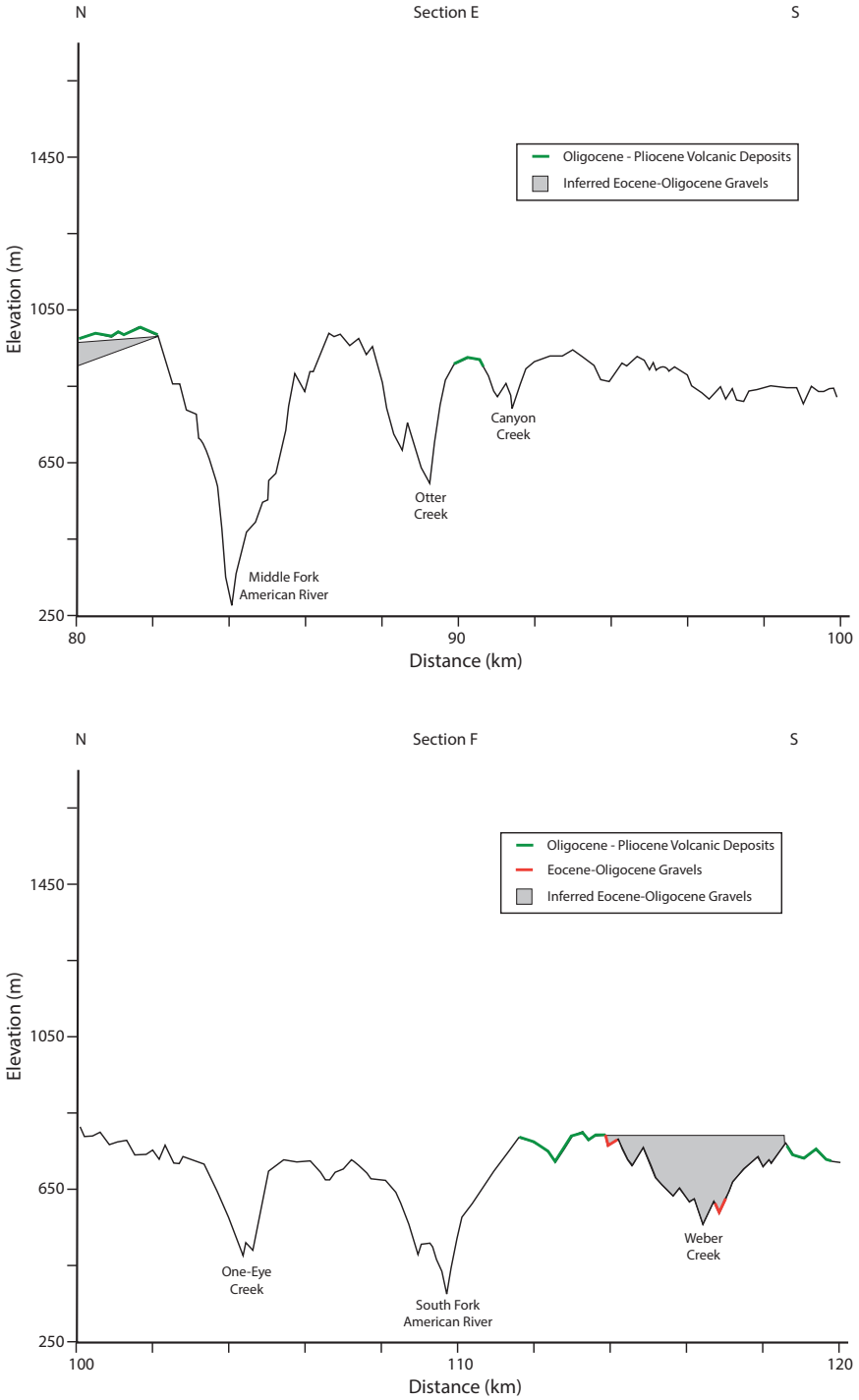


Fig. A1. Continued

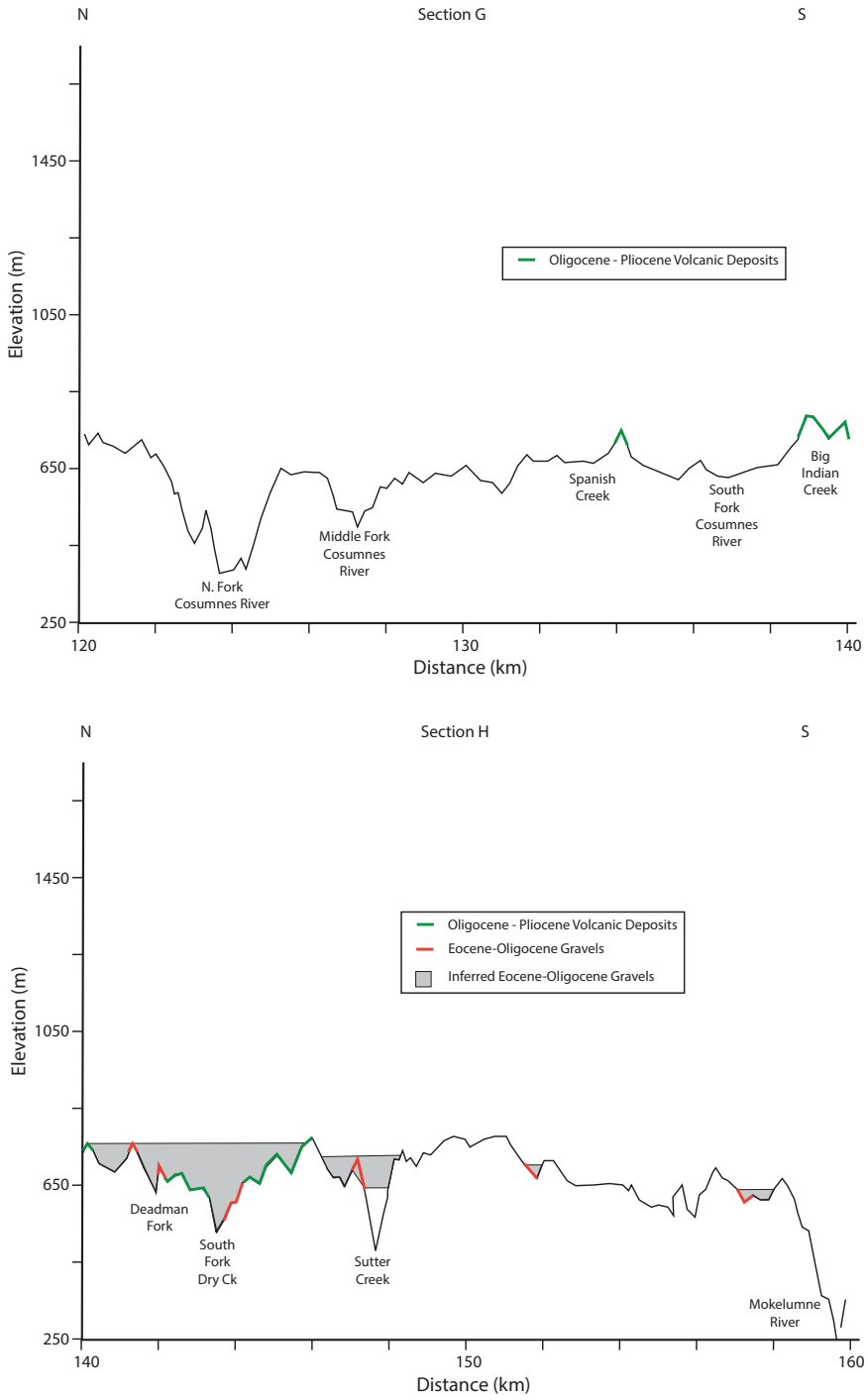


Fig. A1. Continued

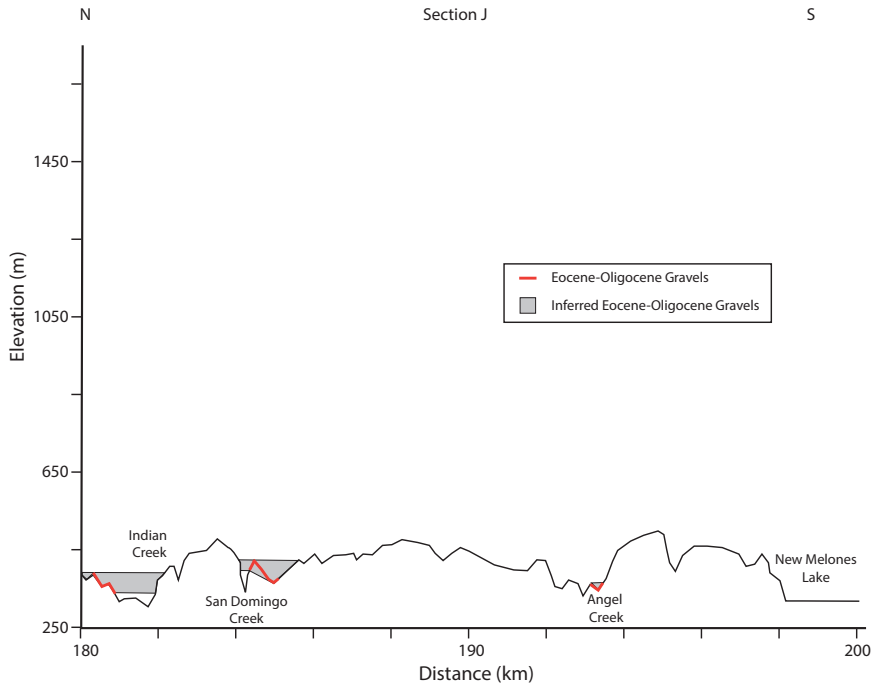
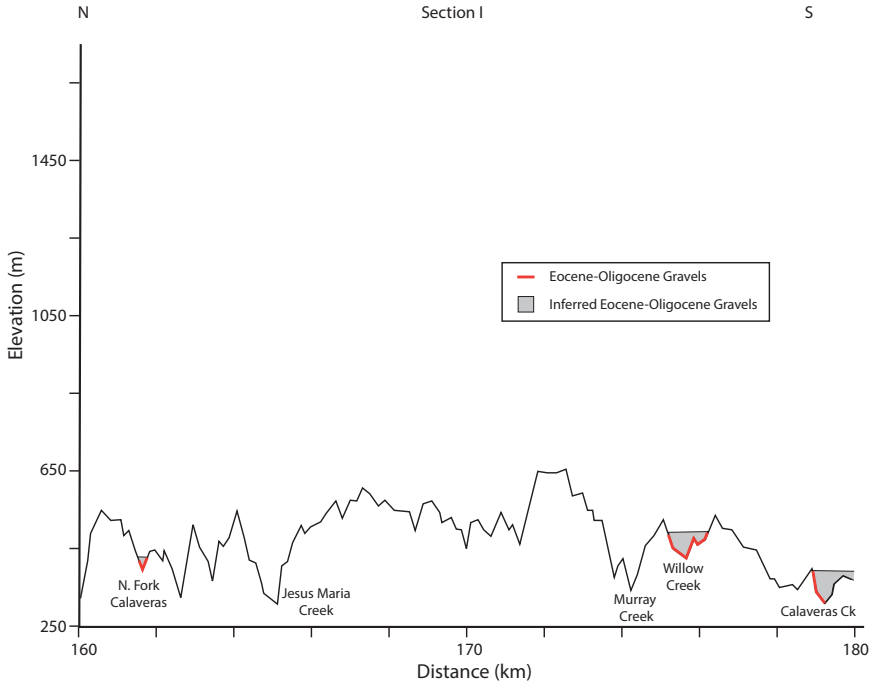


Fig. A1. Continued

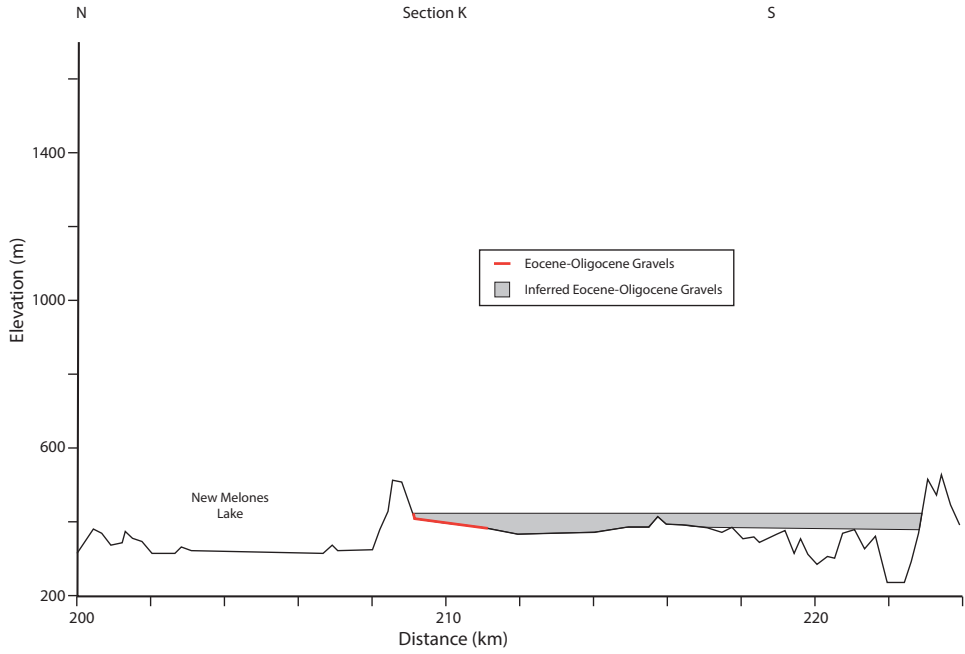


Fig. A1. Continued

CROSS SECTION 2

Each of these plots is part of a continuous north-to-south cross-section. See figure 2 for locations.

Figure A2 is section 2.

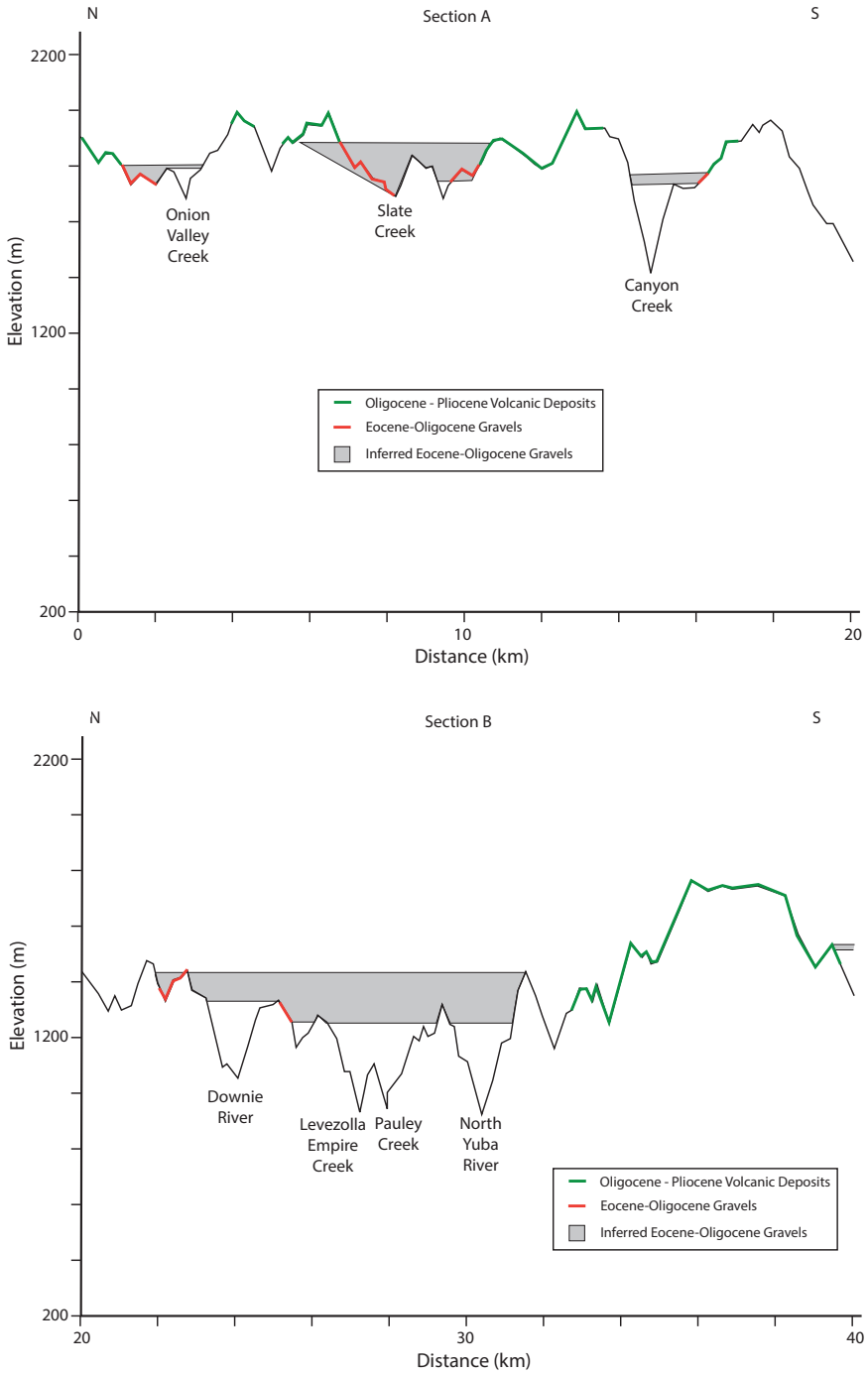


Fig. A2. Cross-section 2. Each of these plots is part of a continuous north-to-south cross-section. See figure 2 for location.

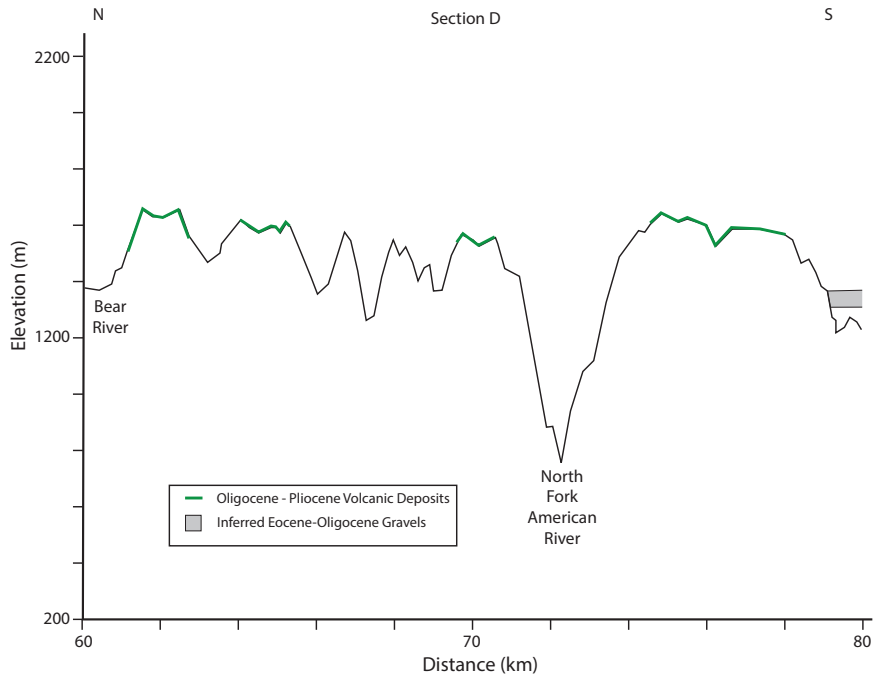
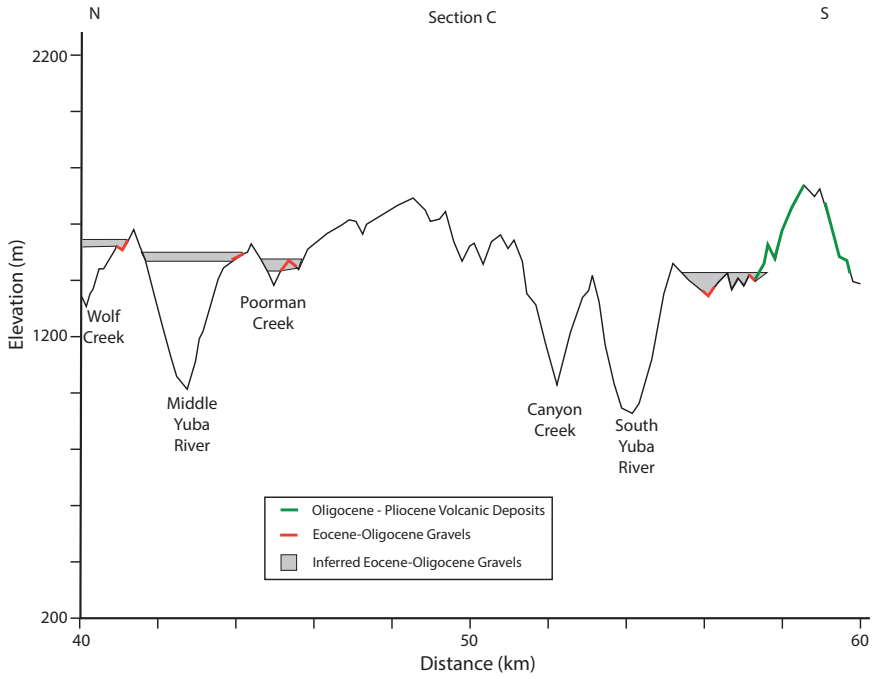


Fig. A2. Continued

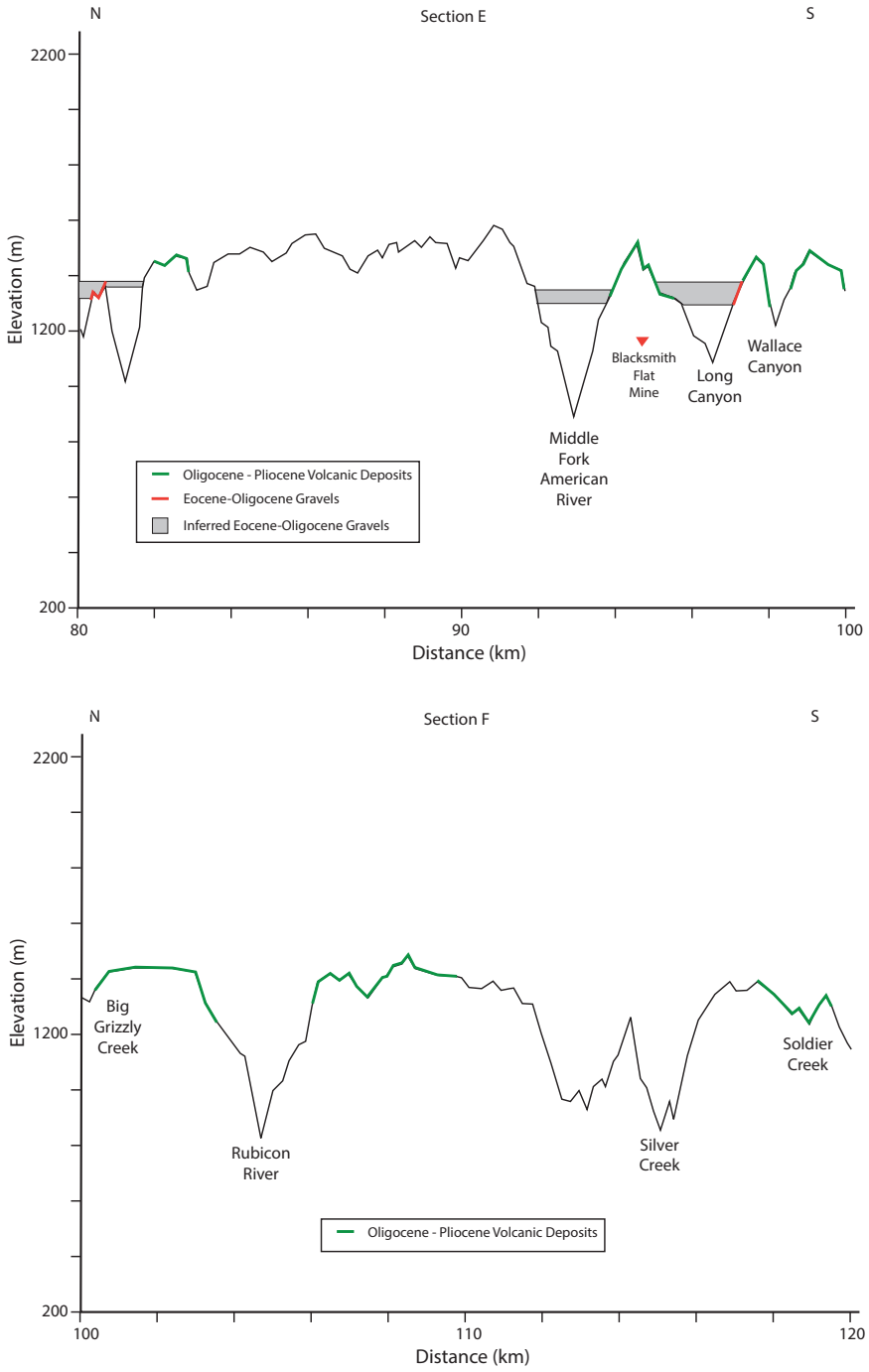


Fig. A2. Continued

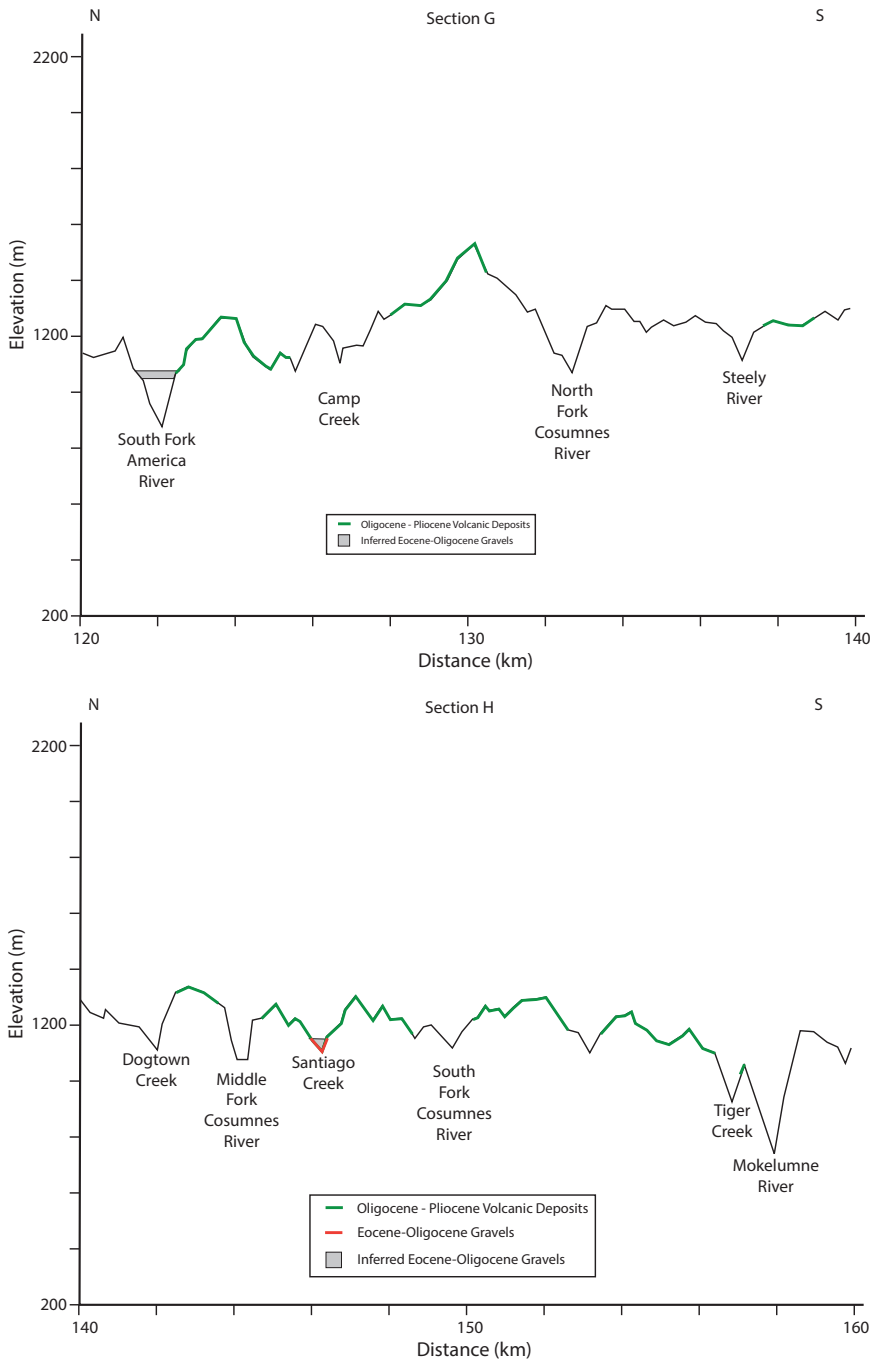


Fig. A2. Continued

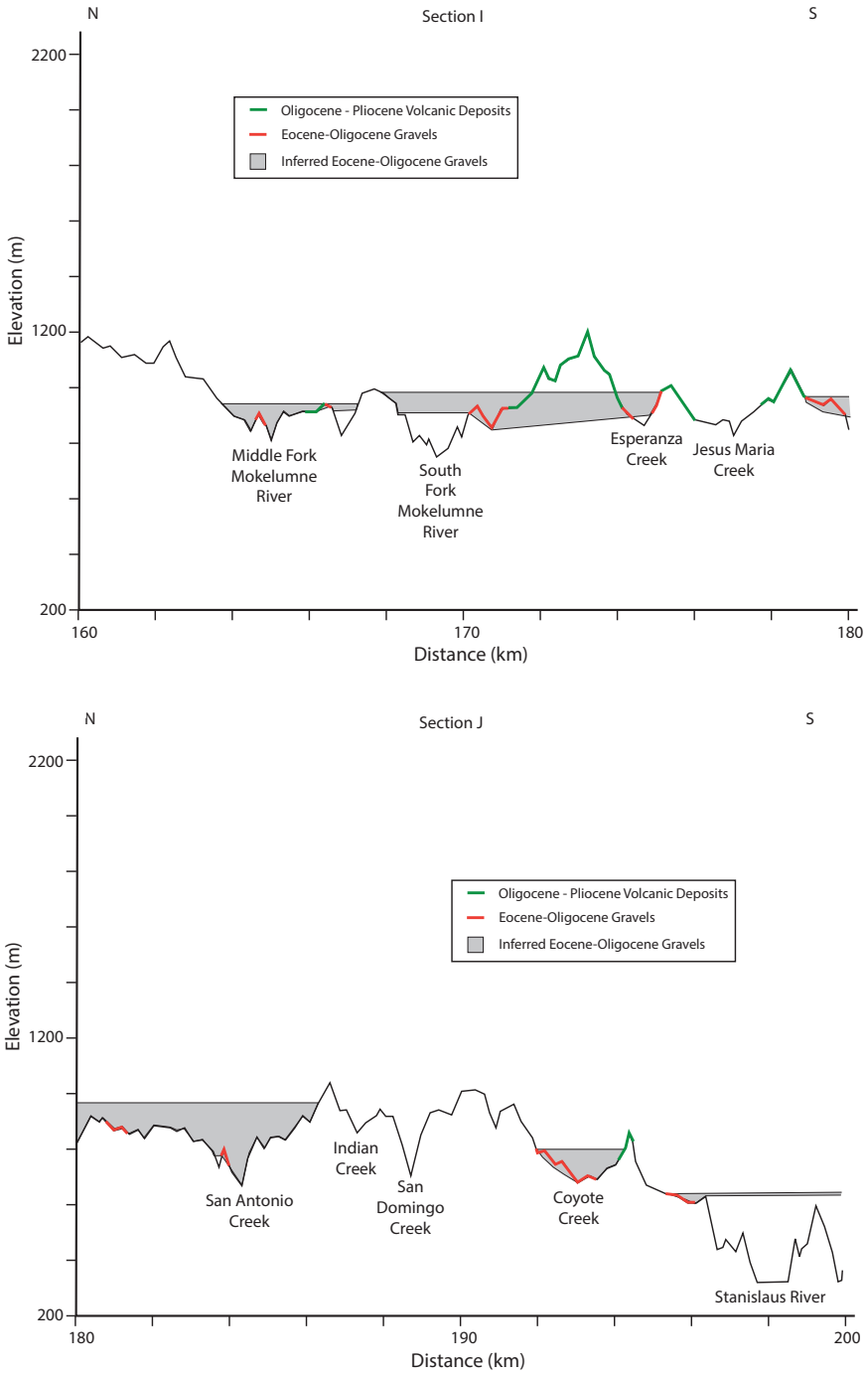


Fig. A2. Continued

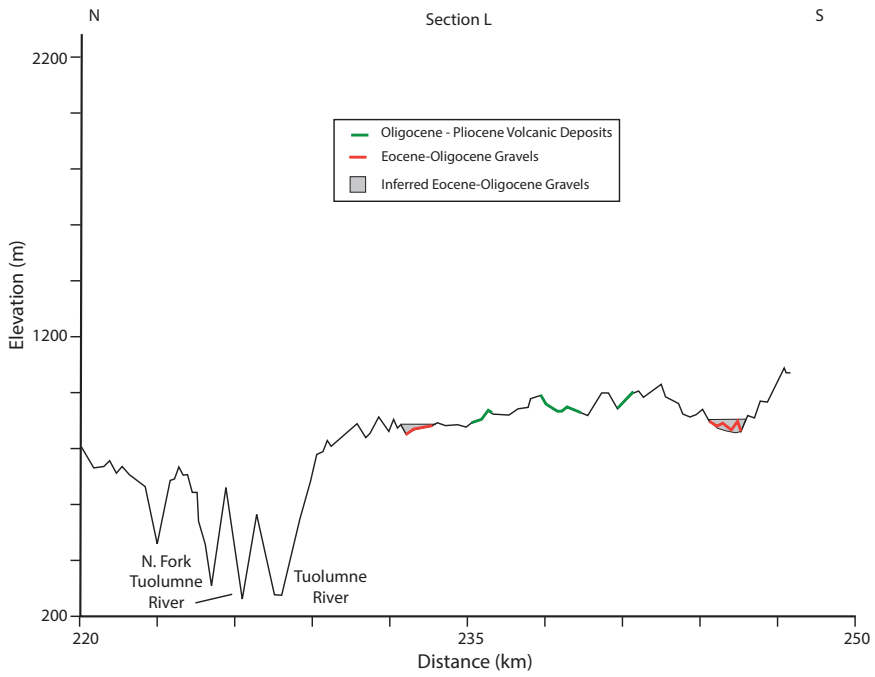
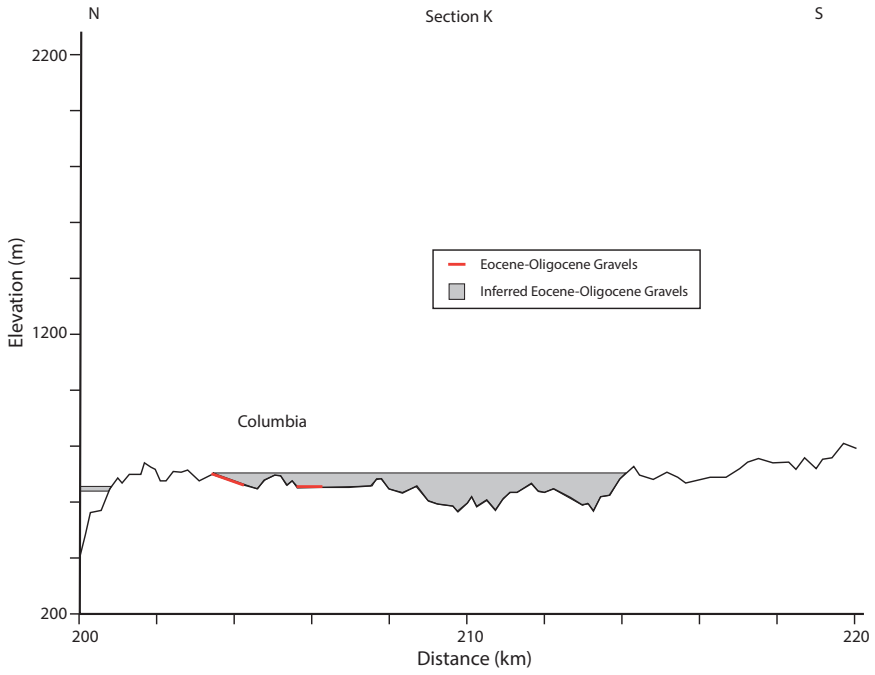


Fig. A2. Continued

CROSS SECTIONS 3 through 22

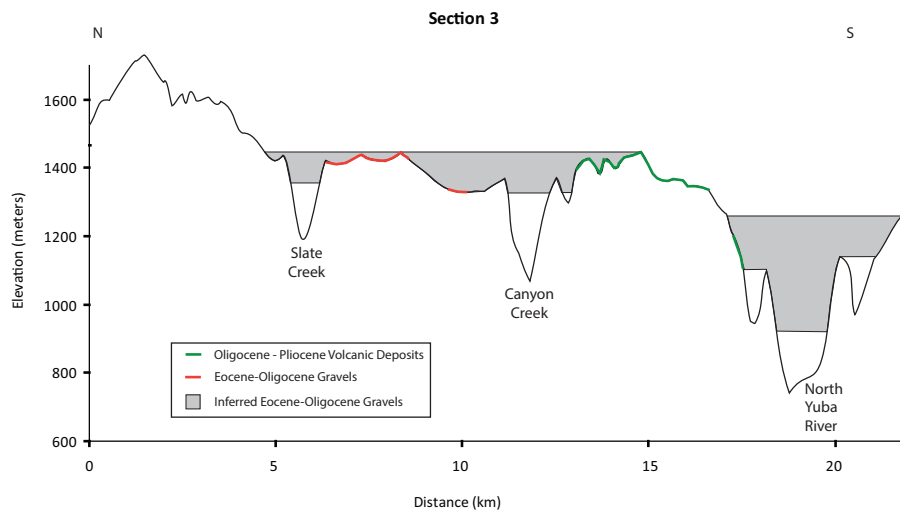


Fig. A3. Cross-section 3. Some cross-sections were too long to fit within a single page and were split into parts A and B. See figure 2 for locations of cross-sections.

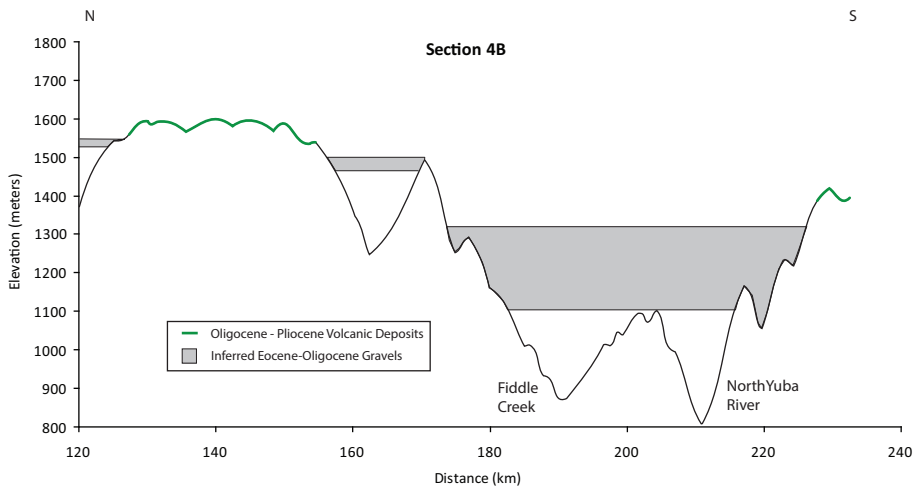
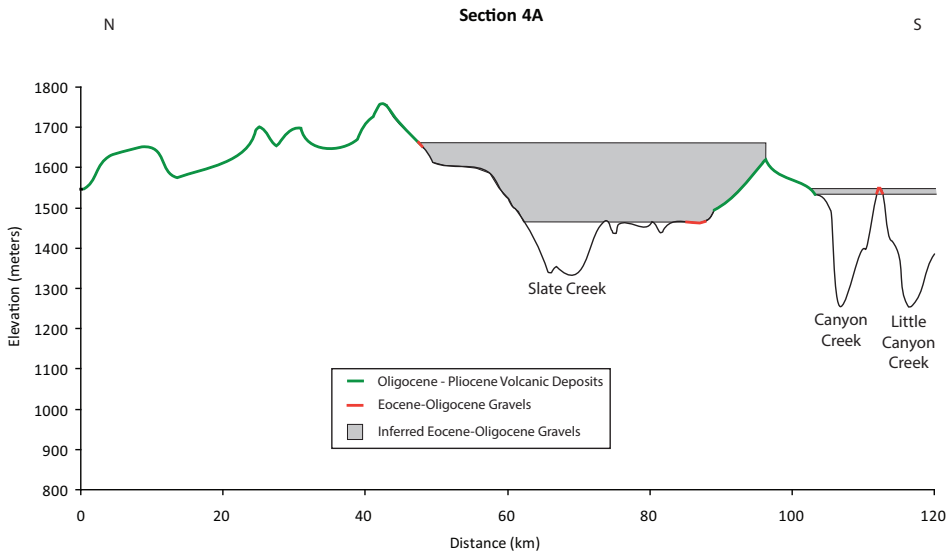


Fig. A4. Cross-sections 4A and 4B.

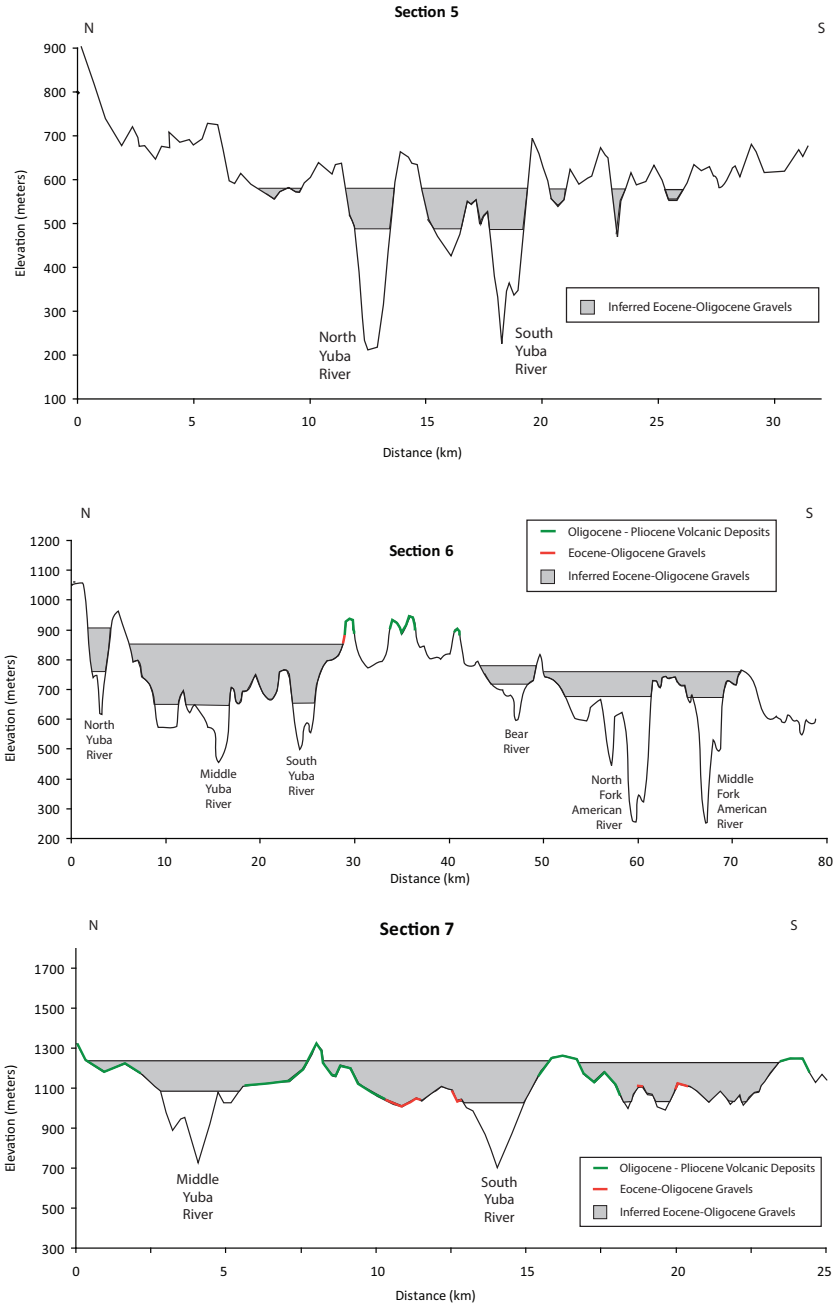


Fig. A5. Cross-sections 5, 6, and 7.

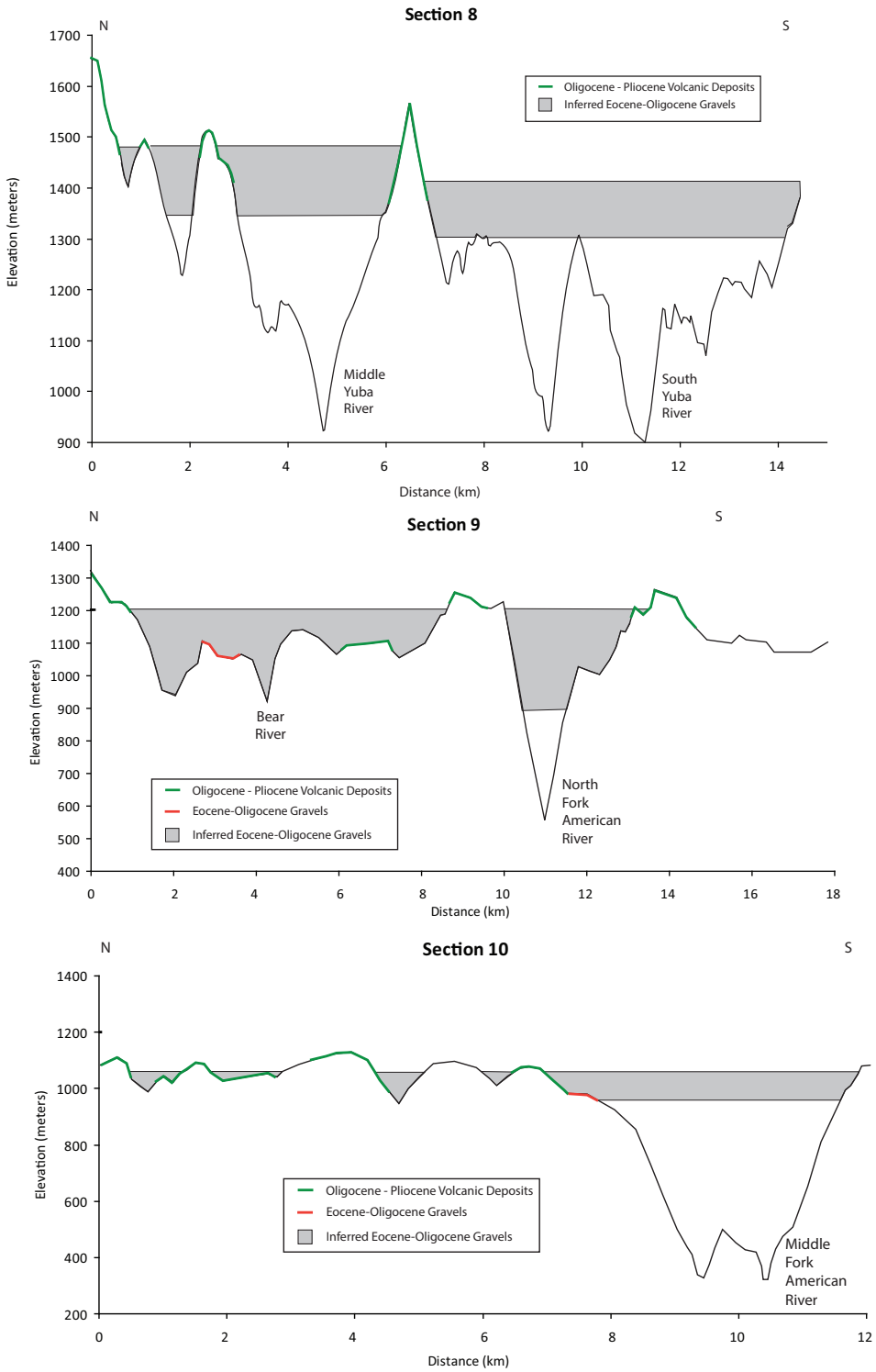


Fig. A6. Cross-sections 8, 9, and 10.

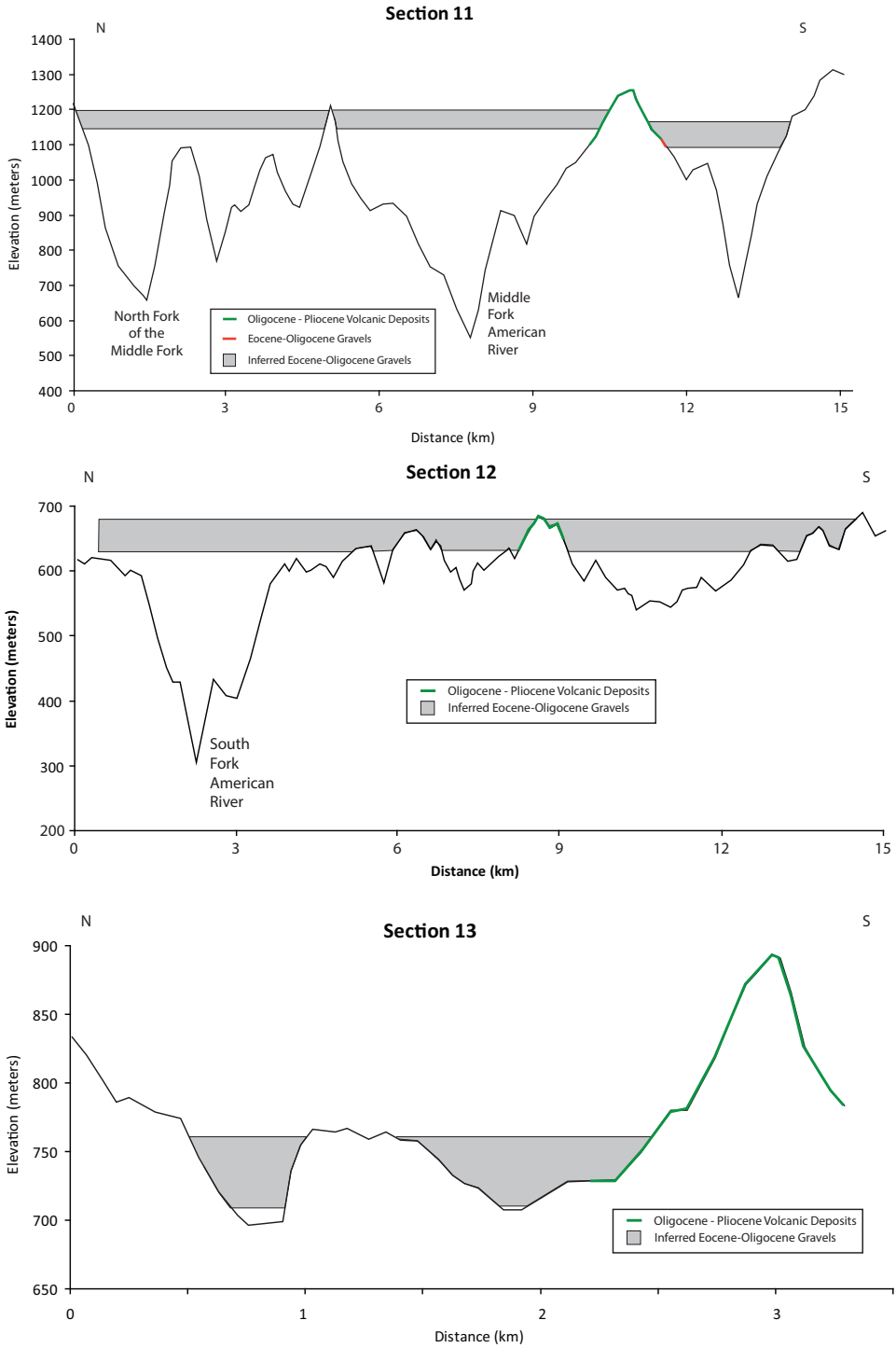


Fig. A7. Cross-sections 11, 12, and 13.

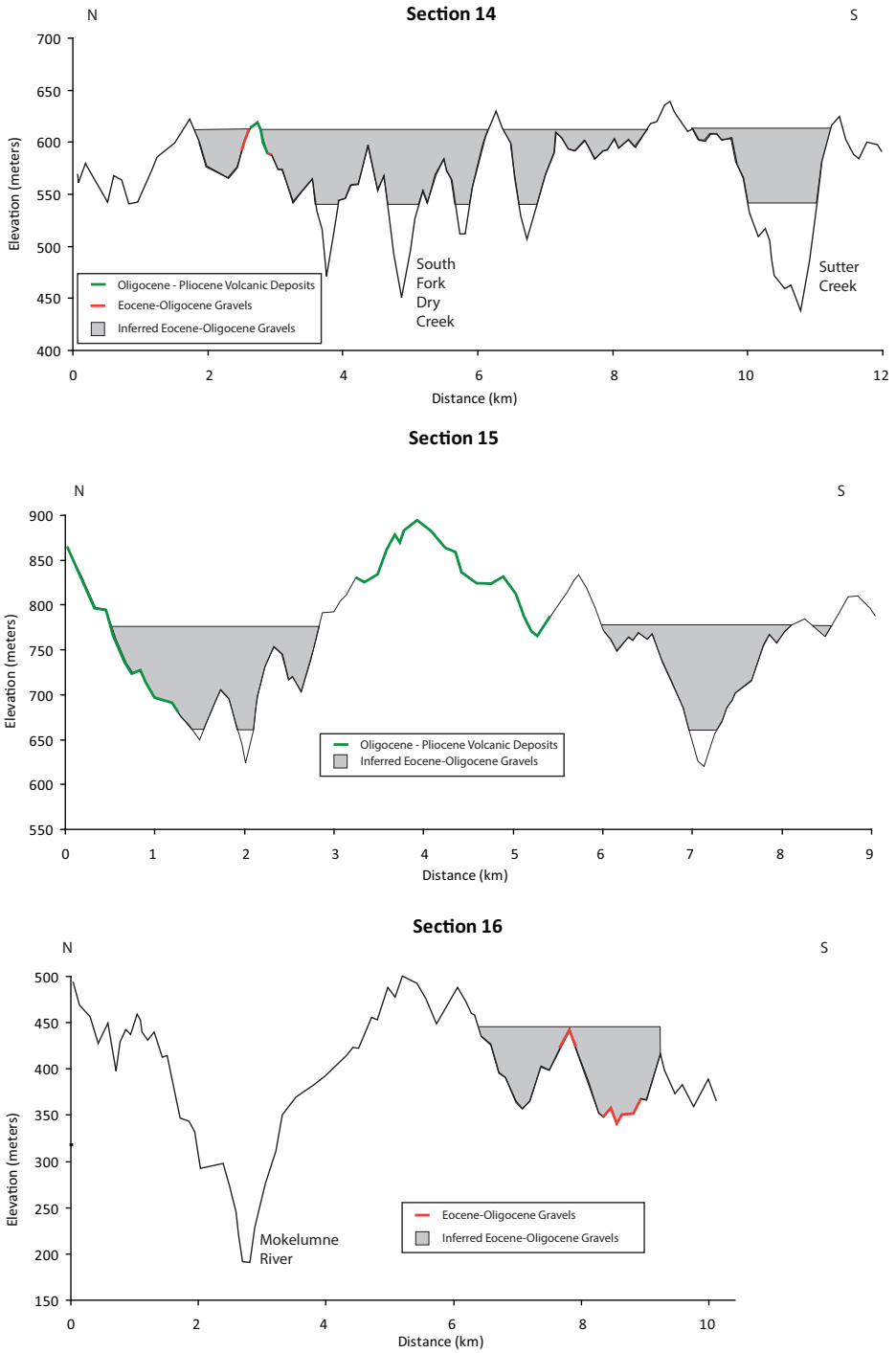


Fig. A8. Cross-sections 14, 15, and 16.

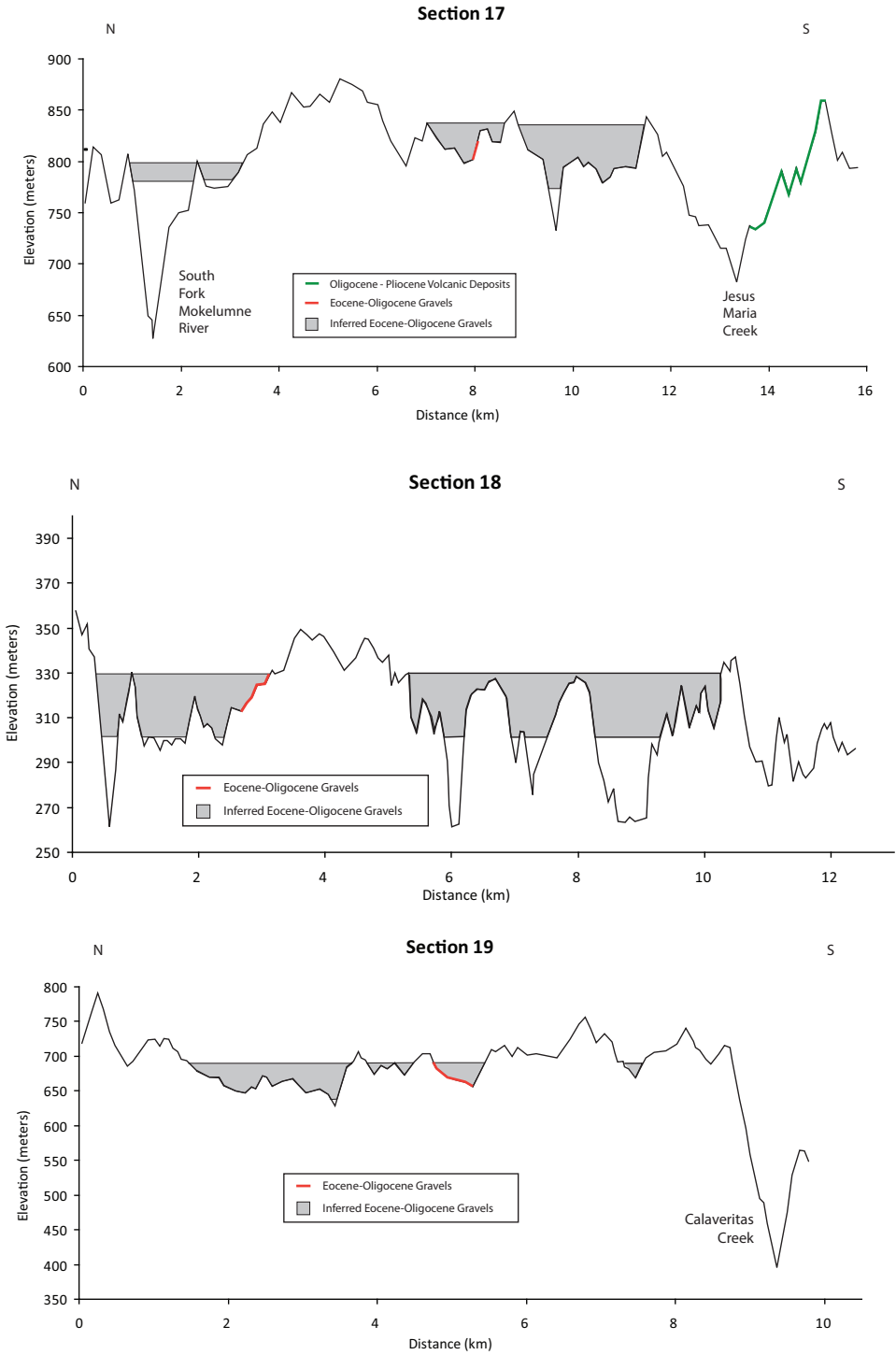


Fig. A9. Sections 17, 18, 29.

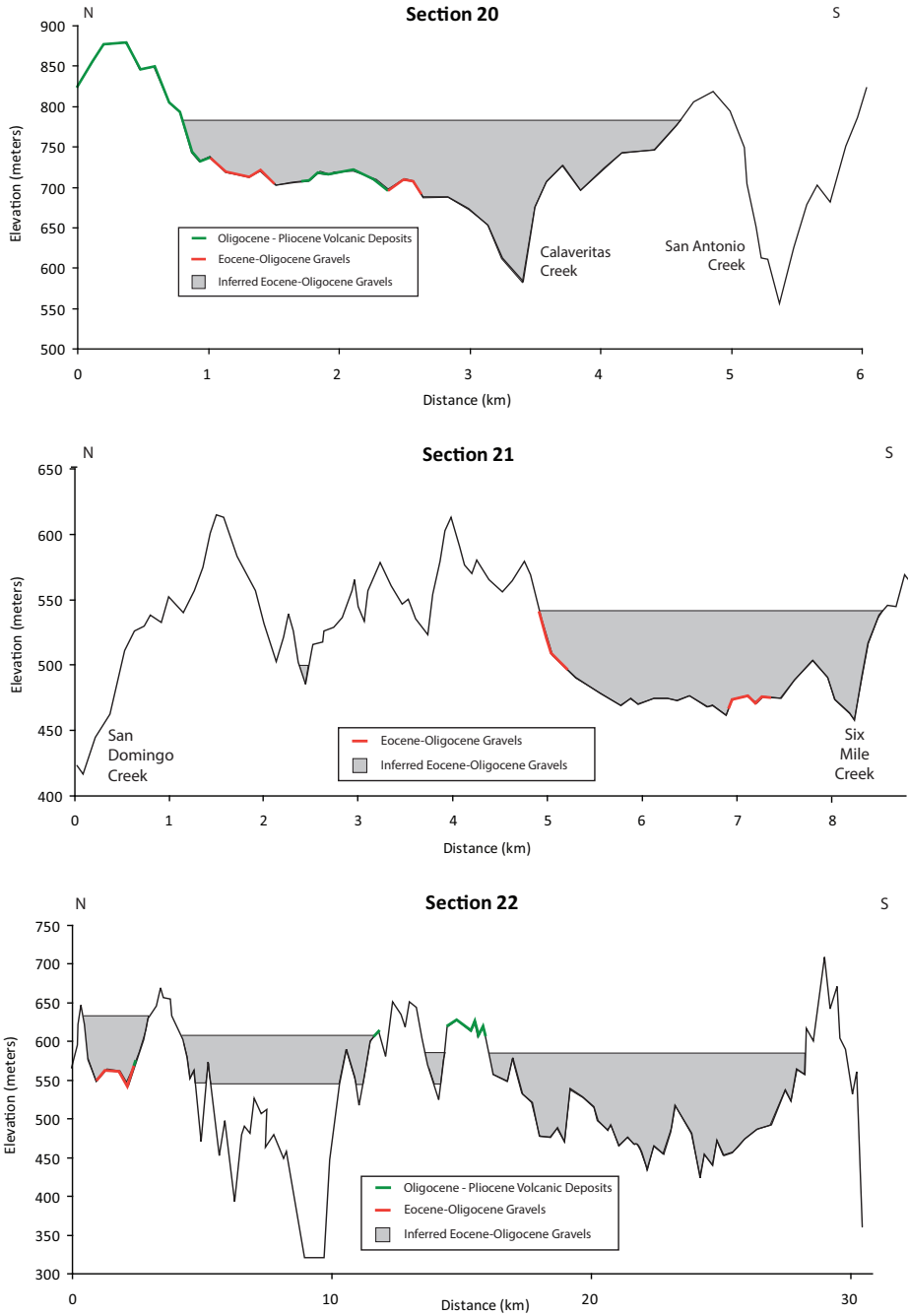


Fig. A10. Cross-sections 20, 21, 22.

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