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Architectural analysis of fluvial conglomerate in the Nanushuk Formation, Brooks Range Foothills, Alaska

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Introduction

The purpose of this report is to present the results of a sedimentological study of Aptian- to Albian-age Nanushuk Formation rocks along the north limb of the Arc Mountain anticline at the Kanayut River, Alaska (Figs. 1 and 2). The goal of this study is to define and interpret lithofacies and architectural elements for the conglomerate in the study area, and then use these interpretations to suggest a fluvial model for the river that deposited the conglomerate.

Methods

Conglomerates at the top of the Nanushuk Formation along the Kanayut River are exposed in a series of benches on the north and south sides of the Arc Mountain anticline (Fig. 2). Photomosaics of the four benches on the north side were constructed using Polaroid film. Visible bounding surfaces were drawn onto an overlay on each of the photomosaics in the field. The character of the bounding surfaces, whether they were erosional or gradational, and whether they were planar, irregular, or curved, was also recorded. Thirty-one vertical stratigraphic sections were measured on the north side of the anticline, and an additional 35 sections were measured on the south side. Paleocurrent measurements were taken on cross-bed orientations within sandstone horizons, on the long axes of logs, and on imbricated clasts where observed in gravel beds, as obvious imbrication was rare. Initially, a preliminary architectural element interpretation was made following the scheme of Miall (1996), but these initial interpretations were later changed to follow more closely the methods of Ramos and Sopeña (1983), which are more applicable to the deposits.

Lithofacies

The conglomerate at the top of the Nanushuk Formation near the Kanayut River consists of eight sedimentary facies, defined on the basis of grain size, lithology, and sedimentary structures. A description and interpretation of each facies follows.

Matrix-supported massive conglomerate (Gmm)

Lithofacies Gmm is a minor facies. It consists of beds, a few centimeters to decimeters thick, composed of matrix-supported, massive conglomerate. Clasts range from 1 mm to 8.5 cm in diameter. Clasts are composed of quartz, black-, green-, brown-, gray- and red chert, and quartzite in a coarse- to very coarse-grained sandstone matrix. The clasts are angular to rounded, poorly sorted, and rarely imbricated. Log casts and small organic fragments are scattered throughout.

Interpretation. Facies Gmm is interpreted as deposits from hyper-concentrated debris flows or bar gravels due to their lack of internal organization and matrix-supported framework (Rust, 1978; Schultz, 1984; Hubert and Filipov, 1989; Miall, 1996). These deposits occupy pre-existing topography, either within channels or on floodplain surfaces.

Clast-supported massive conglomerate (Gcm)

Lithofacies Gcm is the dominant lithofacies in the conglomerate. This facies consists of clast-supported, massive conglomerate in beds a few centimeters to decimeters thick. Clasts range from 1 mm to 21 cm in diameter, and consist of quartz, black, green, brown, gray, and red chert, and quartzite. The clasts are subangular to well rounded and poorly sorted, and the conglomerate may be normally or inversely graded. The matrix is coarse- to very coarse-grained sandstone. Small lenses of 1 mm to 1 cm diameter clasts, composed predominantly of black chert, are common. Log casts and small organic fragments are scattered throughout.

Interpretation. This facies is interpreted as bedload gravel that was deposited from clast-by-clast accretion during higher discharges. Characteristics that support this interpretation include thin bedding a few centimeters to decimeters thick, and a clast-supported framework with no internal organization (Smith, 1974; Hein and Walker, 1977; Miall, 1977; Rust, 1978, Karpeta, 1993).

Clast-supported horizontally stratified conglomerate (Gh)

Lithofacies Gh occurs in most of the outcrops in the study area. It occurs as beds a few centimeters to decimeters thick, composed of clast-supported, horizontally stratified conglomerate. The horizontal stratification is usually recognized by slight clast size variations between crude horizontal layers. Clasts in this lithofacies range from 1 mm to 7.5 cm in diameter. The clasts are composed of quartz, black, green, brown, gray, and red chert, and quartzite. The clasts are subangular to rounded and poorly sorted in a matrix of coarse-grained sandstone. Log casts and small organic fragments are found strewn throughout.

Interpretation. The characteristics of this lithofacies, specifically horizontal stratification of clast-supported conglomerate, support the interpretation that lithofacies Gh resulted from the migration of longitudinal bedforms (Rust, 1972; Gustavson, 1974; Smith, 1974; Smith, 1990; Miall, 1996).

Clast-supported planar cross-stratified conglomerate (Gp)

Lithofacies Gp is a minor component of the conglomerate. This lithofacies is composed of beds a few centimeters to decimeters thick that consist of clast-supported, planar cross-bedded conglomerate. Clasts in the conglomerate range from 2 mm to 8.4 cm in diameter and consist of quartz, black, green, brown, gray, and red chert, and quartzite. The clasts are subangular to rounded, with a small percentage being well rounded. The clasts are poorly sorted in a coarse-grained to very coarse-grained sandstone matrix. Log casts and small organic fragments are found throughout this facies.

Interpretation. Planar cross-stratification in a clast-supported conglomerate indicates that facies Gp was deposited by the migration of large, isolated, gravelly, straight-crested, transverse bedforms (Miall, 1977; Hein and Walker, 1977; Smith, 1990; Karpeta, 1993).

Cross-bedded sandstone (Sc)

Lithofacies Sc is a small proportion of the conglomerate package overall, but it is a major component of the sandstone fraction. This facies occurs as discontinuous lenses or beds a few centimeters to decimeters thick, composed of cross-bedded sandstone. The sandstone is predominantly coarse- to very coarse-grained, and rarely, medium-grained. This facies includes clasts from 4 mm to 4 cm in diameter, either randomly scattered within beds, or as pebble layers along bedding planes. The sandstone grains are angular to sub-rounded and poorly to moderately sorted. Log casts and small organic fragments are rarely found.

Interpretation. This facies was deposited by the migration of straight- or sinuous-crested dunes, as indicated by the cross-bedding in the sandstone (Harms and others, 1982; Allen, 1984; Miall, 1996). It occurs on gravel bar tops and sides, in falling to shallow water conditions (Boothroyd and Ashley, 1975; DeCelles and others, 1991; Miall, 1996).

Horizontally bedded sandstone (Sh)

Lithofacies Sh is also a small component of the package as a whole, but the primary component of the sandstone fraction. It consists of discontinuous lenses, or beds, a few centimeters to decimeters thick. The sandstone is horizontally bedded, and typically coarse-grained, but medium-grained lenses or beds do occur. The sandstone grains are angular to sub-rounded and poorly to moderately sorted, with 1 cm to 3.8 cm diameter clasts occurring locally as lenses or on bedding planes.

Interpretation. Lithofacies Sh forms in lower and upper flow regimes, where horizontally bedded sandstones of this grain size fraction occur (Boothroyd and Ashley, 1975; Harms and others, 1982; Allen, 1984; Todd, 1989; Maizels, 1989; Miall, 1996; Jo and others, 1997). It may occur on gravel bar tops and sides in falling to shallow water, or in high flood stage flows that are not confined to channels (for example, sheet floods) (DeCelles and others, 1991; Miall, 1996).

Massive sandstone (Sm)

Lithofacies Sm is a minor component of the conglomerate package, but it commonly occurs within sandstone-rich sections. This lithofacies consists of medium- to coarse-grained massive sandstone that occurs as discontinuous lenses or layers a few centimeters to decimeters thick. The sandstone grains are angular to sub-rounded and poorly to moderately sorted. Scattered pebbles, ranging from 1 mm to 10 cm in diameter, occur throughout. Log casts and small organic fragments are rare.

Interpretation. The lack of sedimentary structures indicates that lithofacies Sm may have been deposited by sediment-gravity flows, or by rapid deposition during falling flow conditions (Todd, 1989; Maizels, 1989; Miall, 1996; Jo and others, 1997). This lithofacies may also result from post-depositional modification, such as dewatering or bioturbation (Miall, 1996).

Ripple cross-laminated sandstone (Sr)

Lithofacies Sr forms a very minor part of the conglomerate package. It occurs as ripple cross-laminated sandstone in beds a few centimeters thick. The ripples are straight-crested and asymmetrical. It is comprised of coarse-grained sandstone that is angular to sub-rounded and poorly to moderately sorted.

Interpretation. Ripple cross-lamination indicates that this lithofacies resulted from migrating current ripples (Harms and others, 1982; Miall, 1996; Nichols, 1999).

Architectural Elements

The conglomeratic portion of the Nanushuk Formation at the Kanayut River has been divided into six architectural elements. Units of massive, clast-supported conglomerate (MCC) dominate, with smaller proportions of lateral accretion conglomerate (LAC) and channel-fill conglomerate (CH) present. Massive, matrix-supported conglomerate (MMC), tabular cross-stratified conglomerate (TCC), and units of coarse-grained to very coarse-grained sandstone (SS) play relatively minor roles in these deposits.

Massive, clast-supported conglomerate (MCC)

This element is the most common in the conglomerate. It occurs as sheets, usually tabular-shaped bodies, with a flat base bounded by a fourth-order bounding surface according to the classification of Miall (1996). The basal contact can be sharp or erosional. MCC is typically found in vertical successions, consisting of sheets 1 to 7 m thick and tens of meters wide (Fig. 3). The upper contact is typically flat or eroded. Common lithofacies include Gcm and Gh with minor amounts of Sc, Sh, and Sm. Lithofacies Gh is commonly identified by slight variations in clast size between crude horizontal layers. Sheets of MCC may grade laterally into other elements such as MMC or LAC. Scour surfaces or units of SS between them may delineate individual conglomeratic units within a sheet. Individual units may be hard to define when conglomerate is overlain by conglomerate.

Interpretation. Sheets of MCC are interpreted as braided fluvial channel deposits. The absence of lateral accretion surfaces and other types of internal organization imply shallow channels with relatively few large, well-developed macroform bars (Eberth and Miall, 1991). Massive or crude horizontal bedding in conglomerate is commonly attributed to deposition by a longitudinal bar in straight, shallow reaches with high rates of sediment discharge (Ore, 1964; Williams and Rust, 1969; Smith, 1974; Hein and Walker, 1977; Rust, 1978; Ramos and Sopeña, 1983; Miall, 1996). Longitudinal bars are mid-channel bars that are elongated parallel to flow in a diamond or lozenge shape. Leopold and Wolman (1957) described the process by which they are formed using flume experiments and field observations. In an originally straight, single or undivided channel, gravel is carried near the deepest part of the channel. As the flow wanes, gravel is deposited within the channel in the form of a “diffuse gravel sheet,” as described by Hein and Walker (1977). Finer particles are trapped within the original deposit and coarser material is deposited downstream. The flow is diverted around the bar and the stream erodes its banks to compensate.

Massive, matrix-supported conglomerate (MMC)

This element is one of the least common elements, only occurring on Bench 1N (Fig. 3). It consists of discontinuous successions of conglomerate sheets with flat basal surfaces and upper fourth-order bounding surfaces. The basal contacts can be sharp or erosional. Element MMC is composed of individual units of lithofacies Gmm with minor amounts of Gcm, Sm, and Sc. Sheets of MMC are 1 to 13 m thick, extend tens of meters laterally, and show no internal structure.

Interpretation. Sheets of MMC are interpreted as sediment gravity flow deposits that occupy channels, as indicated by their lack of internal structure and character of their bounding surfaces (Miall, 1996). Because of the high levels of sediment concentration (>40%), the flow is described as hyperconcentrated.

Tabular cross-stratified conglomerate (TCC)

TCC is also a minor component of the conglomerate in the study area, and is only documented at Bench 2N (Fig. 4). It occurs as laterally continuous sheets, 1 to 6 m thick, and tens of meters wide. Lithofacies in this element include Gp, and minor amounts of Sc, Sh, and Sm. The foresets dip at ~20º and end at an oblique angle to the bottom contact, forming planar foresets. The bottom contact can be either erosional or sharp, and both top and bottom contacts are fourth-order bounding surfaces.

Interpretation. The presence and character of the foresets indicate that element TCC was deposited as transverse barforms that develop at low rates of discharge (Ore, 1964; Rust, 1972; Smith, 1974; Ramos and Sopeña, 1983; Smith, 1990; Miall, 1996). Transverse bars occur in channels that are deep and are confined between banks that are relatively narrow in width (Rust, 1972). Hein and Walker (1977) observed the occurrence of transverse barforms in the same channels as longitudinal barforms, but under conditions of reduced sediment and water discharge. Transverse bars may also be deposited as large-scale bedforms that formed during flood stage (Collinson, 1970; Smith, 1971).

Lateral accretion conglomerates (LAC)

This element occurs as tabular bodies of conglomerate bounded by fourth-order surfaces on the top and bottom, with gently dipping third-order surfaces internally (Fig. 5). The basal contact may be sharp or slightly erosional. The top contact is either flat or slightly scoured. Lithofacies in this element include Gcm, with minor components of Sc, Sh, and Sm. Element LAC ranges in thickness from 1 to 4 m, and extends laterally a few tens of meters. The internal accretion surfaces have gentle dips of 6º to 16º. Where paleocurrent measurements could be taken, the flow direction varies significantly from the direction of the lateral accretion surfaces. Lateral accretion sets vary in thickness from 20 to 150 cm, with no visible changes in clast size. Element LAC may grade laterally into element MCC.

Interpretation. Element LAC reflects changes to existing bar topography during diminishing flow (Ramos and Sopeña, 1983). When the bar topography increases significantly enough to affect the water flow so that clasts cannot be moved over it, or the flow diminishes but is still strong enough to move clasts along the margins of the bar, element LAC may develop. These lateral accretion surfaces dip toward the channels next to the bars and form at an angle less than 90º to the general flow. Costello and Walker (1972) and Smith (1974) have described similar processes.

Channel-fills (CH)

Element CH ranges in thickness from 0.5 to 7 m and can extend from one to tens of meters laterally. This element has the highest proportion of sandy lithofacies compared to the rest of the dominantly conglomeratic elements. Element CH is composed of different fills depending upon the scale. Smaller scale features may be filled only with sandy lithofacies and lie above a fourth-order surface (Fig. 6), whereas larger scale features may have sandy and gravelly components above a fifth-order surface. Examples of this were described by Williams and Rust (1969) and Bristow (1987). Some of the major channel-fills consist of sandy facies at their base that grade up into gravelly facies (Fig. 3). All the basal surfaces are erosional with a typical concave-up shape. Internal third-order surfaces may mimic this shape (Fig. 3).

Interpretation. Element CH may have formed next to longitudinal bars (Smith, 1990), or it may have resulted from scouring the upper surface of an existing longitudinal bar. Smaller-scale features of element CH may represent the dissection of an existing bar by small, chute channels during falling water (Miall, 1996). Common fill patterns in the larger features of this element include the basal surface below various sandy facies passing vertically into gravelly facies. This may represent the formation of a new active channel (Miall, 1996). It begins as a chute or crevasse channel with deposits of Sh, Sm, or Sc forming at lower rates of discharge. Then, as the flow increases and diverts into this newly developing channel, the competence gradually increases enough to deposit coarser, gravelly facies on top while not eroding away all of the underlying sandy facies.

Units of coarse- to very coarse-grained sandstone (SS)

This element forms thin beds, 0.3 to 2 m thick, that extend up to tens of meters laterally, or small lenses up to 1 m thick and a few meters wide. As sandstone forms a relatively small proportion of the overall package, this element is a minor one in this study. However, it does occur in conjunction with all other elements. Element SS is bounded by fourth-order surfaces when not an intricate part of another element. Its basal contact may be sharp or erosional, and its top contact is typically flat.

Interpretation. The thicker, more laterally continuous beds of this element are interpreted as crevasse splay and floodplain deposits (Ramos and Sopeña, 1983; Miall, 1996). These are produced during high flood stage when water is not confined to existing channels. The bed may extend laterally over various other deposits, including those of longitudinal or transverse bars, or channels (Ramos and Sopeña, 1983). The smaller lenses of this element commonly occur in conjunction with deposits of MCC and TCC. These are interpreted as bar tops and edges that are deposited during falling or waning water flow (Miall, 1996). As the flow decreases, it loses the competency to carry a sand fraction, and deposits of facies Sm, Sc, and Sh develop in channels adjacent to bars or on tops of bars.

Discussion

Fluvial Style

Longitudinal bars dominate the deposits in the study area, with a lesser proportion of identifiable channels, transverse bars, crevasse splays, and sediment-gravity flow deposits. As noted earlier, the dominance of longitudinal bars reflects shallow water depths in a fluvial system (Eberth and Miall, 1991). The dominance of identifiable barforms versus sediment-gravity flow deposits suggests prevailing bed-load transport. The presence of longitudinal bars with simple internal organization and deposits of lateral accretion are interpreted as characteristic features of a gravelly stream with distinct high and low discharges (Smith, 1974). Therefore, the conglomerate in the upper part of the Nanushuk Formation near the Kanayut River is interpreted as the deposits of high energy, gravel-bed, braided rivers, as indicated by the overwhelming proportion of element MCC, rare channels with margins that are hard to identify, and rare to trace proportions of crevasse splay and sediment-gravity flow deposits.

Miall (1996) described a facies model for a shallow, gravel-bed braided river. Most of the characteristics he uses to describe this fluvial style could also be used to describe the deposits in this study. These characteristics include rare to absent sediment-gravity flow deposits, rare recognizable channel margins in outcrop, and the dominance of his element GB (gravel bars and bedforms), consisting of tabular bodies with about 5 percent element SB (sandy bedforms) as lenses or wedges. A representative vertical section and an architectural block diagram from Miall (1996) for a shallow, gravel-bed braided river consists of a changing system of unstable, low-sinuosity channels. Channel depths are typically on the order of 1 m. The deposits in the system form distinctive thick, multi-story conglomerates, similar to the deposits in the Kanayut River area.

Ramos and Sopeña (1983) also identified the conglomerates in their study as deposits of “relatively high energy streams with prevalent bedload transport.” The architectural elements in this study are based on those of Ramos and Sopeña (1983), and the deposits of this study and their study are remarkably similar. One important distinction is the very rare preservation of convex-up bar tops in this study versus the work of Ramos and Sopeña (1983). They suggested that common preservation of such features indicates rapid subsidence during deposition. We interpret the virtual lack of these features in this study to mean little to no subsidence during deposition in the study area. Smith (1990) also cited the absence of floodplain sediments and paleosols and a multi-story geometry in outcrop to strongly suggest that rates of channel migration were high relative to rates of subsidence. The deposits in this study exhibit all of these features.

Quantitative Interpretation of Paleochannel Geometry and Paleohydraulics

Initial estimates for channel width and channel depth can commonly be estimated directly from the field data. The key is to find channel morphologies that are not eroded. The conglomerate in this study does not have signs of high levels of compaction, as evidenced by sutured grain boundaries or flattened clasts, for example. Therefore, channel width and depth can be estimated from measurements taken in the field.

However, these numbers are mere estimates and may not reflect the actual width and depth of channels at the time of deposition.

Five channels were observed in the outcrops. Three are considered major channels, due to their greater lateral extent, and two are minor channels. Major channels range in width from 79.3 m to 85.3 m, and minor channels from 12.4 m to 29.8 m. Channel depths range from 3.6 m to 7.1 m for the major channels, and 1.0 m to 2.9 m for the minor channels. The width:depth ratio was calculated for all of the channels, and ranges from 10.2 to 22.0.

A crude estimate of water discharge (Q) can be calculated from channel width and depth measurements (Chang, 1980). Water discharge (Q) can be estimated using the following equation:

$$B = 1.8\ Q^{0.5}$$

where B = channel width of gravel streams. Estimates of water discharge calculated for the conglomerate channels in the Nanushuk Formation vary from 55.0 m^3/s to 60.0 m^3/s for major channels, and from 1.3 m^3/s to 7.7 m^3/s for minor channels.

The paleogeographic setting of this ancient river was probably very similar to modern braided fluvial systems in northern Alaska that extend from the northern foothills of the Brooks Range to the Arctic coast of Alaska. This setting consists of rolling hills near a topographic high, with relatively high stream gradients. The modern Sagavanirktok River in northern Alaska is a good analog for the paleoriver in the Nanushuk Formation conglomerate in the study area. The Sagavanirktok River, at Pump Station 3 on the Dalton Highway, has had an average discharge of 44.6 m^3/s from 1983 to 2000 (http://ak.water.usgs.gov/Publications/water-data/WY96/sw.stations.list.html). The maximum recorded discharge occurred in 1995 at 60.5 m^3/s, and the minimum recorded discharge occurred in 1983 at 28.2 m^3/s. These numbers are comparable to the estimates for water discharge in this study.

Summary and Conclusions

The conglomerate of the Nanushuk Formation has been divided into eight lithofacies: (1) massive matrix-supported, (2) massive clast-supported, (3) horizontally stratified, and (4) planar cross-stratified conglomerate; (5) cross-bedded sandstone, (6) horizontally-bedded sandstone, (7) massive sandstone, and (8) ripple cross-laminated sandstone.

Six architectural elements have been defined for these units.

1) Sheets of massive, clast-supported conglomerate (MCC) are interpreted as the deposits of longitudinal barforms.
2) Debris flows deposited sheets of massive, matrix-supported conglomerate (MMC).
3) The migration of transverse barforms deposited tabular, cross-stratified conglomerate (TCC).
4) Lateral accretion conglomerates (LAC) were deposited adjacent to bars during diminishing flow.
5) Channels (CH) may have existed adjacent to longitudinal bars, or may have crosscut barforms, eroding the upper surface.

6) More extensive units of coarse- to very coarse-grained sandstone (SS) may represent crevasse splay and floodplain deposits, whereas smaller, more confined units found in conjunction with elements MCC and TCC may represent bar tops and edges in falling discharge.

High-energy, gravel-bed braided rivers deposited the conglomerate in the Nanushuk Formation. The paleotopography was probably very similar to fluvial systems in northern Alaska that extend from the northern foothills of the Brooks Range to the Arctic coast of Alaska.

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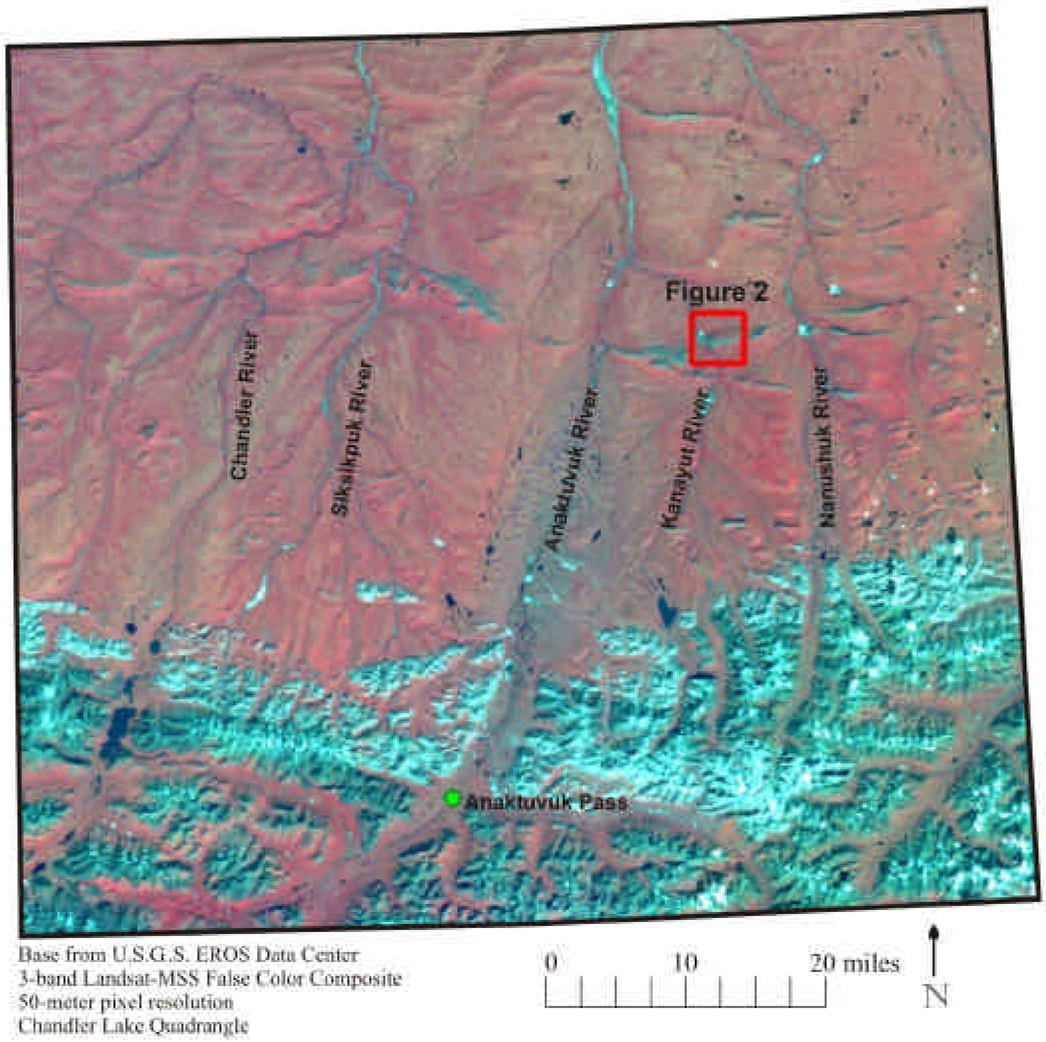

Figure 1. Satellite image of the Chandler Lake quadrangle in northern Alaska, showing location of major rivers, villages, and the study area.

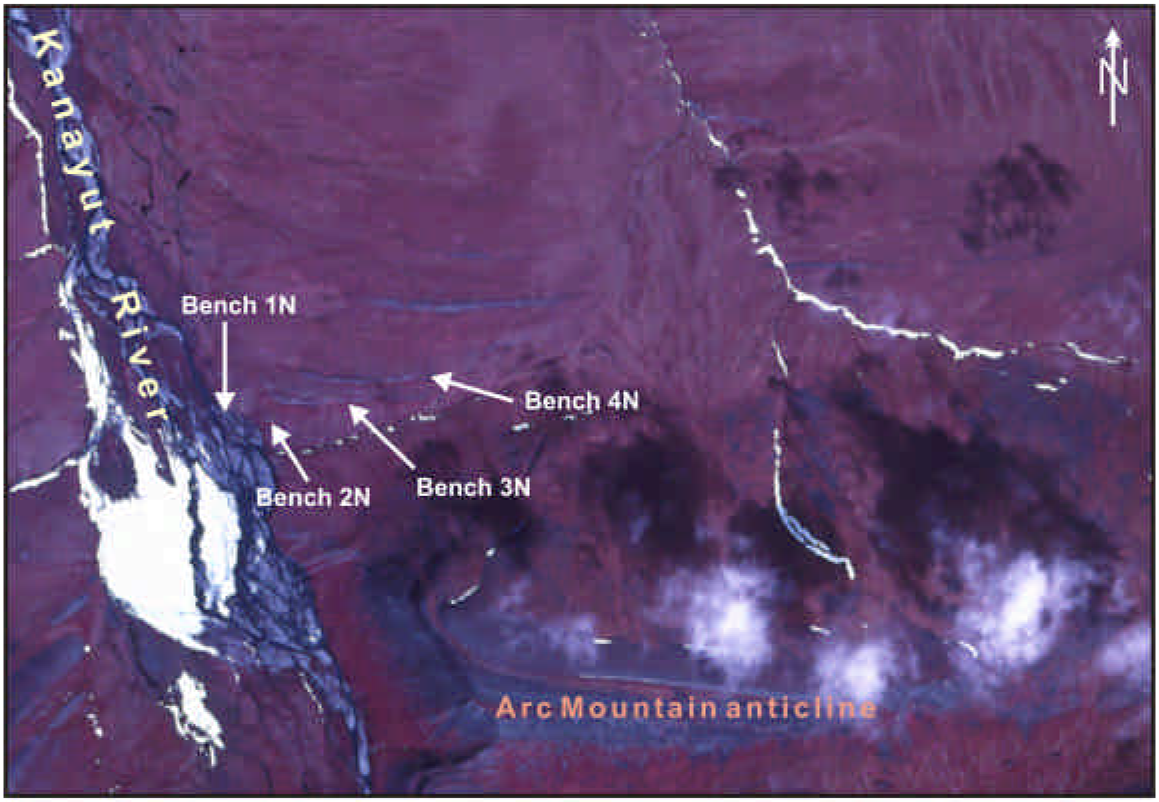

Figure 2. Air photo of study area, showing the four benches measured in this study, located on the north side of the Arc Mountain anticline.

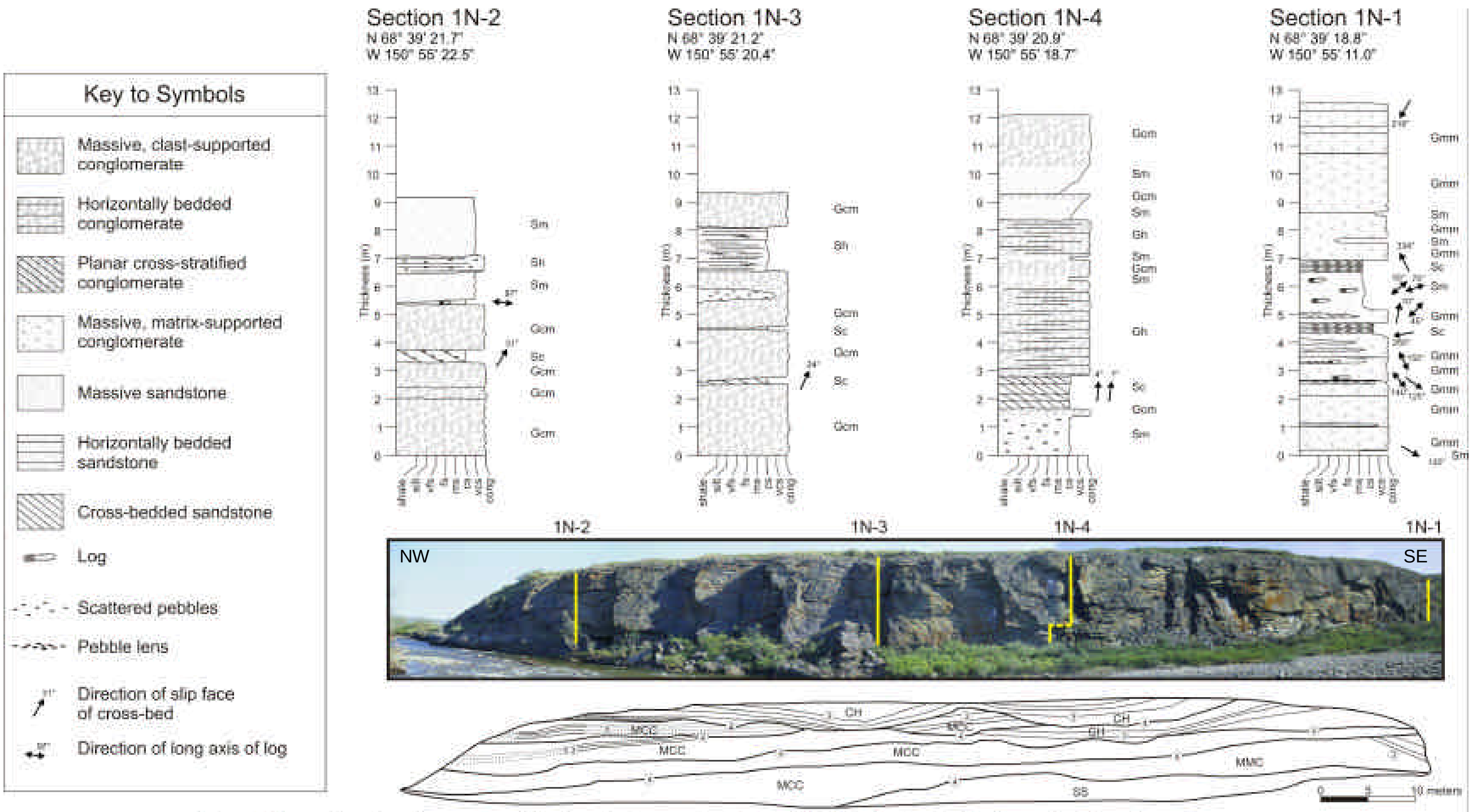

Figure 3. Measured sections, photomosaic, and line drawing interpretations for Bench 1N. Numbers in circles indicate order of bounding surface.

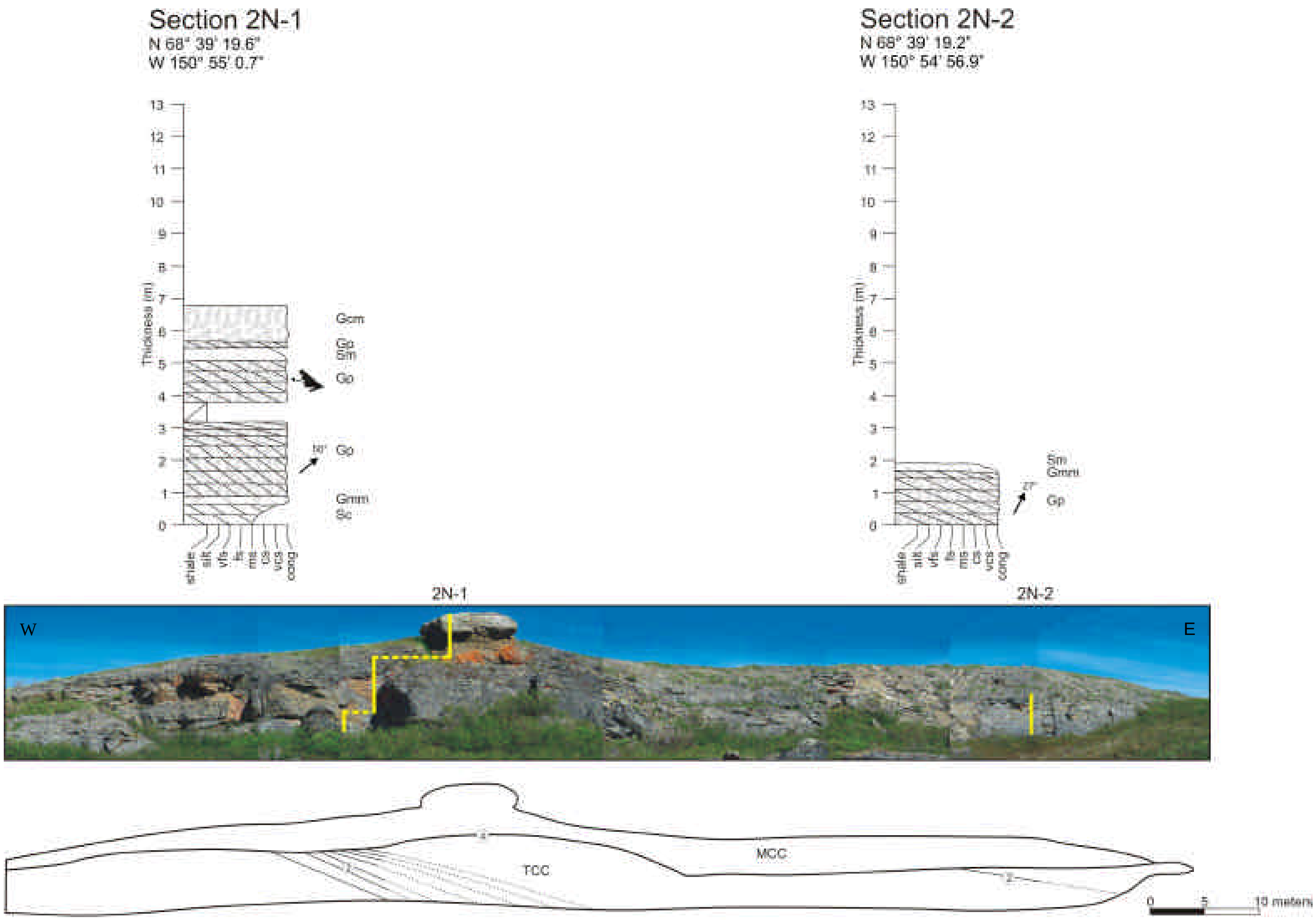

Figure 4. Measured sections, photomosaic, and line drawing interpretations for Bench 2N. See Figure 3 for key to symbols. Numbers in circles indicate order of bounding surface.

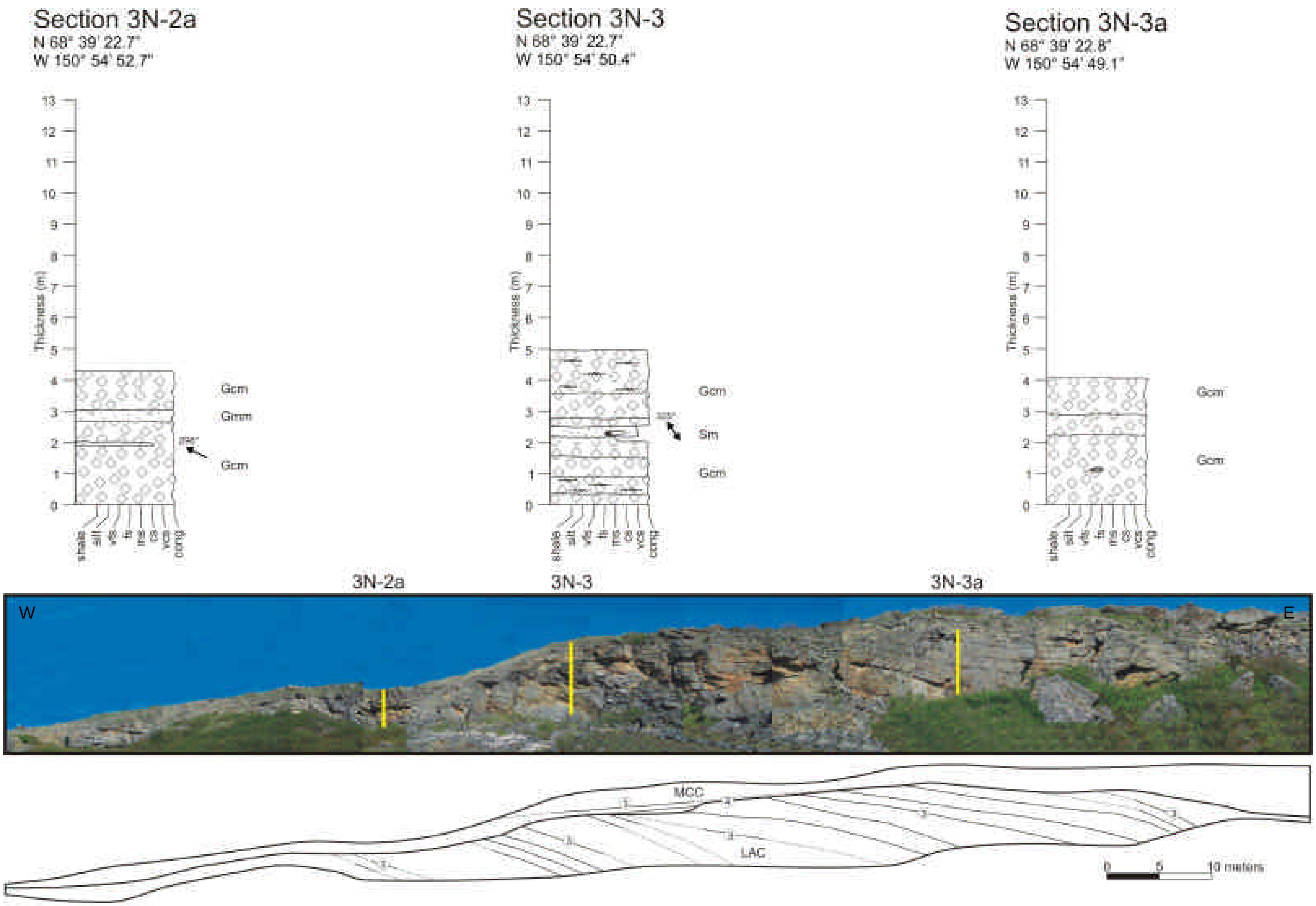

Figure 5. Measured sections, photomosaic, and line drawing interpretations for Bench 3N-b. See Figure 3 for key to symbols. Numbers in circles indicate order of bounding surface.

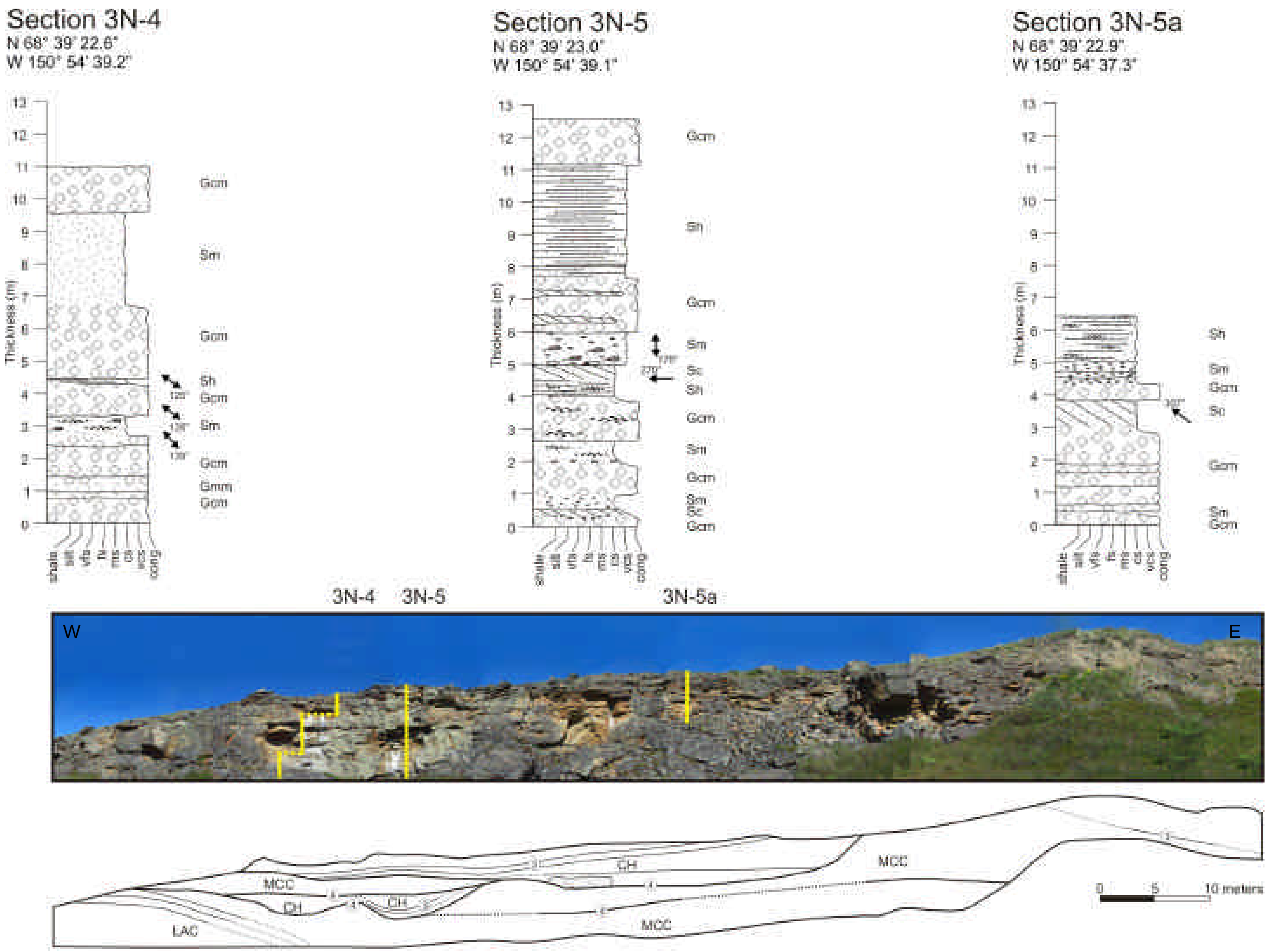

Figure 6. Measured sections, photomosaic, and line drawing interpretations for Bench 3N-c. See Figure 3 for key to symbols. Numbers in circles indicate order of bounding surface.