Critical Zone Structure in the Glaciated Central Lowlands: A Conceptual Model from the IML-CZO

CZO INTENSIVELY MANAGED LANDSCAPES CRITICAL ZONE OBSERVATORY

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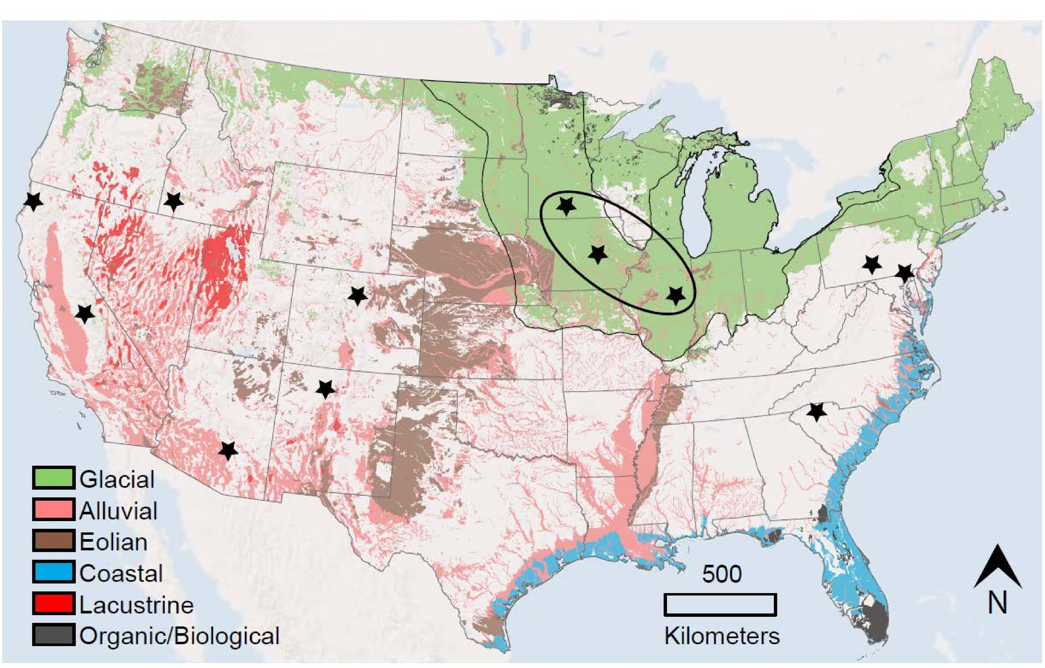
Abstract

The concept of a critical zone (CZ) supporting terrestrial life has fostered groundbreaking interdisciplinary science addressing complex interactions among water, soil, rock, air and life near Earth's surface. Pioneering work has focused on the CZ in areas with residual soils and steady-state or erosional topography. CZ evolution in these areas is conceptualized as progressive weathering of local bedrock (e.g. in the flow-through reactor model). However, this model is not applicable to areas in which weathering profiles form in transported materials including the formerly glaciated portion of the Central Lowland of North America. We present a new conceptual model of CZ evolution in landscapes impacted by continental glaciation based on investigations at three study sites in the Intensively Managed Landscapes Critical Zone Observatory (IML-CZO) The IML-CZO is devoted to the study of CZ processes in a region characterized by thick surficial deposits resulting from multiple continental glaciations, with bedrock at depths of up to 150 m. Here the physical (glacial ice, loess, developing soil profiles) and biological (microbes, tundra, forest, prairie) components of the CZ vary significantly in time. Moreover, the spatial relationships between mineral components of the CZ record a history of glacial-interglacial cycles and landscape evolution. We present cross-sections from IML-CZO sites to provide specific examples of how environmental change is recorded by the structure of the mineral components of the CZ. We build on these examples to create an idealized model of CZ evolution through a glacial cycle that represents the IML-CZO sites and other areas of low relief that have experienced continental glaciation.

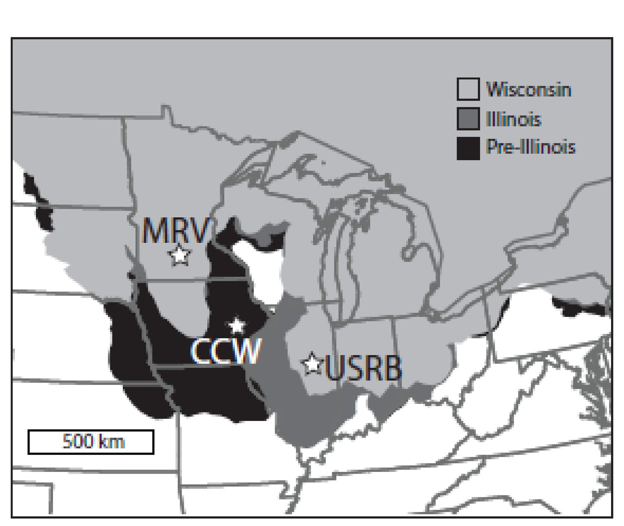
In addition, we identify two main characteristics of CZ structure which should be included in a conceptual model of CZ development in the IML-CZO and similar settings: (1) mineral components have diverse origins and transport trajectories including alteration in past CZs, and, (2) variability in climate, ecosystems, and hydrology during glacial-interglacial cycles profoundly influence the CZ composition, creating a legacy retained in its structure. This legacy is important because the current physical CZ structure influences the occurrence and rates of CZ processes, as well as future CZ responses to land use and climate change.



Soils formed in transported material are common

Generalized map showing surficial materials (Source of data: U.S Geological Survey, Soller et al. 2009) and the locations of CZO field observatories within the conterminous United States. The glaciated portion of the Central Lowland of the Interior Plains (Source of data: U.S Geological Survey, Fenneman and Johnson, 1946) is indicated by the narrow black line. The US CZO network is indicated by the black stars with the exception of Loquillo, Puerto Rico, which is not within the map area. The bold black oval surrounds the three IML-CZO field sites. Colored areas denote continuous cover of unconsolidated sediment. Green "Glacial" areas are underlain by glacial till, glaciofluvial, glaciolacustrine and ice contact deposits. Brown "Eolian" are areas where loess or dune sand is at least 20 feet (6 m) thick at the surface. Blue "Coastal" areas contain both fine-grained sediments characteristic of lagoons and estuaries and coarser beach or shoreline deposits. The red "Lacustrine" areas are underlain by lake and playa deposits. Salmon-colored "Alluvial" areas are underlain by alluvial and colluvial deposits along major river valleys and inland basins. The dark gray areas "Organic/Biological" include recent organic sediments (peat) and biological sediments (marl and shelly materials). The white areas include bedrock or residuum developed from weathering of the underlying bedrock.

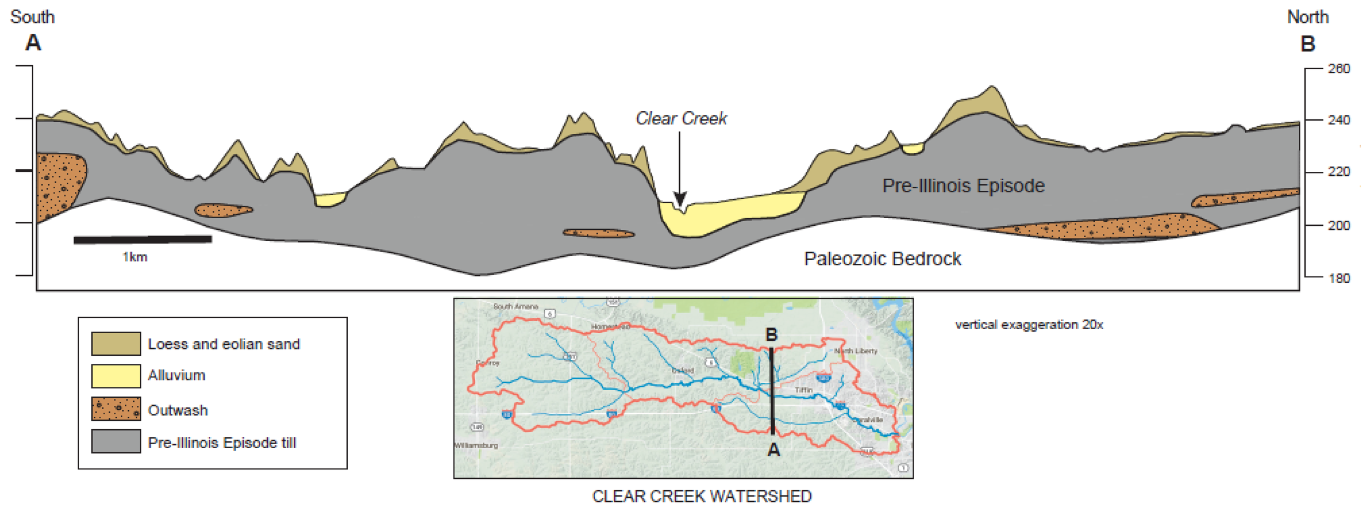
Quaternary Geology of the IML-CZO Study Sites



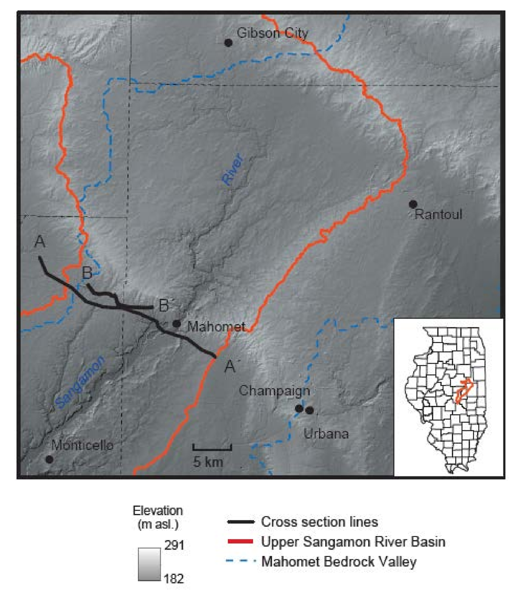
Extent of Midwest USA glaciations based on Fullerton et al. (2003). Source of data U.S. Geological Survey. Wisconsin Episode inAlcludes Marine Isotope Stages (MIS) 2-4. Illinois Episode correlates with MIS 6. Pre-Illinois Episode includes multiple episodes stretching to the earliest Pleistocene. IML-CZO sites shown as stars include the Minnesota River Valley (MRV), Clear Creek (CC), and the Upper Sangamon River Basin (USRB).

Clear Creek Watershed, Iowa

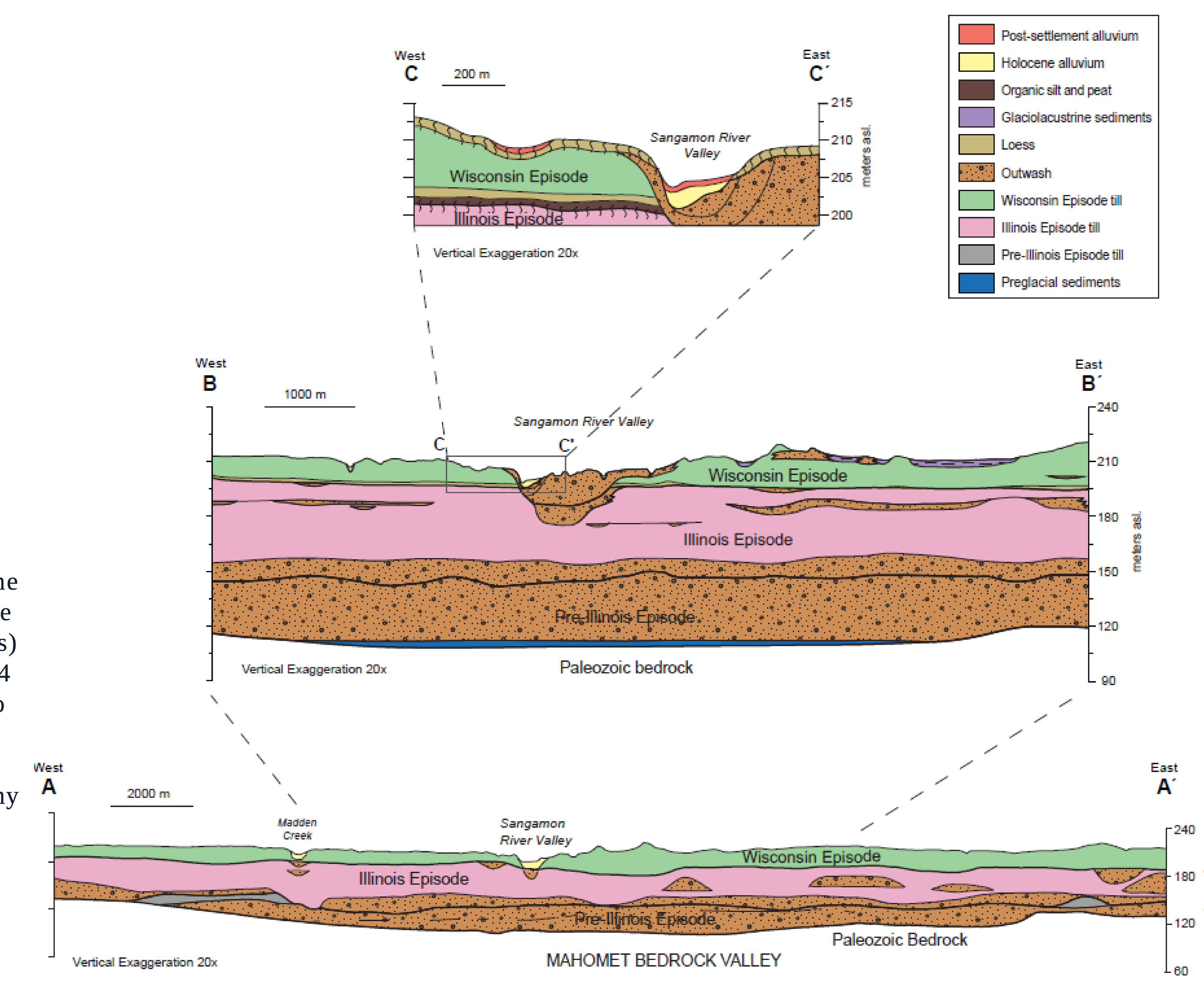
Cross-section of the eastern portion of the Clear Creek Watershed, Iowa. Pre-Illinois Episode tills of the Alburnett and Wolf Creek formations occupy broad bedrock valleys cut into Devonian bedrock. Sand and gravel bodies, interpreted as glacial outwash, are present within and between these till units. At the surface, thick deposits of loess dating to the late Wisconsin – earliest Holocene are present along with alluvium deposited in modern river valleys.



Upper Sangamon River Basin, Illinois

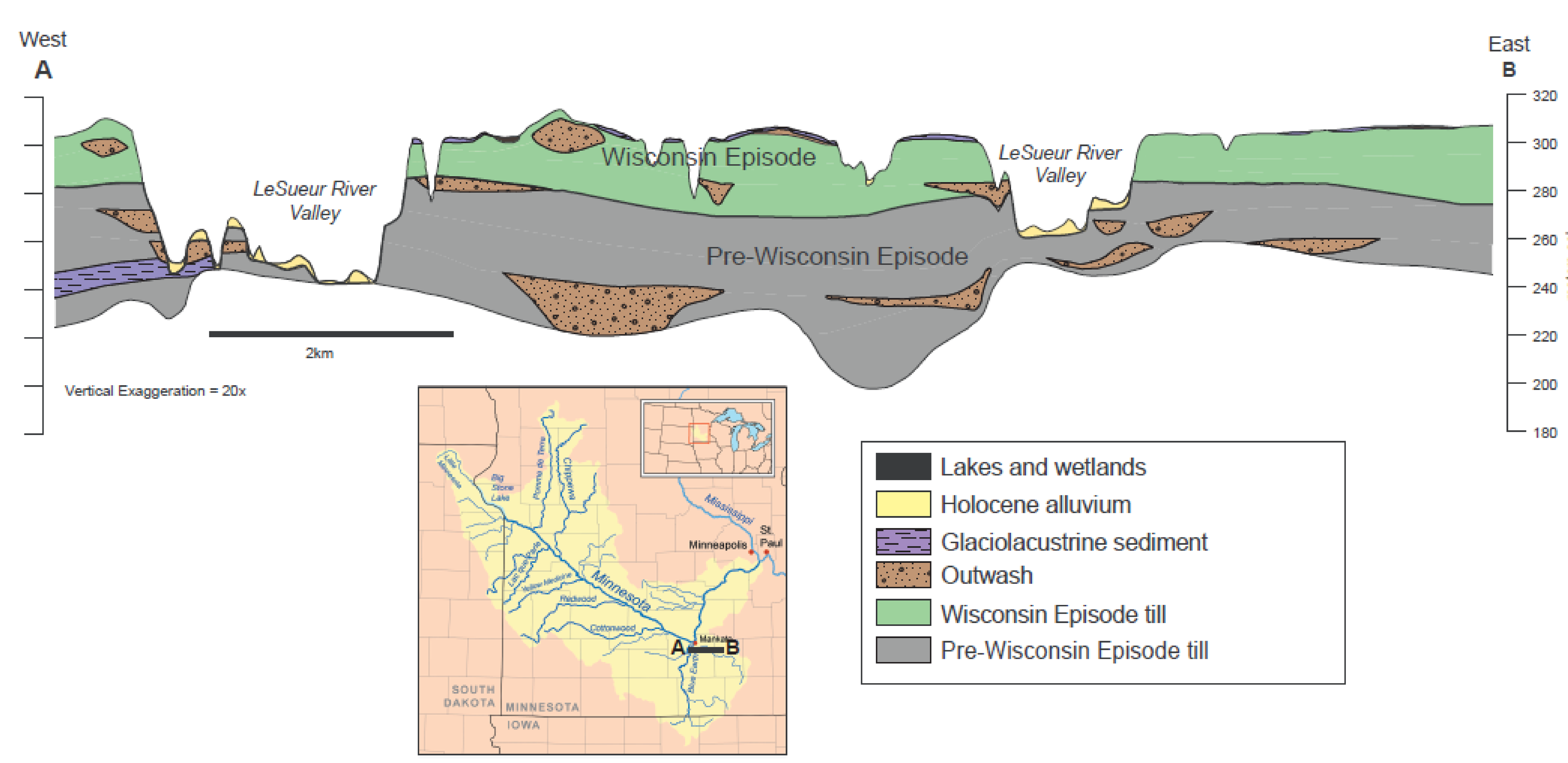


Digital elevation map of a portion of east-central Illinois, showing the locations of cross sections A-A' and B-B' in the USRB with respect to the buried Mahomet Valley. Surface expression of constructional glacial topography (moraines) is dominant. The moraines were formed between about 24 ka and 21 ka, as a fluctuating glacial ice margin receded to the northeast (Grimley et al., 2016a; Caron and Curry, 2016). Late-glacial and postglacial river valleys (e.g. Sangamon Valley) are dissected into the glacial topography and have fills of outwash and alluvium.



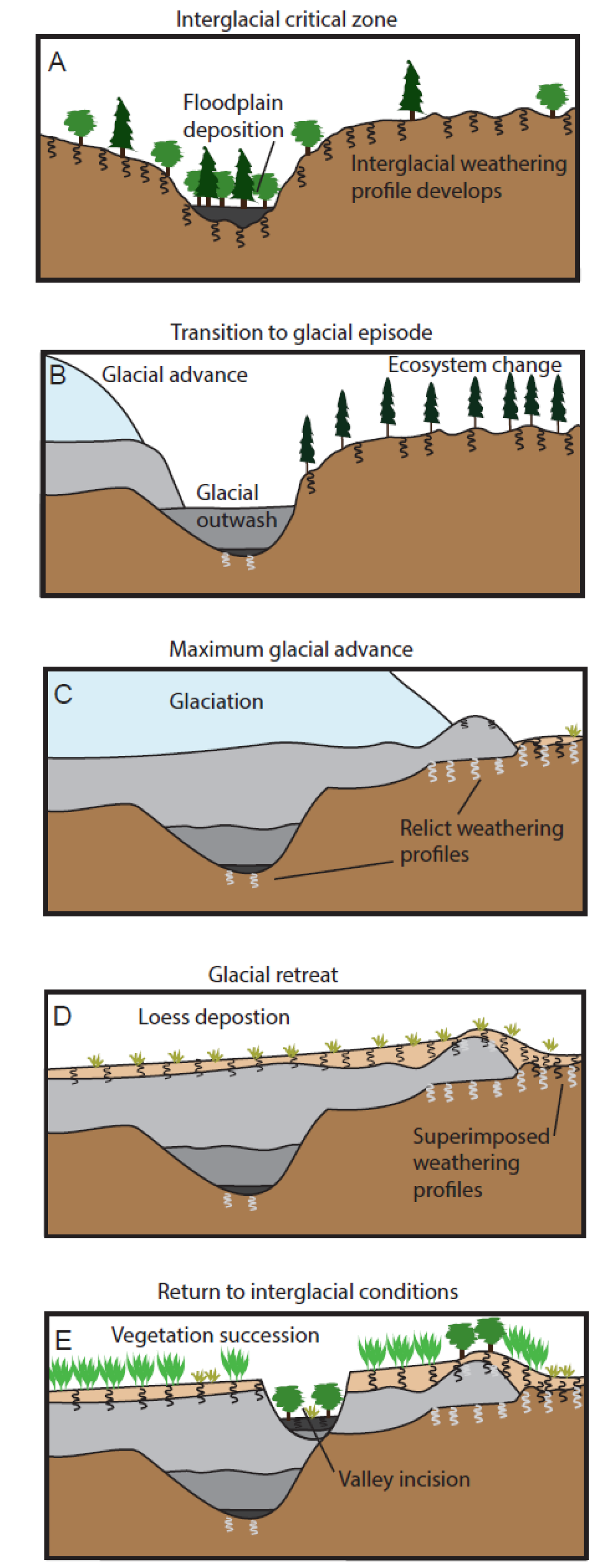
Structure of the CZ in in the USRB. (A-A') Geologic cross section across the MBV showing stacked, laterally extensive till units from multiple glacial events with less extensive, isolated coarse-grained unites in the subsurface and in modern valleys. Modified from (Stumpf and Atkinson, 2015). © 2015 University of Illinois Board of Trustees. Used by permission of the Illinois State Geological Survey. (B-B') Geologic cross section over the western half of the MBV showing divisions with tills from multiple events, two generations of coarse-grained deposits stacked in the Sangamon River Valley and glacio-lacustrine deposits in the near surface at the eastern end of the cross-section. Modified from (Grimley et al., 2016b). © 2016 University of Illinois Board of Trustees. Used by permission of the Illinois State Geological Survey. (C-C') Geologic cross section crossing the Sangamon River Valley showing loess draping the current land surface and a portion of an ancient CZ from a previous interglacial preserved beneath Wisconsin Episode till, loess and peat. Post-settlement alluvium is present within depressions on the upland and above Holocene alluvium. The dominant depositional processes throughout the Pleistocene have been associated with the glaciations. Yet late-glacial and postglacial processes causing river dissection and sedimentation in river valleys have also impacted the structure of the CZ.

Minnesota River Valley



Simplified geologic cross-section through a typical portion of the Minnesota River basin, modified from the central/eastern portion of cross-section B-B' on plate 4 of the Digital Geologic Atlas of Blue Earth County (Runkel et al., 2011). Used by permission of the Minnesota Geological Survey. Minnesota Pre-Wisconsin tills are likely pre-Illinois in age. The surficial geology features abundant glacial lake deposits with modern lake and wetland deposits also present. Knickpoint retreat up the LeSueur River has created multiple terrace surfaces, shown as Holocene Alluvium. Isolated bodies of sorted sand and gravel are present in the subsurface within both Wisconsin Episode and pre-Wisconsin Episode tills.

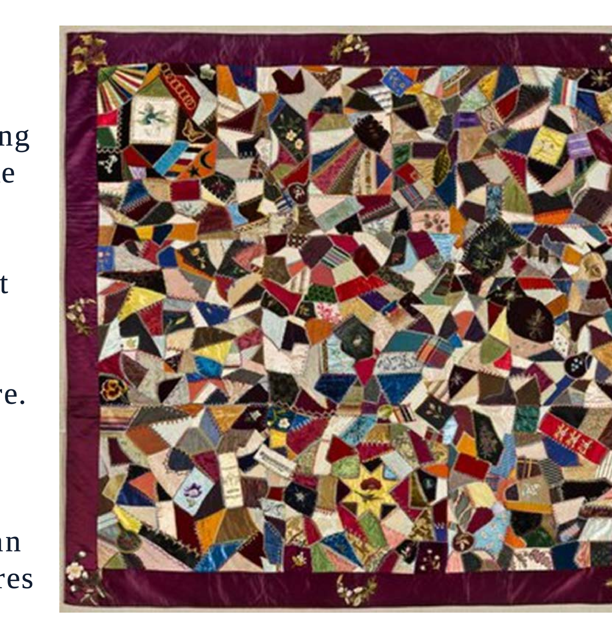
Idealized Evolution of the Critical Zone



Cartoon of idealized CZ evolution through a glacial cycle. A) The landscape developed prior to glaciation. A weathering profile (black squiggles) is developed in the surficial sediments, including alluvium (black) in the major river valleys. B) As glaciers (light blue) crossed the region, they actively eroded their beds depositing glacial till (light grey). Sorted fluvial or lacustrine sediments (dark grey) were deposited in front of the ice margin partially filling the bedrock valleys. Weathering profiles developed on former land surfaces (light grey squiggles) are preserved where glacial erosion did not entirely remove the older sediments. Vegetation beyond the glacial margin was typical of tundra and boreal forest found in northern latitudes today. C) Glacial conditions (dry and cold) continue beyond the ice margin. Windblown sand and silt (loess), shown in tan, accumulated, covering soils developed in the bedrock and preglacial sediments. Minimal chemical and physical weathering occurred beneath the glacier. The weathering profile continued to develop in the landscape beyond the glacial margin. In places, soil formation is superimposed on previous weathering profiles. Sparse tundra vegetation likely colonized areas near the ice margin. D) Following glacier retreat, loess further accumulated on the land surface, completely burying the glacial deposits. The vegetation and soil succession began as tundra was replaced by boreal forest, and later by mixed hardwood/coniferous forest. E) As the climatic conditions moderated during the interglacial, tallgrass prairie and oak-hickory savannas replaced the hardwood forests. Continuing fluvial activity established new drainage networks, and valleys were incised into loess and glacial deposits.

The Patchwork Critical Zone

We propose a new metaphor for the CZ based on the human social systems of this region. Beginning at least 13,000 years ago a diverse group of people with a variety of histories and origins began to arrive in waves. Acknowledging that the history features conflict and colonization, we suggest that the present inhabitants were shaped by their individual and shared experiences of changing local, regional, national, and global human culture. The story of this culture must include both the diversity of its constituents and their ongoing evolution together. The patchwork quilt is a metaphor that has been used to describe American culture which we propose as an image that captures the essential features of the IML-CZO and, more broadly, the CZ of areas that experienced net deposition through cycles of continental glaciation.



This image of the patchwork CZ emphasizes two key characteristics of the CZ of the IML-CZO sites: (1) the mineral components of the CZ are spatially variable and have been influenced by their individual histories of transport and weathering, and, (2) CZ processes vary enormously at timescales ranging from glacial cycles to decades.

CZs of the IML-CZO are characterized by spatial variability in the mineral and geologic components. The physical and chemical properties of the sediments in the CZ vary due to differences in their source areas, prior weathering histories, processes of erosion and deposition, and postglacial alterations. The CZ is a historical body, one whose history must be appreciated to understand its present condition and function. The dramatic and quantifiable impacts of climate change, geomorphic processes, soil development, and vegetation on the CZ structure over the last few million years highlights the need to consider CZ process timescales in reference to variations of climate, vegetation, microbial, and geomorphic processes over those timescales. This point is important for critical zone science even beyond the glaciated Central Lowlands. Climate variability at timescales of centuries to several hundred thousand years is characteristic of the last few million years of Earth history, globally. This variability affected the chemical, physical and biological processes in the CZ across the planet. Similarly, while recent anthropogenic impacts on ecosystem services, hydrology, and climate are pervasive in heavily modified landscapes like the IML-CZO, more subtle changes in land use, climate and water are occurring in the CZ elsewhere. Thus, our new conceptual model of the CZ in the glaciated Central Lowlands of the patchwork quilt motivates future research in other regions with thick sedimentary deposits (e.g., Coastal Plain, Great Plains, large basins) for consideration of the mechanisms that shape CZ structure, timescales over which the structure is shaped, and potential for CZ structure to influence near-surface processes and respond to future environmental changes.

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