MINNESOTA GEOLOGICAL SURVEY

Text Supplement to the

GEOLOGIC ATLAS
FILLMORE COUNTY, MINNESOTA

COUNTY ATLAS SERIES C-8, PART C

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(Published separately by the Minnesota Geological Survey)

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(Published separately by the
Minnesota Department of Natural Resources, Division of Waters)

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PREFACE

The Fillmore County Atlas is a two-part series of plates that describe aspects of the geology, hydrogeology, pollution sensitivity, and other water-related items of interest to the county. The maps are intended to provide general information about the county, for use by (1) people who live in the county; (2) officials and resource managers at local, county, regional, and state levels; and (3) geologists, hydrogeologists, and other professionals interested in or working in the area.

The first step in using the information in this atlas is to locate your area of interest on the maps, using the township/section grid and geographic features shown. Most points in the county can be located to within several hundred feet. The maps can be used as the basis for more detailed, site-specific investigations. As indicated on Plate 1, additional information is available in computerized data bases.

CONTENTS

Partial funding for this project approved by the Minnesota Legislature (M.L. 91, Ch. 254, Art. 1, Sec. 14, Subd. 4[F], and M.L. 93, Ch. 172, Sec. 14, Subd. 11[g]) as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environment and Natural Resources Trust Fund

BEDROCK GEOLOGY (Plate 2)

By

John H. Mossler

INTRODUCTION

Across most of Fillmore County the bedrock formations are exposed or covered by less than 50 feet of unconsolidated deposits. Exceptions are the Root River valley in eastern Fillmore County and the southwestern part of the county, where the deposits are much thicker and may exceed 200 feet. In these areas the contours of the bedrock topography (Plate 4) and the geologic contacts (Plate 2) are generalized because of the scarcity of data.

The geologic history of the earth covers a vast span of time (about 4.5 billion years). In order to have an organized method of discussing geologic history, this time span has been divided into segments, representing rocks of different ages arranged in stratigraphic sequence. See the geologic time scale on Figure 1 and the stratigraphic column on Plate 2. The rocks in southeastern Minnesota represent only some of geologic time, and most of them were deposited in shallow seas during Early and Middle Paleozoic time—relatively late in the earth's history. There also are some younger rocks in western Fillmore County which were deposited during the Mesozoic Era.

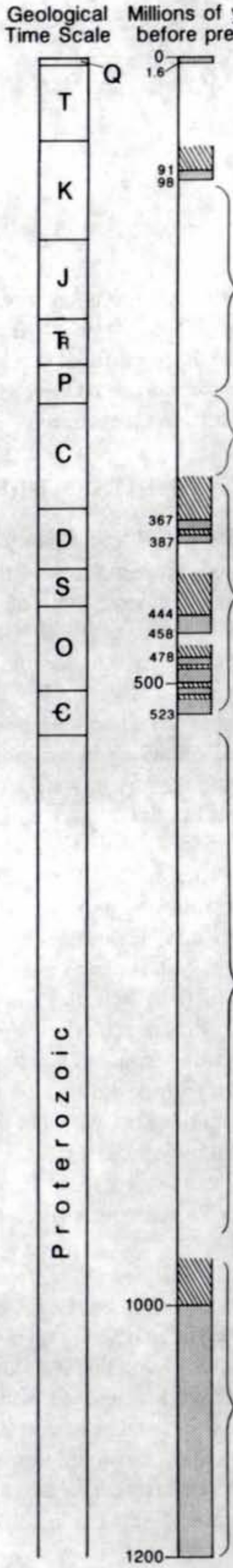
The two rock sequences are shown differently on the map. The Paleozoic rock formations (Cambrian through Devonian Periods) are shown as solid colors separated by black lines representing the geologic contacts. Distribution of the Mesozoic rock formation (Cretaceous Period) is shown by stippling. Near-surface Paleozoic formations generally are well-consolidated rocks that can easily be distinguished from the surficial units. Many of the Paleozoic units have distinct topographic expressions, and form bluffs, divides, or escarpments on the present land surface. In contrast, the Cretaceous Windrow Formation is largely composed of relatively thin (generally less than 50 feet) unconsolidated sand, gravel, and silt. Its distribution is poorly defined because it resembles the cover of younger glacial sediments. The Cretaceous rocks are not an important aquifer, unlike many of the Paleozoic rock formations, and therefore accurate knowledge of their distribution is of less practical value.

To better understand the distribution of the Paleozoic rocks, it is useful to think of them as layers similar to those in a layer cake. They are almost flat-lying and retain their original vertical sequence without having been greatly disrupted or distorted by folds and fractures (see geologic sections on Plate 2). The oldest rocks are at the bottom of the layering and the youngest are at the top, and in Fillmore County all of the older formations are present beneath younger Paleozoic layers. The map identifies the "first bedrock" beneath unconsolidated surficial deposits. The vertical sequence of rock formations can be seen where steams have cut valleys into the surface (see Appendix 1).

GEOLOGIC HISTORY AND STRUCTURE

The oldest rock unit identified in Fillmore County is a Proterozoic gabbro described from cores recovered from two exploratory drill holes in the eastern half of the county. This gabbroic rock was formed about 1200-1000 million years (m.y.) ago (Sims, 1990) when Fillmore County was on the eastern margin of a large north-south-trending geologic feature known as the Midcontinent rift system (Fig. 2a). Fracturing and spreading in the earth's crust allowed molten rock to force its way upward along the axis of the rift and spread across the surface as lava flows. On rift margins, as under Fillmore County, magma was intruded into older crustal rocks but remained below the surface as it cooled to form the gabbro. After rifting ceased, about 1000 m.y. ago, Fillmore County underwent long periods of weathering and erosion over 500 m.y. that left just a thin regolith (soil horizon) on the surface of Proterozoic rock. Figure 2b shows the distribution of Proterozoic rock formations beneath the Paleozoic formations. It is only with deposition of the Paleozoic Mt. Simon Sandstone on this surface about 525 m.y. ago that the record of geologic events resumes in Fillmore County. The missing record is noted on Figure 1 as an unconformity between the Proterozoic surface and the Mt. Simon Sandstone.

All of the Paleozoic rocks in Fillmore County are sedimentary in origin. They were deposited on the eastern limb of a broad lowland named the Hollandale embayment (Fig. 3). Subsidence of the dense Proterozoic lava flows and gabbros in the rift system created this lowland, which became a basin for sediment deposition, over the next 200 m.y. (Mossler, 1987). Subsequent adjustments of basement rocks during the Middle Ordovician (about 450 m.y. ago) resulted in the formation of several localized basins within the broader embayment (Fig. 3) as deposition continued. Influence of the embayment can be seen in the tilt of the Paleozoic rocks, a low regional dip toward the west and southwest, typically of 1° (approximately 92 feet per mile) or less.



Modern landscape is incised. Continental glaciers advance into region.

Area borders shallow epicontinental sea (Zuni) that lies across western interior of North America. Sand, silt, and gravel deposited from low-gradient streams.

Bedrock at surface deeply weathered and eroded.

Diastrophism creating Appalachian Mountains causes slight folding in northern Midcontinent.

Waters of three epicontinental seas cover most of North America: (1) Sauk, (2) Tippecanoe, and (3) Kaskaskia. Muds, sand, and organic carbonate deposited in waters generally less than 150 feet deep. The first two advance from region of Iowa and Missouri. The third advance crosses breaches in Midcontinental arch from west-central Canada. Slight uplift and erosion between marine episodes.

Weathering and erosion of bedrock surface.

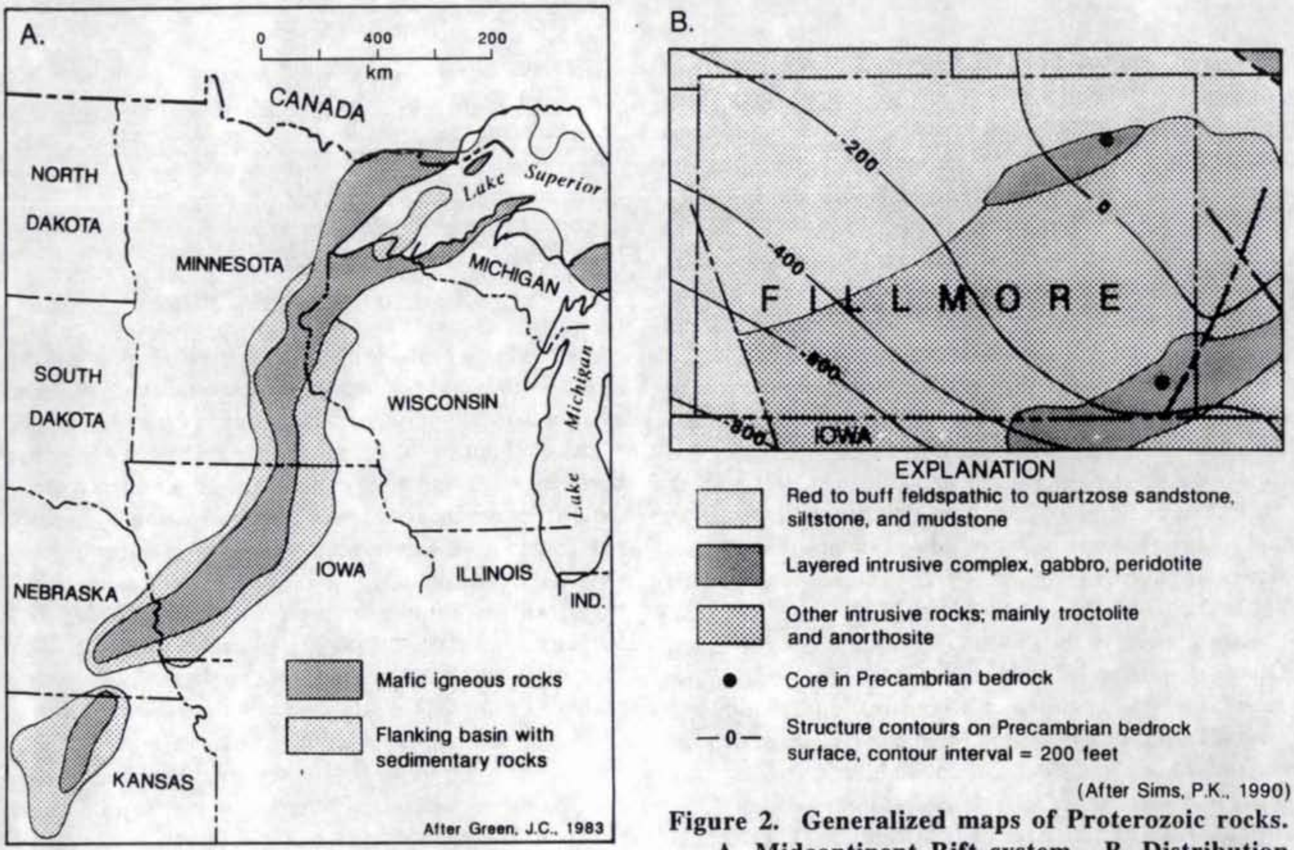
Isostatic adjustment along the Midcontinent rift creates the Hollandale embayment. Most of the geologic record for this interval destroyed.

Formation of Midcontinent rift:
Rifting of the continental crust with plateau volcanism, deposition of terrestrial sediments in alluvial fans along stream courses and in lakes.
Emplacement of igneous intrusions. (Continental crust was gneiss and affiliated rocks; probably Archean in age: 2500+ million years old.)

■ Deposition of rocks that are still preserved in southeastern Minnesota.

▨ Rocks may have been formed, but later removed by erosion.

Figure 1. Time scale showing major pre-Quaternary geologic events in Fillmore County.



After Green, J.C., 1983

(After Sims, P.K., 1990)

Figure 2. Generalized maps of Proterozoic rocks. A, Midcontinent Rift system. B, Distribution of Proterozoic bedrock types in Fillmore County.

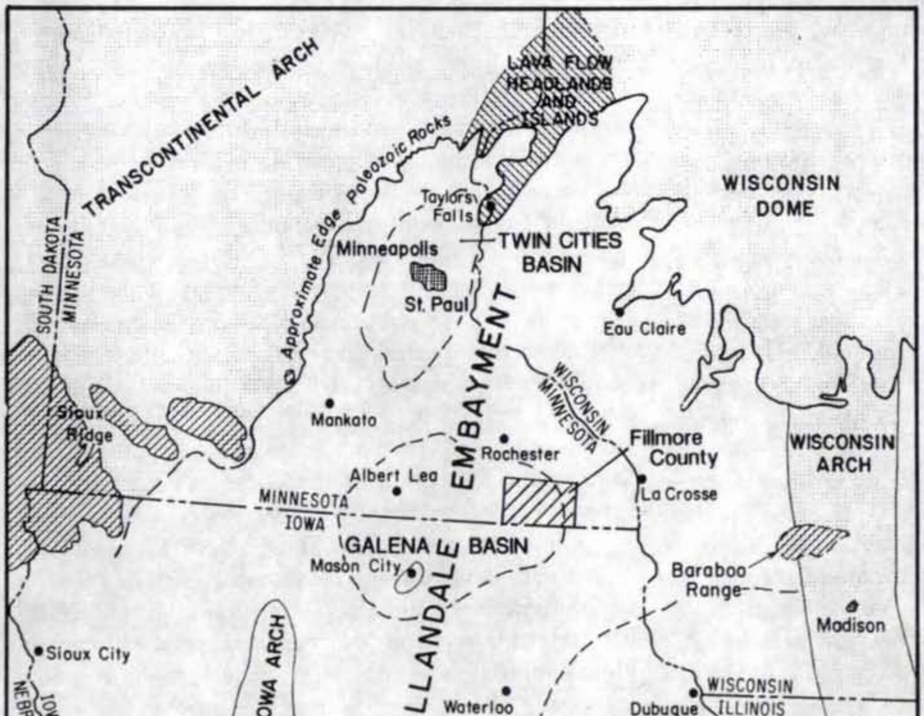


Figure 3. Paleogeography of southeastern Minnesota during Early Paleozoic time. Positive areas are stippled. The Twin Cities, Galena, and east-central Iowa basins developed during Late Ordovician time.

From Late Cambrian time (about 525 m.y. ago) until the Middle Devonian (about 365 m.y. ago), many thin layers of sand, clay, calcareous oozes, and skeletal remains accumulated in shallow continental seas to later become sandstone, shale, limestone, and dolostone. The environments of deposition were varied, but still are recognizable in the rocks. Some basal Mt. Simon Sandstone probably accumulated in fluvial and braided delta fan environments (Mossler, 1992); other coarse-grained sands in the basal and middle parts of the Mt. Simon and in overlying sandstone formations probably accumulated as near-shore sand complexes. Windblown sands are recognizable in the New Richmond Sandstone of the Shakopee Formation (Smith and others, 1993). Rock formations composed of very fine grained sandstone, shale, and siltstone have been attributed both to near-shore tidal-flat environments (Mossler, 1992; Lochman-Balk, 1970) and to deep, offshore waters (Sloan, 1987; Runkel, 1994a). Carbonate rocks of the Lower Ordovician Prairie du Chien Group are interpreted to represent tidal flats and shallow subtidal marine environments (Austin, 1971; Smith and others, 1993). Fossil-bearing Middle to Upper Ordovician carbonates of the Galena Group were deposited as limy muds in waters 30 to 150 feet deep and farther from shore than the Lower Ordovician units (Sloan, 1987). Devonian carbonate rocks were deposited in a variety of marine environments that ranged from near-shore tidal flats to offshore coral reefs (biostromes) (Witzke and others, 1988). Changes in composition within and among rock units in Fillmore County indicate that the shallow seas varied in depth and location, and sometimes receded from the area altogether.

In addition to the pre-Mt. Simon unconformity and the post-Devonian unconformity, at least six widespread unconformities exist within the Upper Cambrian, Ordovician, and Devonian marine sedimentary sequence (stratigraphic column on Plate 2). These unconformities represent time intervals when the shallow seas receded and significant erosion took place on an exposed land surface. During the very long intervals after the Early Ordovician and after the Late Ordovician, most of the continent was exposed (Fig. 1).

Following a long hiatus after deposition of the Devonian carbonate rocks (from about 375 to 97 m.y.), the record of sediment deposition in Fillmore County resumed with the Windrow Formation currently treated as Late Cretaceous in age. The basal Windrow Formation—the Iron Hill Member—is a residuum of unconsolidated, weathered residual rock material, which formed on the older Paleozoic rocks. It is overlain by the Ostrander Member, interpreted to be sands, gravels, and silts deposited in braided streams that flowed westward into a shallow sea that covered the western interior of the United States (Witzke and Ludvigson, 1994). It has been suggested (Bleifuss, 1966) that both the Iron Hill residuum and Ostrander gravels may be younger than Cretaceous, and therefore age assignments are provisional. In Fillmore County, only the glacial deposits of the last 2 million years are younger than the Windrow Formation.

GEOLOGIC STRUCTURE

In addition to the gentle, southwestward, regional dip of the Paleozoic sedimentary rocks, several small geologic structures locally influence the attitude of the rock layers. These are folds in the Paleozoic strata where the rock has been deformed into anticlines and synclines. The axes of these folds are inclined rather than horizontal, commonly plunging in a western or southwestern direction consistent with the regional dip. In Fillmore County, most are small, with amplitudes from crest to trough of less than 50 feet. However, the major Allamakee/Mineral Point anticline, which extends from Iowa north-northwest across eastern Fillmore County and southwestern Houston County, has an amplitude of more than 100 feet. Because most of the folds are so small, they are difficult to map or even identify in outcrop. Therefore the traces of fold axes shown on the bedrock map are only approximate.

Minor faults with less than 50 feet of displacement have been reported by D. Kohls (unpublished field notes, 1959-1961) and by Sloan (1987). However, most evidence for such faulting is indirect, such as two different formations being in close proximity, but at the same elevation without a visible fault plane. Faults of such small displacement are difficult to detect with the limited amount of outcrop in Fillmore County.

Joints are relatively smooth cracks. They differ from faults in that the rocks on either side of the joint have not moved relative to one another. In Fillmore county, most joints are in the fine-grained limestones of the Galena Group and Platteville Formation. Joints generally form vertical or near-vertical planes of parallel to subparallel surfaces known as a set. Different joint sets can form intersecting planes in the rock. Weiss (1953) and Bleifuss (1966) observed two major joint directions in the Stewartville Formation of the Galena Group—one set approximately N.90°E. and the other N.45°-50°E.

Joints are perhaps the most important structural feature in Fillmore County, because they allow water to be rapidly transferred from the surface into the subsurface. This results in relatively large amounts of slightly acidic ground water coming into contact with carbonate rock and increasing the size of joints by dissolution. This dissolution increases the amount of water that can enter the bedrock and over time leads to the sinkholes, caves, and other phenomena observed in karst terrain.

Wopat (1974), in a study in western Fillmore County, observed that sinkholes had developed selectively along certain joint sets oriented from N.10°E. to N.20°E. and from N.90°E to S.70°E. These observations were made on exposures in sinkholes. In contrast, very few sinkholes had formed along joints measured in quarries that had orientations of N.40°-70°E. (Wopat, 1974). It is probable that the fractures with the most sinkhole development are compression joints, which developed at orientations normal to regional stresses. When the compressive forces that created them died, they became tension joints or open fractures. The northeast-trending joints probably are shear joints that generally are closed or tight and less subject to water transport and carbonate dissolution (Heyl and others, 1959).

The geologic structures observed in the bedrock of Fillmore County are the result of at least three episodes of deformation in the upper Mississippi valley. The first took place prior to deposition of the New Richmond Sandstone, and the second prior to deposition of the St. Peter Sandstone. The third occurred in Late Paleozoic time (post-Devonian, and probably Pennsylvanian) according to Heyl and others (1959) and Ludvigson (1976). It was probably related to concurrent mountain building (diastrophism) in Arkansas and Oklahoma (Fig. 1).

SURFICIAL GEOLOGY (Plate 3)

By

Howard C. Hobbs

INTRODUCTION

Soil units defined in the county soil survey (Farnham and others, 1958) were grouped by parent material for preliminary surficial geologic maps. Additional information was needed for the geologic map because soil surveys are of limited use in identifying and mapping layers of sediment deeper than 5 feet.

Some Quaternary sediments are visible in places such as roadcuts, ditches, gravel pits, and the tops of rock quarries. These exposures contain a few feet to tens of feet of sediment that can be sampled and studied in place. MGS geologists examined exposures and located new ones in Fillmore County during the summers of 1992 and 1993. These included basement excavations, road-construction sites, stream cuts, and sinkholes being dug out in preparation for sealing. Exposures are important because the geologist can see a vertical sequence of materials and may be able to follow layers for hundreds of feet. Unfortunately exposures are not always where geologists most need the information. There geologists turn to other techniques.

To obtain information about deep sediments, samples were collected by drilling. These samples were briefly described in the field, examined and described in detail in the laboratory. Shallow holes drilled with a Giddings soil auger mounted on a pickup truck range from 10 to 25 feet in depth—deep enough to obtain relatively unweathered samples for laboratory analysis. Deeper borings are contracted to professional drillers. Auger-split spoon borings were the most cost-effective in the depth range of 25 to 100 feet; these samples were collected with a tube pounded down and pulled up through the hollow stem of an auger, so that the tube provides an undisturbed sample from a known depth. An additional method, Rotasonic drilling, is more expensive, but it produces a continuous core from a greater range of depths.

ANALYSIS AND INTERPRETATION

Quaternary sediments are characterized on the basis of color, banding or bedding, texture, acid reaction, and contacts between different layers. In Fillmore County they were commonly gray when first deposited. Long exposure to air has oxidized the iron in the minerals from the surface downward, and the color changes upward to grayish brown, to brown, to reddish brown. If the sediments are water-saturated, they stay gray, because the iron is not exposed to oxygen. Permeable sediments, because they drain more rapidly, oxidize faster than impermeable ones. Brown to reddish colors in sediments imply a greater degree of weathering and alteration.

Reaction to hydrochloric acid can also be used to recognize weathering in sediments. Most Quaternary deposits in Fillmore County originally contained the mineral calcium carbonate (lime). As sediments weather, the slightly acid water percolating downward gradually leaches away the lime. If sediment contains calcium carbonate, it will fizz when dilute hydrochloric acid is dropped on it; leached sediment will not. Because leaching is a process that works downward from the surface, a leached layer beneath a calcareous layer implies that the leached zone was exposed to weathering before being buried. This was one technique used to recognize the older alluvium (**pal**) under Wisconsinan alluvium (**wal**) in section C-C' on Plate 3.

Texture is a measure of the different sizes of grains within the sediment. It is characterized by the percentages of gravel, sand, silt and clay size fractions. Descriptive terms, such as loam, silt loam, and sandy clay loam, are based on the relative grain-size distributions.

The very coarse sand fraction (1-2 mm) obtained in the texture analysis is used for sand counts. The sand grains are counted under a microscope, and classified as to probable source—Precambrian, Paleozoic, or Cretaceous bedrock. Precambrian grains came from the crystalline rocks of the Canadian Shield; they are divided into light (granite), dark (basalt, greenstone, slate), and red (rhyolite and sandstone). Paleozoic grains came from the sedimentary rocks of southeastern Minnesota and similar rocks in southeastern Manitoba. The Paleozoic grains are chiefly carbonate (limestone and dolostone), together with some sandstone and shale. Cretaceous grains from western Minnesota, the Dakotas, and western Manitoba are chiefly shale, together with some limestone, but can be distinguished from the Paleozoic shale and limestone. Some grains of polished quartz or chert are from the Cretaceous Windrow Formation in Fillmore County. The various rock grains in the glacial sediments are used to infer the probable path the ice took to reach Fillmore County.

Clay minerals are identified using an X-ray diffractometer, because they are too small to be studied with a microscope. The clay minerals are grouped as (1) expandable clays, largely derived from Cretaceous shale; (2) illite, largely from Paleozoic sedimentary rocks; and (3) kaolinite plus chlorite, largely from Canadian Shield rocks. The results are comparable to the major source categories for the coarse sand.

Paleomagnetism is a way to arrive at an approximate date for when the sediment was deposited. It is possible to determine whether the earth's magnetic field at the time of deposition was "normal" (like today's) or "reversed" (south magnetic pole near the north geographic pole, and vice versa). The field has alternated between normal and reversed many times through geologic history, and the approximate dates of these reversals are known. The most recent reversal occurred about 790,000 years ago (Izett and Obradovich, 1994). The samples analyzed from Fillmore County were all normal, indicating that they are likely to have been deposited less than 790,000 years ago. However, some of the glacial sediments in the county are heavily weathered and were not suitable for analysis by this technique.

The map and sections on Plate 3 are interpretations––ideas about the origin and mode of deposition of the material, as well as the similarities and differences among materials across the county. The interpretations are based partly on data collected and partly on knowledge of geologic processes governing the origins of rocks and sediments. For example, where a geologic contact does not go through a data point, the geologist, in placing the line on the map, is guided by experience, as well as the data available, landforms, changes in slope, or changes in soil texture.

SCALE AND PRECISION

Scale is the relationship between distance on the map or cross section and distance on the ground. At the scale of 1:100,000, 1 inch on the map represents 100,000 inches on the ground, or more than 1.5 miles.

Scale is important to understanding data shown on maps, because it affects how closely a point or line on the map corresponds with a true location on the ground. For instance, at the scale of 1:100,000, the contact lines between map units are about 0.008 inch wide. This represents 800 inches, or 67 feet on the ground. In practical terms, nearly invisible errors in mapline placement can correspond to a couple hundred feet on the ground. For this reason, the maps in the atlas should not be used to infer geologic boundaries or conditions for small, site-specific projects. Although the maps indicate the type of geologic environment to be expected in the region, an individual site must be investigated more thoroughly. The data points (Plate 1) were digitized from topographic maps at the larger scale of 1:24,000, and their plotted precision is greater than that of the geologic contacts plotted on the final 1:100,000 scale map.

Scale also sets practical limits on the size of the geologic units shown on the maps. The narrowest unit on the surficial geologic map is about 0.04 inch wide, which corresponds to 4,000 inches, or 333 feet on the ground. Units narrower than this are omitted on the map, although they really exist on the ground. An example of this is along the South Fork of the Root River, where alluvium is present throughout the valley, but is shown on the map only where the valley is wide enough to accommodate the 0.04-inch width of the map unit.

GLACIAL HISTORY

The glacial history of Fillmore County began about 2.5 million years (m.y.) ago with the onset of continental glaciation. The surface had been undergoing erosion and weathering since Cretaceous time, about 65 million years ago. It is likely that the preglacial surface was flat or gently rolling, with wide, shallow bedrock valleys. It is not clear if, at the time of the earliest glaciation, the Mississippi was the master stream of the region. The valleys that survive from this postulated landscape are in the southwestern corner of the county. They are covered by thick till and are not easily studied.

One of the early glaciations was the most widespread. It covered all of Minnesota except for a small part of eastern Winona and Houston Counties adjacent to the Driftless area of southwestern Wisconsin. The local direction of ice flow in Fillmore County was probably from west to east, although regionally the ice was moving south into central Missouri. Almost all of the till of this early glaciation has been eroded. Remnants are mostly along bedrock drainage divides in eastern Fillmore County; they are oxidized and completely leached of calcium carbonate.

Although we do not know the age of the earliest glacial deposits in Fillmore County, it appears that the rest of the glacial sediments are younger than about 790,000 years (Fig. 1). The eastern half of Fillmore County was not covered by ice during these later glacial events. A deposit of calcareous outwash (psg) under a leached zone, just east of Lanesboro, is interpreted as the youngest, and most eastern, of the later glaciations, but does not have a defined age. It is likely that during the Pleistocene, when Fillmore County was free of ice for long interglacial periods, erosion, valley incision, and karst development were similar to what we see today.

Between about 25,000 and 12,000 years ago the late Wisconsinan glaciers remained west and north of Fillmore County. Radiocarbon dates ranging from 18,700 to about 22,000 years before present were obtained (J.A. Mason, oral commun., 1995) from wood fragments in stream

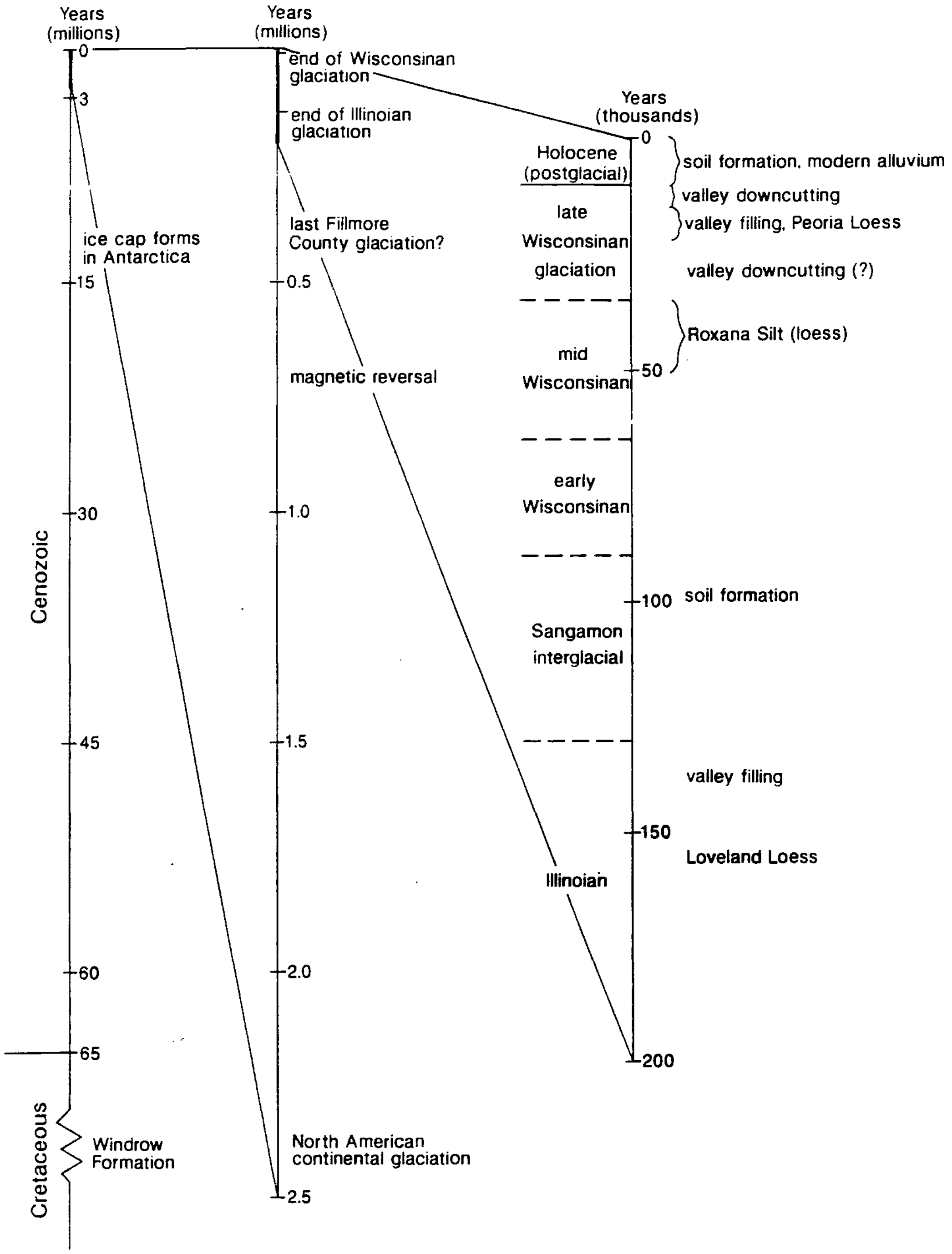


Figure 1. Most of the events discussed in this section occurred during the Quaternary Period, which began about 2 to 2.5 million years ago and continues into the present. This is the time period during which much of North America and other parts of the world were repeatedly covered by thick masses of glacial ice. The Quaternary Period is subdivided into two intervals, the Pleistocene and the Holocene. The Pleistocene extends from about 2.5 million years ago to 10,000 years ago, the Holocene from 10,000 years ago to the present.

sediments (**wal**). At this time, rock fragments (**wc**) were eroding from valley walls and mixing with the alluvium below.

Beginning about 22,000 years ago, fine dust called loess was carried by prevailing winds from the west and northwest (Mason and others, 1994). This loess, in places more than 50 feet thick, is equivalent to the Peoria Loess (Johnson, 1976), a widespread unit named after Peoria, Illinois. During that time, the Iowan Erosion Surface (Ruhe and others, 1968; Mason and others, 1994) developed where loess was being deposited and blown away again almost as fast as it fell. The boundary between the regions of deposition (thick loess) and wind erosion (thin loess) is shown on Plate 3 as the western edge of the thick-loess stipple pattern. As finer particles were removed from the surface soil, an armor of pebbles and larger stones was left behind. Some of these stones were sandblasted on several sides, indicating that they shifted position during the several thousand years of loess deposition. The wind erosion ended before the loess stopped falling, because most of the Iowan surface is covered by a few feet of loess. The full thickness of loess is generally attained within a few hundred feet of the edge of the erosion surface, although there are "windows" of thin loess within the main body of the thick loess. Some windblown sand is also present in Fillmore County as narrow stringers on the Iowan Erosion Surface, patches in the thick-loess area, and adjacent to valleys floored by alluvial sand (**wal**). Loess was eroded from steeper slopes into the valley bottoms. This reworked loess mixed with angular clasts of bedrock forms the silty colluvium that overlies the rocky colluvium. Modern (<10,000 years old) alluvium (**hal**) is largely derived from the loess.

At least two older units of loess have been recognized under the Peoria Loess in Fillmore County. These are not widespread and are not mapped separately. One of these, the Roxana Silt (named after a town in Illinois) has a finer texture than the Peoria, is slightly redder, and is leached, whereas the Peoria Loess is calcareous. Dates from the Roxana Silt in Wisconsin and Illinois range from about 35,000 to 50,000 years ago (Leigh, 1991). Unlike the Peoria, the Roxana was blown in from the east—presumably from the Mississippi River valley. The other loess unit is older than the Roxana and is thought to be equivalent to the Loveland (a town in Iowa) Loess (Johnson, 1976). It is similar in texture to the Peoria Loess, but is leached and redder (more oxidized).

The last glacial ice had melted north of Fillmore County by about 12,000 years ago and was gone from Minnesota by about 10,000 years ago (Wright, 1972). Melting of the ice sheets had two main effects on Fillmore County. (1) Vegetation stopped the wind erosion, and modern soils began forming; and (2) drainage from glacial lakes eroded and deepened the sediment-filled Mississippi valley. This caused local streams to cut down through sand and gravel in the valley bottoms (**wal**), creating terraces, remnants of which can be seen today. The terraces are mainly preserved in three settings: (1) on the inside of meander loops, (2) in wide parts of valleys, as in the Root River near Rushford, and (3) in alcoves in valley walls, especially where tributaries join larger stream. In the deeper valleys, a significant amount of material mapped as **wal** underlies material mapped as **hal** (cross section D-D' on Plate 3).

After the glacial lakes had drained, the sediment-carrying capacity of the major streams was reduced. Valleys began to refill with sediment, this time mostly fine organic-rich alluvium. In the Root River drainage this is most apparent in Houston County, but the fill extends into the Rushford area. Starting in the mid-19th century, runoff from plowed fields deposited large amounts of soil as overbank sediment. This "post-settlement" alluvium buries pre-settlement soils in valley bottoms to depths of 7 or 8 feet in places. Modern soil conservation has reduced the erosion, and streams are cutting down to their former gradients. In some small valleys in Fillmore County, the pre-settlement soil horizon is becoming visible as a dark or black layer beneath several feet of gray to brown, fine sediment.

KARST—AQUIFERS, CAVES, AND SINKHOLES (PLATES 8 AND 9)

By

E. Calvin Alexander, Jr., and R.S. Lively

INTRODUCTION

Almost everyone in Fillmore County knows about the region's caves, numerous springs, and many sinkholes. Residents and non-residents alike have visited the caves and fished or picnicked by a favorite spring or spring-fed stream. Sinkholes, while a familiar feature of the landscape, are probably not as welcome. The caves, springs, and sinkholes are visible parts of a landscape known as karst (White, 1988; Ford and Williams, 1989).

> *Karst signifies terrain with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural waters than is found elsewhere. The word is also used adjectivally to refer to rock, water, streams, caves and other features making up such a landscape.*
>
> *(Jennings, 1971).*

Much of the rock in Fillmore County is slightly soluble in natural waters. As precipitation and ground water move across and through this bedrock, the rock slowly dissolves, at an average rate of about 1 mm per thousand years. The solution is not uniform, but is enhanced along joints and cracks. The result is karst. Fillmore County contains more karst features than the rest of Minnesota combined, making it the karst capitol of the upper Mississippi valley.

Karst features (Fig. 1) are so common that most of the Fillmore County Atlas at least touches on karst in some fashion. The presence or absence of specific karst features directly influences the suitability of any specific site for various land uses. A beautiful karst spring can enhance the value of a piece of property. On the other hand, a sinkhole can be a source of future ground-water problems, and an

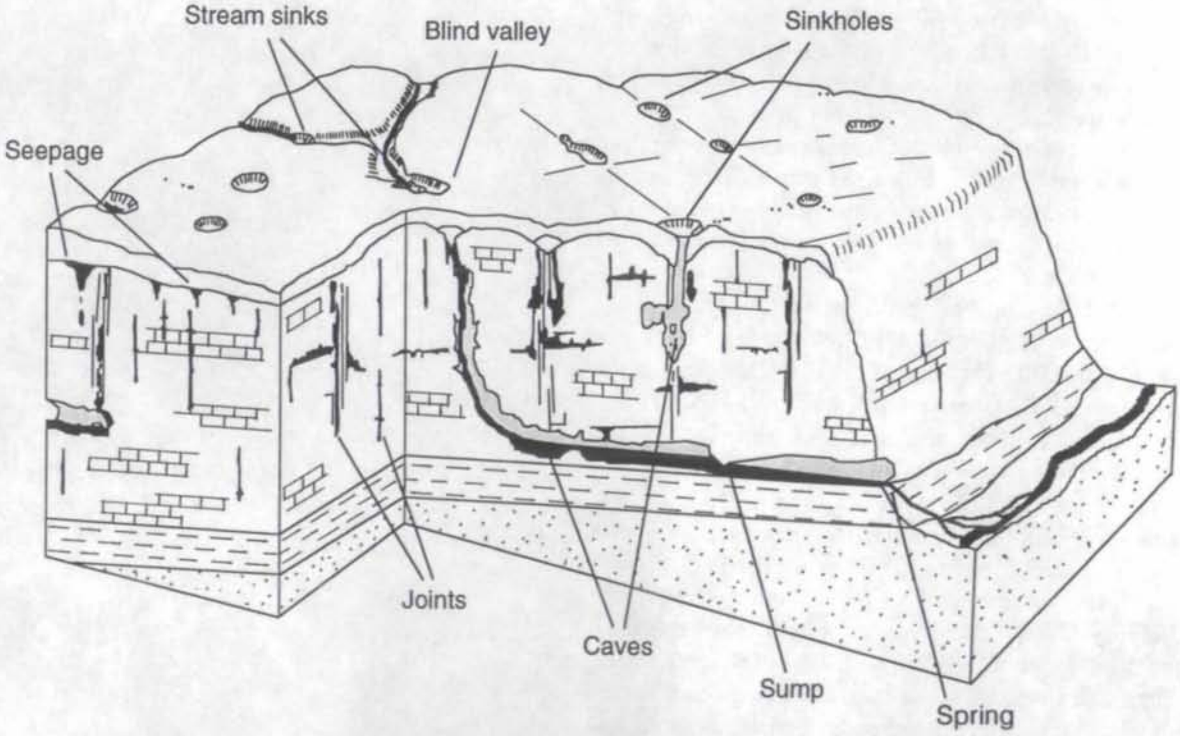


Figure 1. Common relationships between bedrock formations and karst drainage in Fillmore County. The karst features in the sketch have been exaggerated relative to the rock formations.

immediate hazard if it develops catastrophically. Known karst features are shown on the maps of sinkholes and sinkhole probability (Plate 8) and springsheds (Plate 9). In addition, the maps of bedrock geology (Plate 2), depth to bedrock—bedrock topography (Plate 4), bedrock hydrogeology (Plate 6), and pollution sensitivity (Plate 7) are relevant to understanding how karst affects or is affected by human activities. This chapter discusses how the maps and data bases of the Fillmore County Atlas can be used to understand and manage water resources in karst aquifers.

Bedrock aquifers are defined as karst aquifers if a significant portion of the porosity and permeability was produced by solution (Quinlan and others, 1992). In Fillmore County the limestone and dolostone formations are aquifers because solution enlargement of joints and bedding planes has created significant secondary porosity and permeability—something not present initially. The shallow parts of these karst aquifers are highly susceptible to ground-water contamination because the solution-enlarged conduits and passageways funnel water from the surface into the ground-water system and allow that water to move rapidly over considerable distances.

The effects of karst can extend well beyond the carbonate aquifers. Ground water flowing through a karst aquifer can also move into adjacent nonkarst aquifers, where it may return to and again become part of the surface flow. The water in karst aquifers commonly carries surface contaminants and is generally high in calcium, magnesium, and bicarbonate ions dissolved from the carbonate bedrock. When karst waters return to the surface, either directly or via adjacent aquifers, the contaminants and characteristic chemistry become part of surface streams and rivers.

Dolostone and limestone are the most common soluble rocks. Dolostone is composed primarily of the mineral dolomite plus some calcite; limestone is primarily calcite plus some dolomite. See the box on the following page. There are other soluble rocks in which karst can develop, but dolostone and limestone are the only ones of importance to the karst of Fillmore County. The bedrock geologic map (Plate 2) shows the distribution of the carbonate units in Fillmore County. Figure 1 illustrates some common relationships between these bedrock units and karst in Fillmore County. The bottoms of the deep valleys in eastern and northeastern Fillmore County are the only areas not underlain by carbonate bedrock and not susceptible to karst formation.

JOINTS

For water to penetrate a thickness of carbonate rock—the rock itself is essentially impermeable—there must be openings that create significant secondary porosity and permeability. In the carbonate units in Fillmore County the openings are pervasive and systematically oriented sets of vertical fractures called joints. They range from hairline cracks to features wide enough to walk through and may extend vertically through the entire rock unit. Other zones of enhanced permeability are horizontal bedding planes where different types of rock, such as limestone and shale, are in contact with each other. These joints and bedding planes form an intersecting network of connections through which ground water moves and contacts the rock interior. As solution takes place, the joints are enlarged and over time become integrated into conduit systems capable of carrying large amounts of water. Joints are visible in the many limestone quarries in Fillmore County and can also be seen in any sizable outcrop of rock.

Figure 2 illustrates the variety of joints found in Fillmore County carbonate bedrock. The larger Type I joints may be traced for miles horizontally and commonly cut vertically through several formations. Type I joints range from less than an inch to several feet in width, and most are filled with sediment; in the geologic literature

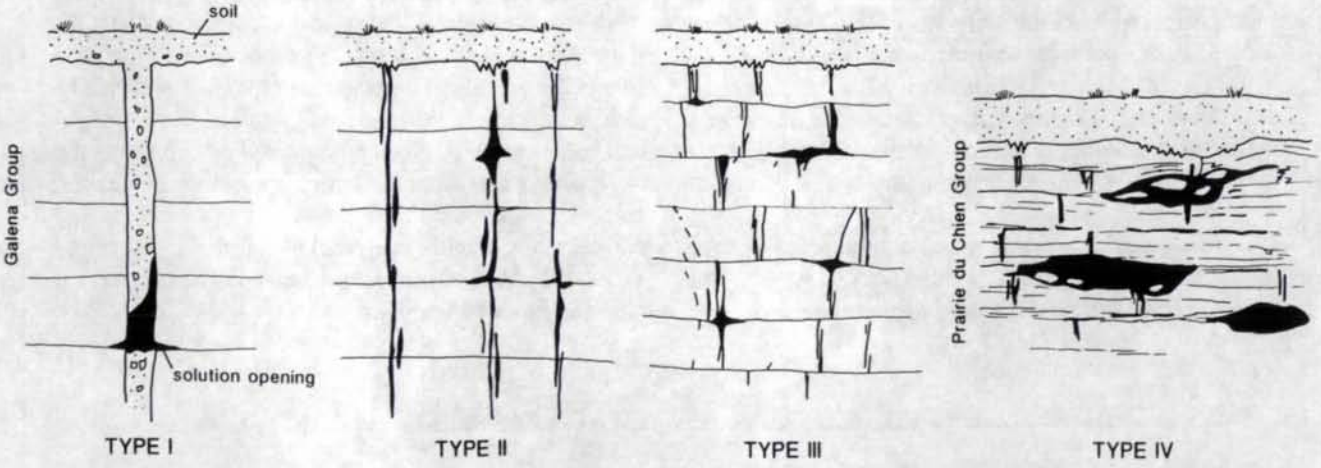


Figure 2. A classification scheme for joints in Fillmore County. See text for discussion.

(Ford and Williams, 1989), they are commonly referred to as master joints. Type II joints range from a few millimeters to about an inch in width and may completely cut through individual bedrock formations. In outcrops and quarries, the typical spacing of Type I and II joints is about 30 to 100 feet apart. Type III joints are different in that they cut across only an individual layer within a formation and are very closely spaced. They also connect with bedding plane partings to form a continuous network of paths through which water can move. The Type IV joints are found in the Prairie du Chien Group and do not appear as an integrated network when seen in outcrop or in a quarry wall. Where observed in outcrops, Type IV joints do not show the systematic patterns of the Type I, II, and III joints, but caves and sinkholes demonstrate that Type IV joints can be longer than half a mile. Although joints are generally too narrow to be shown at the scale of the Fillmore County Atlas maps, they do exist and make up a very important part of the hydrogeology.

The staining of exposed joint surfaces, bedding planes, and conduits visible in quarries illustrates their capacity to transmit water through the rock. The rusty, brownish stains are deposits of iron carried by ground water. The impermeable bedrock through which the water has not moved is various shades of gray. In the winter, frozen waterfalls where quarries and roadcuts intersect water flowing along bedding planes are visible examples of the capacity of the rock to transmit water along discrete pathways.

CAVES

Caves are a characteristic feature of karst landscapes and have long fascinated humans. Any dissolution of carbonate rock will form a cavity, but a cavity is not usually considered a cave until it has grown large enough for human entry and exploration. Fillmore County has hundreds of caves—probably more than the rest of Minnesota combined. Some are dry for all or part of the year; others contain through-flowing streams. A cave may be a single passage with one connection to the surface, tubes with multiple branches, or large multilevel mazes with many possible surface connections. The larger, wetter caves contain stalagmites, stalactites, and other deposits formed by precipitation of calcium carbonate when ground water enters an air-filled cavity below the surface. Sediments, also common in caves, are typically a combination of unconsolidated materials transported from the surface and insoluble residues from the carbonate rock. Studies of cave sediments, measurements of the age of precipitates, and an understanding of the relationships between sediments and precipitates allow the cave development to be tracked through time.

It is possible to classify caves into groups that relate to the processes by which they formed. One group is known as **network caves** (Palmer, 1991). In Fillmore County network caves, which occur where surface water enters the bedrock, have developed in the Dubuque and Stewartville Formations. Mystery Cave, the longest and one of two commercial caves in Minnesota, is a network cave with at least 12 miles of mapped passages. Other examples are Spring Valley Caverns, the Forlorn River System, and Goliath Cave. The three-dimensional nature of the passages in Mystery Cave and extensive silty sediment fills indicate that its development has been influenced by flooding. Narrow sinuous passages and sorted sand and gravel deposits extending through the cave demonstrate that stream flow has also been a factor in forming the cave. Ages of

KARST CHEMISTRY

Carbon dioxide is present in the air and formed by biological activity in the soil. Water (H_2O) and carbon dioxide (CO_2) combine to form carbonic acid (H_2CO_3), a weak acid that slowly dissolves the minerals calcite and dolomite. The process of dissolution involves a series of chemical reactions (White, 1988) that are summarized by the general equations for carbonate solution given below.

These chemical reactions are natural processes and as the arrows indicate, they are also reversible. The water reacts with the calcite and dolomite until it is saturated, carrying the dissolved minerals as calcium (Ca^{+2}), magnesium (Mg^{+2}), and bicarbonate (HCO_3^-) ions. If the water becomes supersaturated by losing some CO_2 or being heated, some of the Ca^{+2} and HCO_3^- ions combine to precipitate calcite until the chemical balance is restored. Such precipitated calcite forms the stalactites, stalagmites, and other speleothems in caves, as well as the crust that accumulates in teakettles and coffee pots. Chemical analyses indicate that most ground waters in Fillmore County are saturated to supersaturated with calcite and dolomite.

$$CaCO_3 \text{ (calcite)} + H_2O \text{ (water)} + CO_2 \text{ (dissolved carbon dioxide gas)} \leftrightarrow Ca^{+2} \text{ (calcium ion)} + 2HCO_3^- \text{ (bicarbonate ion)}$$

$$CaMg(CO_3)_2 \text{ (dolomite)} + 2H_2O + 2CO_2 \text{ (dissolved carbon dioxide gas)} \leftrightarrow Ca^{+2} + Mg^{+2} \text{ (magnesium ion)} + 4HCO_3^-$$

speleothems show that some passages in Mystery Cave are older than 160,000 years. The same passages contain sediments originally deposited on the surface by glaciers and later transported into the cave by streams. In passages along the commercial tour route in Mystery, some sediments and precipitates have ages of about 12,000 years (Milske and others, 1983), and speleothems can be seen actively growing in the cave today.

Other long caves are known as **branchwork caves** (Palmer, 1991). These have formed near the bottom of the Cummingsville Formation and function as outlets that return subsurface waters to the surface. The longest branchwork cave in the region is Coldwater Cave in northeastern Iowa, with more than 12 miles of mapped passages. In map view, these caves resemble a surface stream and its tributaries on a topographic map. Some passages still show evidence that joint patterns have controlled water movement through the rock. Significant branchwork caves in Fillmore County include Pine Cave, Tyson's Spring Cave, and Stagecoach Cave.

Niagara Cave near Harmony, Minnesota, is an example of an **intermediate cave** system, having characteristics of both network and branchwork caves. Niagara, like Mystery Cave, is a commercial cave open for tours. The cave extends vertically through three formations—it begins in the Dubuque Formation, extends through the Stewartville, and ends in the Prosser Limestone. Like many caves in Fillmore County, Niagara Cave contains an underground river, but it also has a large waterfall near the entrance.

In addition to large caves in the Dubuque, Stewartville, Cummingsville, and Prosser Formations, Fillmore County also has caves developed in the Spillville, Maquoketa, Platteville, St. Peter, and Shakopee Formations. The Crawlway is a cave with about 2000 feet of passage developed entirely within the Platteville Formation. The Prairie du Chien Group in Fillmore County has some small examples of another class of caves known as **ramiform caves**. In map view, they resemble inkblots, consisting of rooms randomly connected in three dimensions with short passages leading off to dead ends or openings too small to map. Larger examples of this class of caves are found in Winona and Wabasha Counties and in southwestern Wisconsin.

Some sizable caves in Fillmore County are in the St. Peter Sandstone. These are different from caves in the carbonate rocks in that they formed by erosion of loosely cemented sand, rather than by chemical solution of the rock.

People react to caves very differently. For some people a cave inspires the thrill of adventure and exploration. The same cave fills other people with fear. The exploration of caves is a activity that, if properly done, is safe, enjoyable, and depending upon the cave, comparable in difficulty to outdoor sports such as hiking and rock climbing. Anyone interested in cave exploration should first try the commercial tours in Niagara Cave and Mystery Cave. Both caves provide an excellent opportunity to see the carbonate bedrock from the inside. Visitors can observe fossils, stalactites and stalagmites, rock stratigraphy, and the relative ease with which water is able to pass through "solid" rock.

For more in-depth activity, visitors should contact an organization such as the Minnesota Speleological Survey and learn how to explore caves safely to protect both themselves and the caves. Most of the caves of Fillmore County probably remain to be discovered. During the preparation of this atlas, for example, the extent of explored and mapped passages of Spring Valley Caverns northwest of Spring Valley increased from about 3/4 of a mile to over 5 miles.

SINKHOLES

Sinkholes are a ubiquitous, visible feature in karst terrains. They are generally unwanted, with a status that ranges roughly from a nuisance to an actual hazard. Fillmore County contains a very large number of sinkholes, probably in excess of 10,000 that are active, as well as a much larger number of paleosinkholes that are buried and currently inactive. The areas where sinkholes are most common are shown on Plate 8. The locations of over 6,000 active sinkholes are recorded in the sinkhole data base, but the list is far from complete; thousands are not recorded in the data base, because time and money are limited.

The general properties of sinkholes in Fillmore County are described in the text on Plate 8. Figure 3 shows generalized cross sections of some common sinkhole types in Fillmore County. Both catastrophic collapse and slow subsidence can damage buildings on top of sinkholes.

Water-storage structures are especially prone to such damage, and indeed their construction can artificially induce a sinkhole to form (Aley and others, 1972). The larger the water-storage structure, the greater the probability that it will fail. The probability for failure of the structure becomes higher as the sinkhole probability increases. Facilities containing wastes, such as manure-storage lagoons and sewage ponds, will require extraordinary precautions if constructed in the two highest probability units on the map—high probability and sinkhole plains. Any water-storage facility has a significant risk of failure if located in the four areas of highest probability. A construction site needs to be evaluated for: (1) intrinsic risk of the site—the site's sinkhole probability from Plate 8; (2) size of the facility—any structure larger than about 30 feet probably will overlie one or more karst features if major joints and paleosinkholes are spaced 30-100 feet

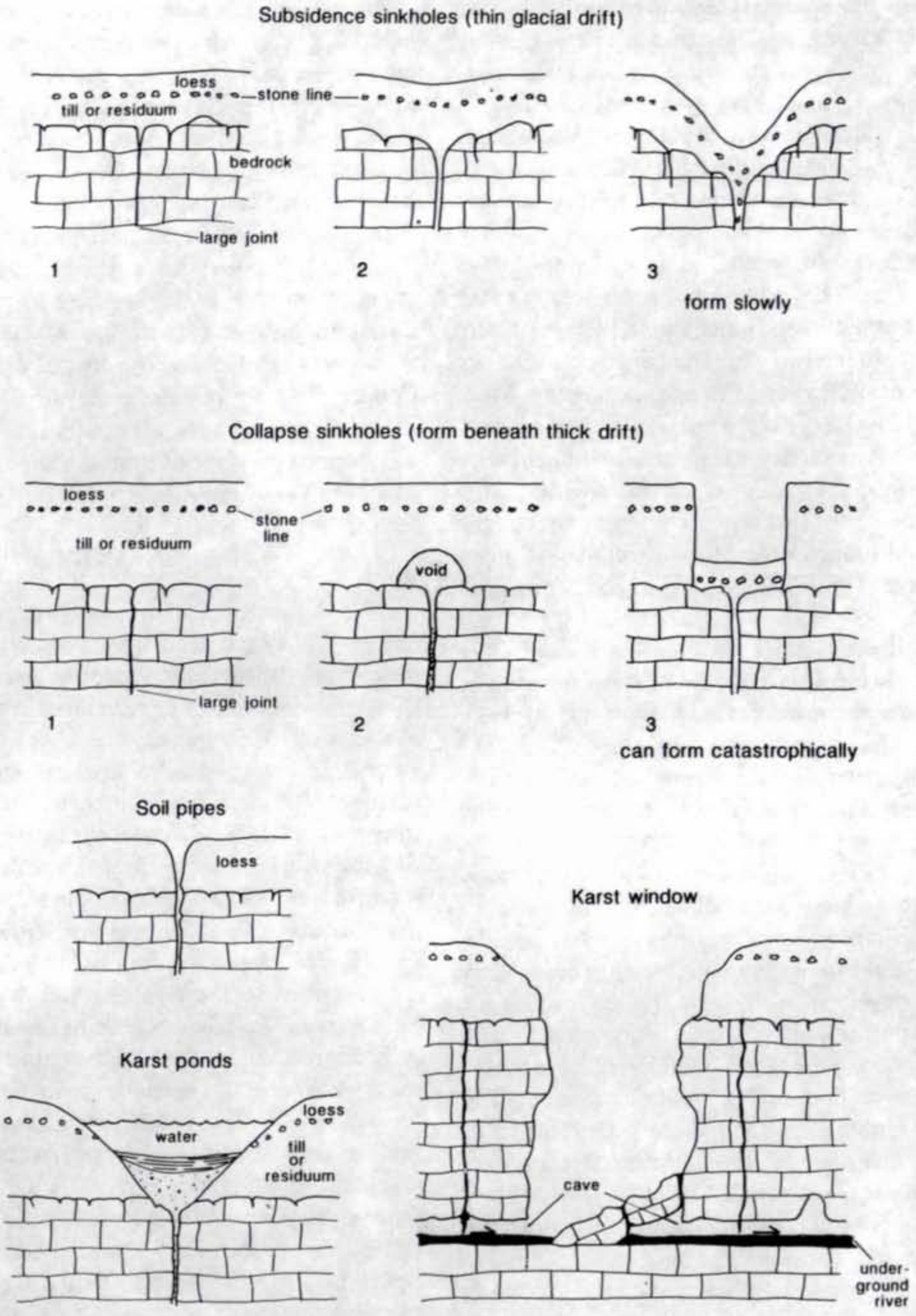


Figure 3. Sinkhole formation.

Sinkholes form where surface materials are eroded through the solution channels in the underlying bedrock. If that erosion is slow compared to the rate at which the land surface adjusts, a slow subsidence sinkhole forms. If the subsurface erosion is rapid compared to the rate at which the land surface adjusts, a void can form in the unconsolidated materials above the bedrock surface, and when the roof of that void fails, a catastrophic sinkhole can suddenly appear.

The drains in the bottoms of both subsidence and catastrophic sinkholes can be plugged by debris. Water may temporarily collect in such plugged sinkholes and form ponds. As sinkholes continue to grow, they eventually form karst windows. In Minnesota the erosion process was interrupted by cycles of glacial deposition before the sinkholes evolved into karst windows.

A stone line is present beneath the loess in places, but not everywhere, in Fillmore County—see the section on Quaternary geology for discussion.

apart; and (3) the contamination danger if the facility fails and its contents are released into the environment—the draining of a farm pond does not present the same danger as the collapse of a sewage lagoon.

Sinkholes are such unwelcome parts of karst landscapes that many of them are artificially filled. Hundreds and perhaps thousands have been filled in Fillmore County alone. This "filling" process may simply involve packing the sinkhole with soil. More complex methods include digging out the sinkhole to the bedrock surface, plugging any bedrock crevices and backfilling with layers of impermeable materials. The goal of all such efforts is to stop the erosion caused by surface water running into the sinkhole and to return the land surface to some other more productive use. The more sophisticated sinkhole filling procedures are generally successful, although with all methods, the possibility remains that the sinkhole will reopen. Additional complications may arise after filling or sealing a sinkhole. Figure 4a is a block diagram showing a typical sinkhole acting as a stream sink. Figure 4b shows one potential consequence of sealing the sinkhole without providing an adequate alternative place for the surface water to go. The drainage has simply relocated along the joint in the bedrock and a new sinkhole has formed nearby.

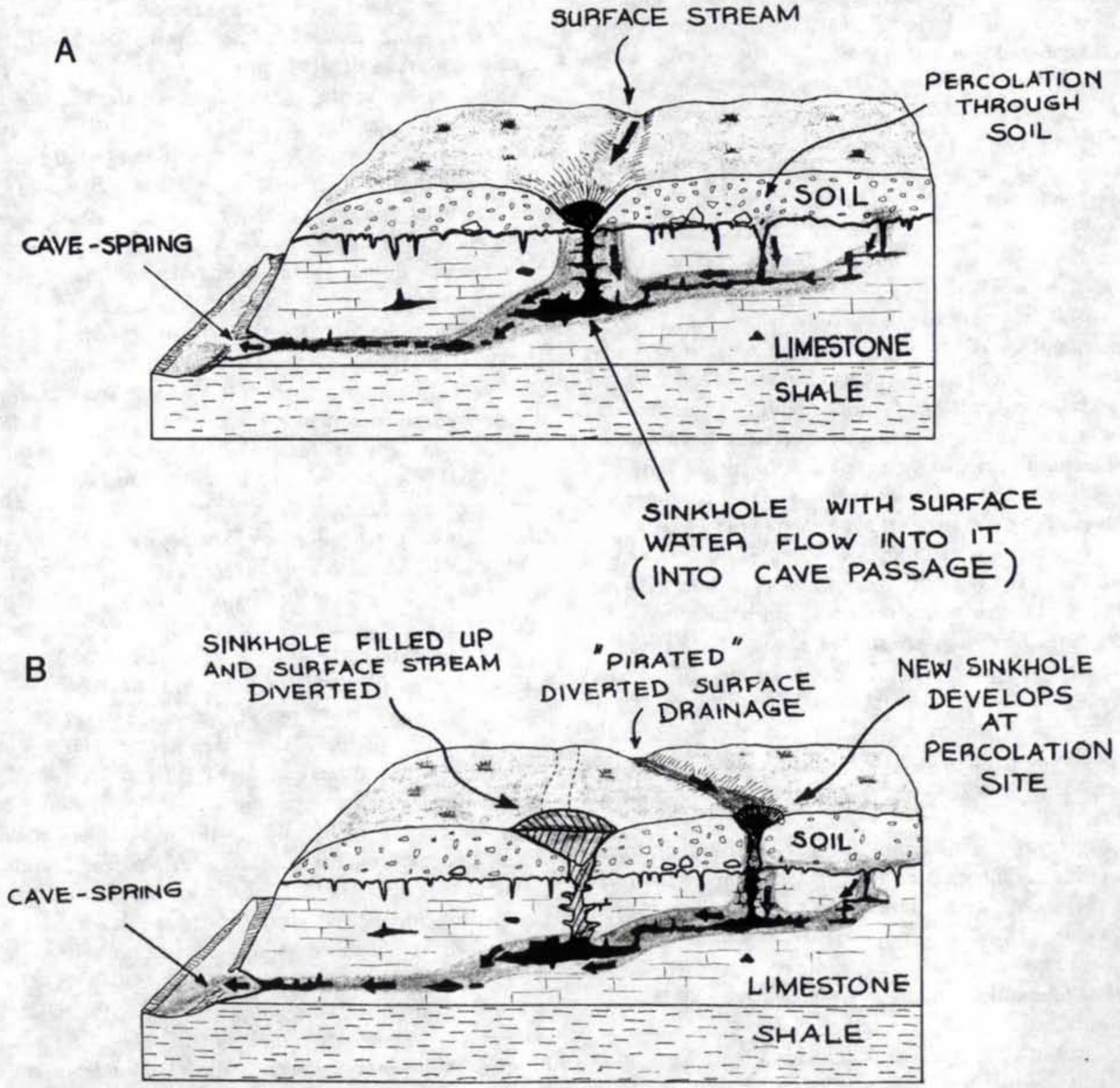


Figure 4. One possible consequence of sinkhole filling. A, sinkhole on surface. B, after filling sinkhole. Artwork by Ramesh Venkatakrishnan.

KARST HYDROGEOLOGY

The karst of Fillmore County can usefully be divided into two geologic categories: the karst in and on the Cedar Valley Group, the Wapsipinicon Group, the Maquoketa/Dubuque Formations. and the Galena Group (all grouped as the so-called upper carbonate aquifer); and the karst in and on the Prairie du Chien Group. These are separated by the Decorah/Platteville/Glenwood (see the stratigraphic column on Plate 2) Formations, which function as a confining unit, and the St. Peter Sandstone. The edge of this confining bed (Plates 2 and 9) is very convoluted because stream erosion has cut into the relatively flat-lying layers of bedrock in a complex pattern. The Prairie du Chien rocks form the bedrock surface in the central and eastern parts of the county, and underlie both the upper carbonate rocks and the Decorah/Platte-ville/Glenwood confining unit to the west. The highest sinkhole densities, the largest caves, and the most extensive conduit systems occur in the rocks of the upper carbonate units. The karst in the Prairie du Chien rocks is more subtle but still dominates the ground-water hydraulics in many areas.

Where either karst aquifer is near the surface, water from the surface can reach that aquifer in a matter of hours to days. Where both aquifers are present, people are using increasing amounts of water from the deeper Prairie du Chien aquifer—which is protected by the confining unit—because of pollution in the upper carbonate aquifer.

The speed with which surface pollutants reach a karst aquifer and move within it is discussed in the following chapter on chemistry in the section titled Ground-water Residence Time. The residence time—length of time since the water left the atmosphere and entered the ground-water system—is estimated from dye traces or on the basis of radioactive isotopes of hydrogen and carbon in water samples. In both aquifers, there are areas where the ground-water residence times are short, and the waters are much more likely to be polluted. A few miles west of the basal contact of the upper carbonate aquifer with the underlying confining beds, the residence times of the water in the deeper Prairie du Chien can be thousands to tens of thousands of years; such waters contain no evidence of modern pollution.

Figure 5a is an example of a conduit system in the western and southern parts of Fillmore county. Water that flows across surface glacial deposits for several miles before encountering a blind valley—where it then sinks into a karst system—is known as allogenic recharge. The basins that carry the surface runoff are called allogenic springsheds or basins.

The York blind valley sketched in Figure 5a is in the Spillville Formation. The water that sinks in the blind valley flows in bedrock conduits through the relatively impermeable Maquoketa and Dubuque Formations and may traverse several miles horizontally before reaching the top of the Stewartville Formation. From there the water cascades down vertical joints and may dissolve sizable vertical shafts in the subsurface. The waterfall in Niagara Cave is an example. At the bottom of these shafts the conduits return to a more horizontal orientation, and eventually carry the water to a spring where a surface valley, in this case the Upper Iowa River valley, intersects the conduit system. At this point ground water again becomes part of the surface flow, but at a location that is not strongly controlled by the stratigraphy.

Figure 5b illustrates the conduit geometry that underlies many of the units mapped as sinkhole plains (Plate 8), which occupy highlands between entrenched river valleys. In contrast to the previous example, spring locations in this configuration are tightly controlled by stratigraphy. The springs develop at the contact between the base of the Cummingsville and the top of the Decorah Shale. Sinkholes on the upland surface all feed water into integrated conduit systems in the bedrock that drain along the top of the Decorah to the springs.

Recharge generated from precipitation falling directly on the karst surface is called autogenic recharge. The underlying basins are called autogenic springsheds or basins. The diagram shows that the subsurface springsheds do not correspond to the topographic divides on the land surface. Dye placed into some individual sinkholes on the subsurface divide emerged from two or more springsheds. Subsurface interbasin areas were interpreted where dye traces from nearby sinkholes emerged at different springsheds.

Figure 5c illustrates the conduit geometry thought to underlie the western part of the Duschee Creek basin in the south-central part of Fillmore County. The basin is developed in the Prairie du Chien Group and feeds water into the large springs at the Lanesboro State Fish Hatchery. Small springs and seeps emerge at the tops of the Decorah and Platteville Formations all around the basin. That water, and any surface runoff, flows down across the Decorah and Platteville/Glenwood subcrops and then sinks into diffuse stream sieves over the St. Peter subcrop, making its way downward into conduits in the Prairie du Chien. Precipitation and runoff also infiltrate through the soil across the rest of the basin area. A small intermittent stream in the central part of the basin formerly sank through the New Richmond Sandstone Member of the Shakopee Formation. Dye traces demonstrated that water from that stream sink traveled 2.5 miles to the springs at the Hatchery in 8 to 10 hours. The dye pulses detected in the Hatchery springs were much more complex than those of traces in the upper carbonate aquifer, an indication that the Prairie du Chien conduits are more complex than those in the upper carbonate aquifer.

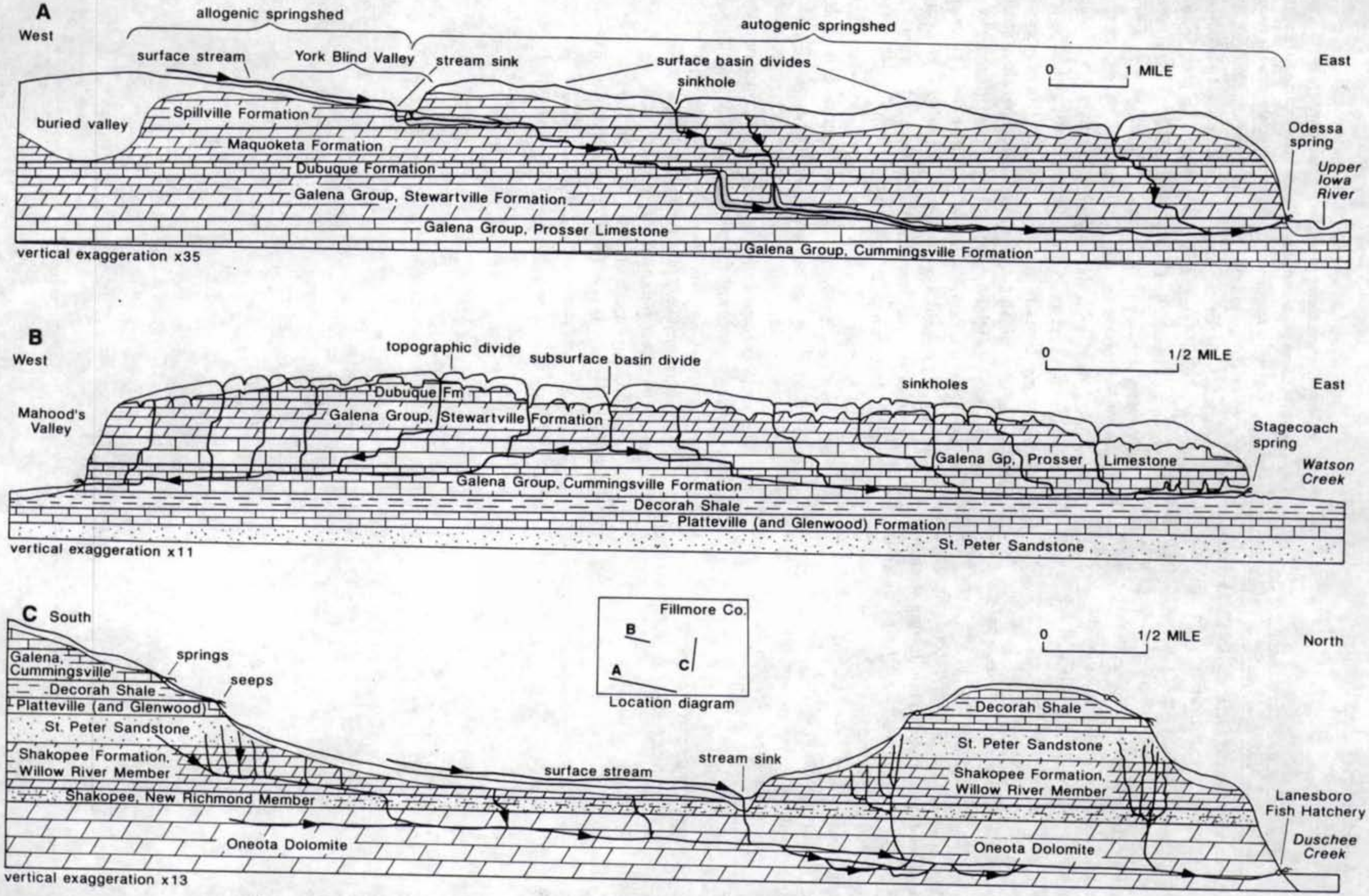


Figure 5. Three examples of conduit flow in Fillmore County. See text for discussion.

The springsheds map (Plate 9) outlines the allogenic and autogenic parts of the basins that feed several of Fillmore County's large karst springs. Flow paths were determined by dye traces and cave mapping from input points, such as sinkholes and stream sinks, to the springs where the water returns to the surface. It will take years of study to map all of Fillmore County's springsheds and underground rivers. Although we know that much of the white area on Plate 9 includes parts of springsheds, the necessary tracing has not yet been done to map them. The tracing done for the Fillmore County Atlas was concentrated along the major paved roads in order to prepare for spills of hazardous materials in transportation accidents.

Monitoring wells appropriate for sandstone or other conventional aquifers can yield an incomplete and even erroneous picture of pollutants moving in karst aquifers (Quinlan and Ewers, 1985). The springshed map can assist with the development of effective monitoring strategies in Fillmore County. For example, if hazardous material were released in one of the allogenic springsheds, it would either move along the surface to a sinkpoint, or flow directly into a sinkhole. Pollutants could also infiltrate through the unsaturated zone of an autogenic springshed. For these examples, the spring resurgence of that springshed is the best place to monitor for the pollutant. However, for release sites outside the colored areas, data do not suffice to predict where the pollutant should be monitored, and site-specific traces would be a necessary part of a monitoring system design.

SUMMARY

Karst features and processes affect water resources in Fillmore County. Although influenced by surface features, ground-water systems in karst are independent of natural features such as ridges, surface streams, and surface watershed boundaries, and also features such as roads, county or state lines, and property boundaries. Studies have demonstrated that ground water in karst systems can move very rapidly. With speeds of miles per day not unusual, pollutants introduced into these karst systems by human activities on the surface can be transported long distances in a very short time. In other karst areas, transport speeds may be only inches per year. These areas are considered to be less prone to pollution hazards, but still have some potential for becoming polluted. Karst ground-water systems can be systematically mapped, understood, and rationally managed. However, the process takes time, resources, and the support of private land owners, and municipal, state, and federal governments.

The Fillmore County atlas project was designed to obtain geologic and hydrologic information that could be used to produce maps, data bases and other types of hydrogeologic data that resource managers, professionals, and private citizens can use to better protect and manage the water resources of the county. If one is interested in a specific site, first locate that site on the various maps in the atlas. Next understand how the geology and karst hydrology of the site affect potential activities at the site. It is very important to appreciate that the hydrogeology that directly affects the site or is affected by the site may extend for several miles beyond the site. In the karst hydrogeology of Fillmore County, truly "no man is an island."

GROUND-WATER CHEMISTRY

By

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INTRODUCTION

In Fillmore County, as elsewhere, precipitation infiltrates the surface soil and rock and then percolates downward. It becomes ground water upon reaching the water table. As it moves, water reacts with the soil and rock and acquires a chemical signature that is characteristic of the materials it has encountered. By sampling and analyzing ground water, the chemical characteristics of aquifers and the interchange of water between the aquifers can be determined. A study of general water chemistry can show if ground water is suitable for drinking and other uses. Water-chemistry data are also essential for evaluating the susceptibility of an aquifer to surface contamination. Measurements of tritium and nitrate levels in water were used to check pollution-sensitivity assessments based on limited information.

Water samples from 104 domestic and municipal wells throughout Fillmore County were collected from 1992 to 1994 by the staffs of the Department of Geology and Geophysics at the University of Minnesota and the Minnesota Department of Natural Resources. Four upper principal bedrock aquifer systems in the county were sampled. In stratigraphic order from the land surface downward, the aquifer systems are the informally-known carbonate* (11 samples), the St. Peter-Prairie du Chien-Jordan (72 samples), the Franconia-Ironton-Galesville (16 samples), and the Mt. Simon (5 samples). The physical hydrogeology of these aquifers is discussed in Plate 6, Bedrock Hydrogeology. The locations of the sampled wells are shown on Figure 1. Temperature, pH, Eh, conductivity, dissolved oxygen and alkalinity for each well were measured at the time of sampling. Water samples for laboratory analysis of major cations and anions were collected in polyethylene bottles. Cation samples were acidified with 6N HCl to retard precipitation. Cations were analyzed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, EPA method 200.8) and anions were analyzed using Dionex Series 4000I ion chromatography (EPA method 300). Tritium (^3H) activities in the water were measured to determine if the water entered the ground before or after 1953. Water from 23 wells with undetectable tritium were sampled for carbon-14 to determine older ground-water residence times.

The results of the analyses are summarized by aquifer in Table 1. A complete compilation of the data can be obtained from the Division of Waters, Minnesota Department of Natural Resources. The bar graphs in Figure 2 display the chemical characteristics of the upper carbonate, St. Peter-Prairie du Chien-Jordan, and

Atoms, Ions, and Chemical Units

Most dissolved materials in ground water are present as charged atoms or molecules, called ions. Positively charged ions are given the name cations, while negatively charged ions are called anions. Major cations in natural waters include calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^+) and potassium (K^+). Major anions are bicarbonate (HCO_3^-), sulfate (SO_4^{-2}) and chloride (Cl^-). The total number of positive charges in any water sample must equal the total number of negative charges. This electrochemical balance provides one tool for checking the accuracy of water analyses.

Ion concentrations in ground water are commonly expressed in two units, milligrams per liter (mg/L) or parts per million (ppm). In fresh water, the two units are numerically equal. One part per million is the same as one milligram (mg) of solute per thousand grams of solution because one liter of fresh water weighs one kilogram. Milligram equivalents per liter (meq/L) is another concentration unit used in discussing, analyzing and presenting ground-water chemical data. This unit can be used to determine the proportions of cations and anions that are available for chemical reactions in water. It takes into account the charge on the ion as well as the concentration. Meq/L values are based on the number of electrical charges present in the dissolved ions. One meq/L of any ion has the same number of electrical charges as one meq of another ion. To convert from mg/L to meq/L, the ion concentration is multiplied by the charge (valence) of the ion, and then divided by the atomic weight (or molecular weight if a molecule) of the ion. Examples of how to convert mg/L to meq/L are illustrated in Figure 3. All three units are used in the following discussion.

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*Includes the Cedar Valley Group, the Wapsipinicon Group, the Maquoketa-Dubuque Formations and the Galena Group.

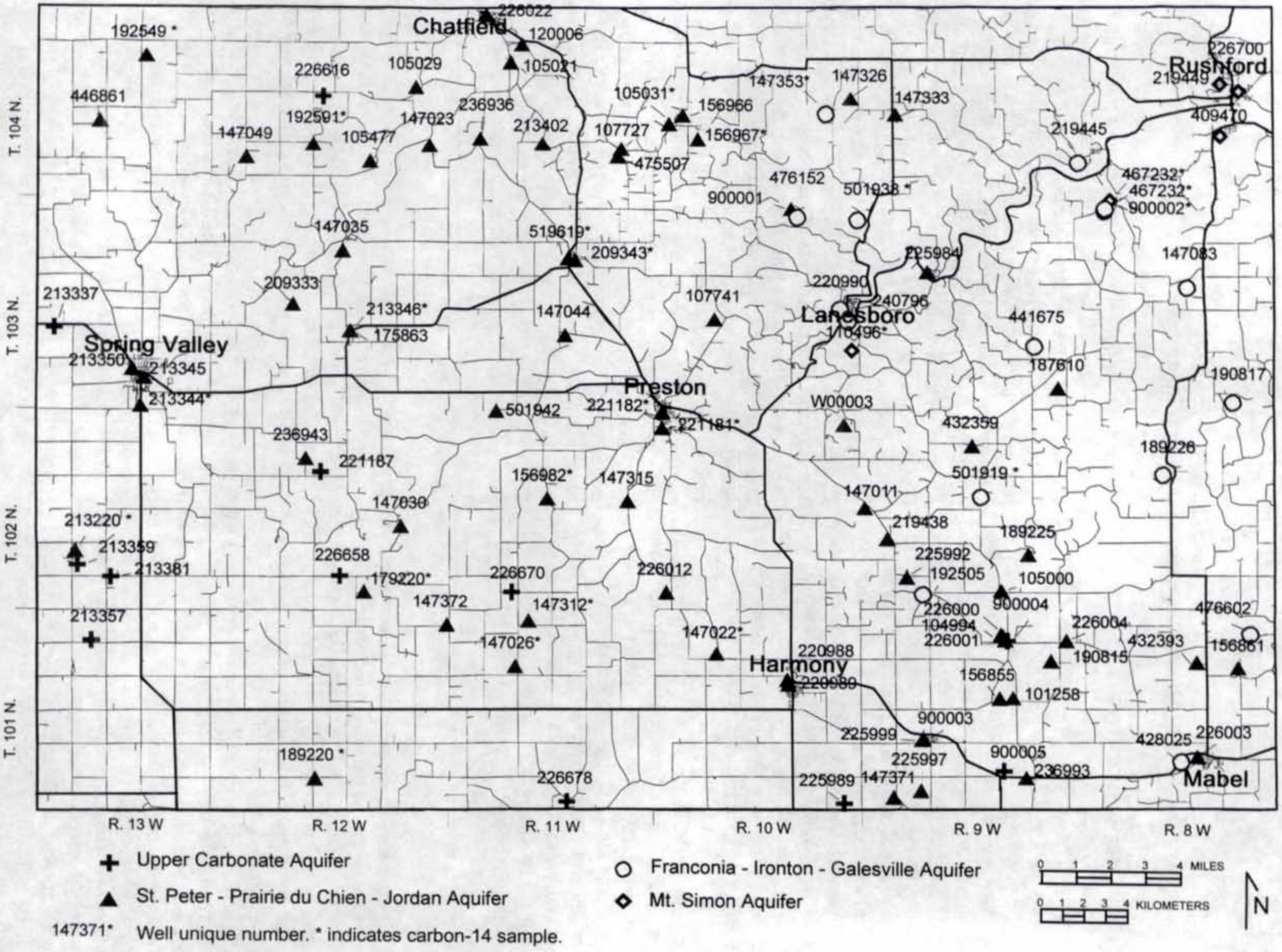


Figure 1. Distribution of sampled wells by aquifer.

Table 1. Summary of ground-water chemistry for four aquifers in Fillmore County.

	Well Depth	Temp	pH	Conductivity	Eh	Dissolved Oxygen	Ca	Mg	Na	K	Fe	Mn	Sr	Ba	Si	Alkalinity	Cl	Br	NO3-N	SO4	HCO3	Hardness	TDS	Tritium	^{14}C	$D^{13}C$
units	feet	°C	pH unit	µS/cm	mV	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	TU	%modern	per mil
Upper Carbonate Aquifer																										
Min	50	7.4	7.08	310	140	0.0	55.1	14.3	2.72	0.62	0.02	0.001	0.039	0.062	3.9	196.0	2.11	0.01	0.02	14.9	239.1	212.6	349.6	11.6	-	-
Max	283	10.4	7.77	1010	324	10.5	135.8	57.8	41.70	6.70	1.00	0.111	0.272	0.188	14.3	351.0	70.70	0.13	31.20	68.3	428.2	576.5	818.5	25.0	-	-
Average	131	9.3	7.34	703	220	4.9	92.5	30.8	12.71	2.21	0.25	0.025	0.139	0.111	6.6	279.5	31.68	0.04	8.46	31.8	340.9	357.7	560.2	17.0	-	-
Count	8	11	11	11	8	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	0	0
St. Dev	86	0.8	0.19	240	69	4.4	30.4	13.0	12.49	2.00	0.32	0.038	0.083	0.039	3.6	63.7	25.93	0.04	8.98	17.1	77.7	119.5	169.6	3.9	-	-
St. Peter-Prairie du Chien-Jordan Aquifer																										
Min	60	6.0	7.13	280	-165	0.0	43.1	14.9	1.47	0.47	0.00	0.000	0.035	0.009	0.0	177.0	0.15	0.01	0.01	9.8	215.9	204.8	326.2	0.4	0.3	-12.6
Max	1222	12.4	7.77	1140	716	12.7	117.6	37.7	16.01	5.47	7.31	0.047	0.153	0.149	13.3	329.0	60.95	0.07	15.50	51.6	401.4	418.2	655.6	23.1	88.5	-9.3
Average	424	9.6	7.45	519	145	4.5	76.6	23.0	3.23	1.38	0.48	0.012	0.101	0.054	7.7	251.4	5.45	0.01	2.31	22.1	306.8	285.8	449.2	7.4	36.6	-10.9
Count	87	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	17	17
St. Dev	236	0.8	0.14	156	156	4.1	16.9	4.1	2.48	0.82	1.09	0.012	0.024	0.030	2.4	33.6	8.70	0.01	3.52	6.2	41.1	46.0	67.8	6.0	26.9	0.9
Franconia-Ironton-Galesville Aquifer																										
Min	245	7.8	7.14	310	-194	0.0	52.4	17.0	1.44	0.63	0.01	0.005	0.047	0.014	4.6	213.0	0.39	0.01	0.01	12.6	259.9	233.9	369.5	0.4	28.7	-14.3
Max	730	11.4	7.93	910	609	13.0	61.6	32.5	2.97	5.31	7.09	0.072	0.815	0.086	7.7	267.0	3.47	0.01	2.33	27.6	325.7	289.3	461.3	19.4	77.2	-8.8
Average	512	9.6	7.54	466	-3	2.5	62.4	25.9	2.30	2.14	1.36	0.024	0.166	0.050	6.2	241.8	1.10	0.01	0.27	20.1	294.9	262.4	417.0	2.2	54.0	-11.4
Count	14	16	16	16	13	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	4	4
St. Dev	133	1.0	0.16	174	200	3.9	6.7	3.8	0.43	1.55	1.86	0.015	0.173	0.027	1.0	15.4	1.03	0.00	0.62	4.6	16.8	15.5	24.5	4.8	20.0	3.0
Mt. Simon Aquifer																										
Min	366	10.2	7.53	490	-113	0.1	56.8	20.2	5.69	1.83	0.19	0.019	0.106	0.037	3.3	210.0	6.46	0.01	0.01	19.1	256.2	226.1	409.46	0.4	0.2	-11.9
Max	1070	10.8	7.68	1140	30	1.3	76.9	30.4	121.50	6.20	0.63	0.033	0.959	0.203	6.0	240.0	175.00	0.63	0.04	95.0	292.8	294.8	790.43	0.9	0.8	-11.5
Average	676	10.4	7.59	769	-40	0.4	63.2	25.0	44.12	5.28	0.44	0.024	0.570	0.081	4.6	226.6	56.99	0.13	0.01	46.1	276.5	260.6	525.1	0.5	0.5	-11.7
Count	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	2	2
St. Dev	257	0.2	0.06	267	74	0.5	6.2	4.7	47.19	2.53	0.19	0.006	0.351	0.070	1.1	12.9	70.38	0.28	0.02	29.8	15.8	28.7	163.86	0.2	0.4	0.3

Note: µS – Microsiemens; mV – millivolts; per mil – parts per thousand.

%modern: $(C/C_0)*100$. where C_0 is the specific activity (disintegrations per unit time per unit mass of sample) of carbon-14 in the earth's atmosphere, and C is the activity of carbon-14 in the sample.

Alkalinity is expressed as $CaCO_3$.

Hardness is the total hardness expressed as $CaCO_3$. Hardness = $2.5\,(Ca^{2+}) + 4.1\,(Mg^{2+})$, where Ca^{2+} and Mg^{2+} are the concentrations of Ca^{2+} and Mg^{2+} ions in mg/L.

Total Dissolved Solids (TDS) is the sum of the cation and anion concentrations expressed in mg/L.

Nitrate (NO_3) is expressed as molecular nitrogen (N). 1 mg/L nitrogen equals 4.5 mg/L nitrate.

Franconia-Ironton-Galesville aquifers, while the pie charts in Figure 3 show the percentages and relative concentrations of major ions. The primary (U.S. Environmental Protection Agency, 1994) and secondary (U.S. Environmental Protection Agency, 1994) standards for public drinking-water supplies were used as the criteria for evaluating and comparing the water quality data.

COMPARISON OF GROUND-WATER CHEMISTRY AMONG AQUIFERS

All of the ground water in Fillmore County contains calcium, magnesium, and bicarbonate as the dominant ions. As Figure 3 indicates, the calcium and magnesium cations account for more than 46% of the total average meq/L of ions in solution, while the bicarbonate anion makes up more than 36%. The average concentrations of Ca^{+2}, Mg^{+2}, and HCO_3^- decrease downward from the upper carbonate aquifer to the St. Peter-Prairie du Chien-Jordan aquifer (Table 1 and Figure 2). Waters recently recharged (tritium > 10 tritium units, TU) contain about 6.5-10 meq/L of Ca^{+2} and Mg^{+2}, compared to older water (tritium < 0.8 TU) that contains about 4-6 meq/L of Ca^{+2} and Mg^{+2}. Alexander (1995, personal communication) suggested the additional Ca^{+2} and Mg^{+2} result primarily from activities of people at the land surface, such as agriculture.

Fillmore County ground water exceeds 200 mg/L of hardness (expressed as $CaCO_3$ equivalent) and is commonly softened for household uses. Because Ca^{+2} and Mg^{+2} are the major contributors to water hardness, the variations of the hardness among the upper three aquifers are similar to the variations of Ca^{+2} and Mg^{+2}. Water with this hardness has noticeable effects during use, causing scale deposits in pipes, excessive soap consumption, and formation of scum coatings on surfaces.

The pH (acid concentration) of the ground waters in Fillmore County ranges between 7 and 8 pH units. These neutral to slightly basic waters form when somewhat acidic rain waters (pH = 4 to 6) dissolve carbonate minerals in the soil and rock. As acidity of the water decreases (pH increases), calcium, magnesium, and bicarbonate ions are released. This process of changing the pH also increases the buffering capacity (ability to resist changes in pH) of water .

Total dissolved solids (TDS) is a measure of the concentration of material dissolved in the water. TDS is calculated from the concentrations of the major cations and anions. In Fillmore County, the TDS of ground water ranges from approximately 320 to 820 mg/L. The upper carbonate aquifer has the highest average TDS (560 mg/L) and widest range (349-818 mg/L). The average TDS values of the aquifer systems are between 417 and 560 mg/L, bracketing the 500-mg/L secondary drinking-water standard. Total dissolved solids decrease with depth in the upper three aquifers but then increase in the Mt. Simon aquifer.

Other significant ions in Fillmore County ground water include sodium (Na^+) and potassium (K^+). Although these ions are more soluble in water than Ca^{+2} and Mg^{+2}, they are lower in actual concentration. Minerals rich in sodium and potassium in the county are mostly feldspars in sandstone, siltstone, till, and soil. These minerals are more resistant to weathering and dissolution than carbonate minerals. The upper carbonate aquifer system has higher average concentrations of Na^+ and K^+ (12.71 mg/L and 2.21 mg/l, respectively) than either the Franconia-Ironton-Galesville or the St. Peter-Prairie du Chien-Jordan aquifer systems (Table 1). The Franconia-Ironton-Galesville aquifer is somewhat higher in K^+ than the St. Peter-Prairie du Chien-Jordan aquifer. The average concentration of both Na^+ and K^+ is higher in the Mt. Simon aquifer than in any of the three overlying aquifers, averaging 44.12 mg/L and 5.28 mg/L, respectively. Human activities can have a significant influence on the concentrations of these ions in shallow ground water systems. Salt used for deicing highways and potassium-rich "potash" fertilizers applied on farmland, for example, add sodium and potassium to the uppermost aquifer in the county. Unlike Na^+ that has a higher average concentration in the upper carbonate aquifer than in the St. Peter-Prairie du Chien-Jordan aquifer, potassium increases only slightly. This may occur because potassium ions are nutrients and are removed from the infiltrating water by plant roots or because they are more efficiently adsorbed onto clays than are sodium ions.

Elevated nitrate concentration in ground water is one of the principal concerns for safe drinking water. Unlike most elements in ground water, nitrate is not a product of weathering and solution of rocks in Fillmore County. Instead, nitrate is produced by human and animal activities and is distributed on the land as fertilizer, refuse dumps, animal feed-lot wastes, and septic-tank discharges. In Minnesota, the nitrate content of water is normally reported as nitrate-nitrogen (NO_3^-–N). According to the primary drinking-water standards, nitrate-nitrogen concentrations should not exceed 10 mg/L. Higher levels are undesirable for drinking water because they are potentially toxic to young infants (Driscoll and others, 1986). Results from this study show that nitrate levels vary both across the county and vertically between the aquifers. Water samples from the upper carbonate aquifer average 8.5 mg/L and range from 0.02 to 31.2 mg/L. Four of 11 samples had nitrate concentrations higher than 10 mg/L. This elevated nitrate is a result of surface water entering the aquifer through the numerous fractures and solution-enlarged

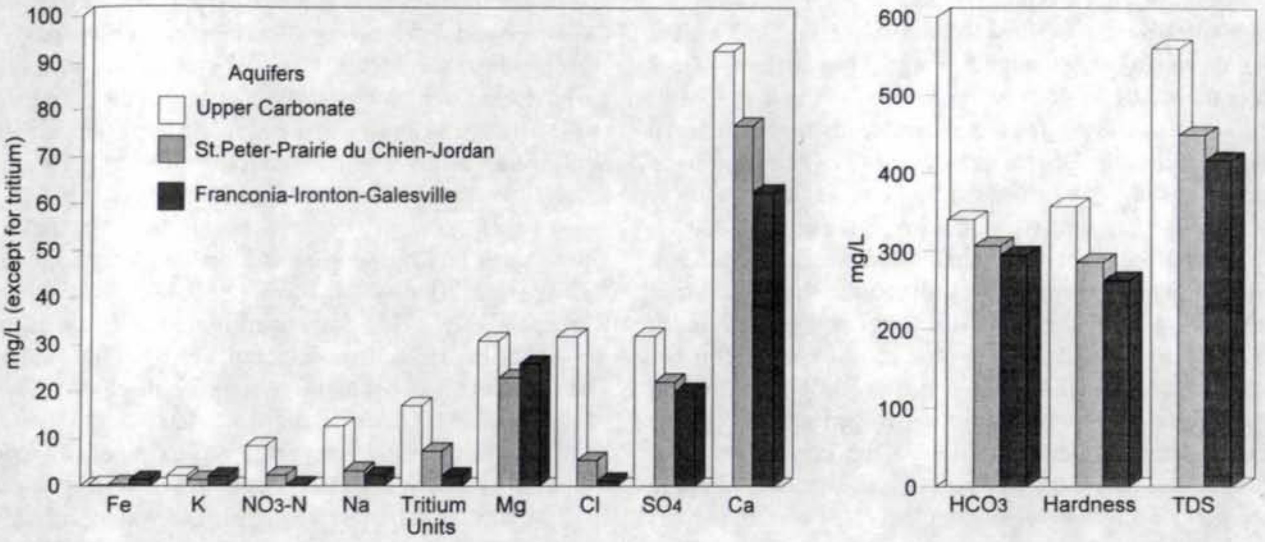
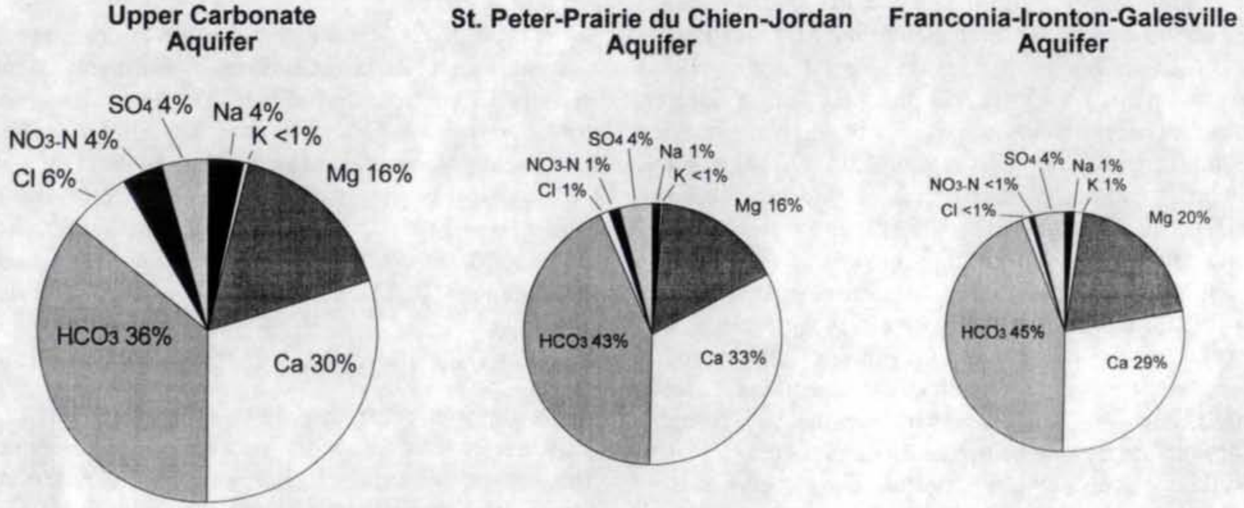


Figure 2. Comparison of major chemical parameters by aquifer.



Note : The sectors in each pie represent the percent average meq/L of each ion in the aquifer.

The sizes of pies are proportional to the average total meq/L in each aquifer.

The percent cations and anions are calculated as milligram equivalents per liter (meq/L), where meq/L = (mg/L x valence) / molecular weight.

Example 1. To convert 90.2 mg/L Ca^{+2} to meq/L:

Atomic weight $Ca^{+2} = 40.08$

Ca^{+2} valence = 2

$90.2 \text{ mg/L } Ca^{+2} = \frac{90.2 \times 2}{40.08} = 4.50 \text{ meq/L } Ca^{+2}$

Example 2. To convert 340 mg/L HCO_3^- to meq/L:

Molecular weight $HCO_3^- = 61.01$

HCO_3^- valence = 1

$340 \text{ mg/L } HCO_3^- = \frac{340 \times 1}{61.02} = 5.57 \text{ meq/L } HCO_3^-$

Figure 3. Percentages of major cations and anions in Fillmore County aquifers.

conduits in the carbonate rocks. In the underlying St. Peter-Prairie du Chien-Jordan aquifer system, nitrate levels are lower (average 2.3 mg/L) but still vary from less than 0.01 to 15.5 mg/L across the county; five of 72 samples show nitrate concentrations higher than 10 mg/L. Where the Decorah-Platteville-Glenwood confining unit (see Plate 6) overlies the St. Peter-Prairie du Chien-Jordan aquifer, nitrate-nitrogen levels are generally lower than where it is absent (Zhang and Alexander, 1994). The Franconia-Ironton-Galesville aquifer has even lower nitrate-nitrogen concentrations, averaging 0.27 mg/L with a range of 0.01 to 2.3. The Mt. Simon aquifer has the lowest average nitrate-nitrogen (0.01 mg/L) of all the aquifers. The low nitrate-nitrogen concentrations can indicate water that entered the aquifer systems before elevated nitrate concentations were prevalent in the surface environment, water that infiltrated in regions with limited nitrate sources, or water which has been denitrified, a process by which bacteria convert nitrate to nitrogen gas in a reducing environment.

The maximum chloride (Cl^-) concentration in Fillmore County aquifers is 175 mg/L, well below the secondary drinking-water standard of 250 mg/L. Chloride concentrations average 32 mg/L, ranging up to 70 mg/L in the upper carbonate aquifer. Chloride in the St. Peter-Prairie du Chien-Jordan aquifer averages 5 mg/L. Chloride concentration in the Franconia-Ironton-Galesville aquifer is lower than in the St. Peter-Prairie du Chien-Jordan aquifer, averaging 1.1 mg/L, with a maximum of 3.5 mg/L. In the Mt. Simon aquifer, chloride concentrations are significantly higher, averaging 59 mg/L, with a range of 6.5 mg/L to 175 mg/L. The potential sources of part of the chloride in the near-surface aquifers are potash fertilizer, water-softener salt, and deicing salt. Chloride in deep aquifers is thought to originate mainly from deep connate brines or perhaps dissolution of chloride-rich minerals.

Sulfate concentrations in Fillmore County ground water are relatively low with an average of less than 46 mg/L, and maximum concentrations below 95 mg/L. These values are well below the 250 mg/L of the secondary drinking-water standard. Sulfate mainly comes from oxidation of sulfides (mostly pyrite) or dissolution of sulfate minerals (such as gypsum) in the rock and soil. Detergents in household wastes, waste water from treatment plants, and agricultural fertilizers can also contribute sulfate to the shallow ground water system (Safe Drinking Water Committee, 1977, p. 425). The upper carbonate aquifer has a higher average sulfate concentration (32 mg/L) compared to the two lower aquifers (<23 mg/L), indicating a likely surface source of sulfate. However, sulfate concentrations in the Mt. Simon are higher than those in the upper carbonate aquifer.

In contrast to most dissolved species in Fillmore County ground water, average total iron (Fe) concentrations increase downward from the upper carbonate aquifer to the Franconia-Ironton-Galesville aquifer, and then decrease in the Mt. Simon aquifer. Water in the upper carbonate aquifer has an average iron concentration of 0.25 mg/L, slightly lower than the secondary drinking-water standard of 0.3 mg/L. Iron concentrations in the St. Peter-Prairie du Chien-Jordan and the Franconia-Ironton-Galesville aquifer systems average 0.48 and 1.36 mg/L, respectively. This downward increase is related to the oxidation-reduction potential (Eh) of the water. The water in the upper aquifers contains more dissolved oxygen and is more oxidizing than water in the lowest aquifer. Most ferrous iron (Fe^{+2}) was oxidized to ferric iron (Fe^{+3}) and precipitated out of the water in the shallow aquifer systems. Iron in ground water probably comes from dissolution of iron-bearing minerals, iron oxides and sulfides, in sedimentary rocks, although waste water can contribute some iron to the shallow aquifers. Elevated iron concentrations in Fillmore County ground water do present problems for water users. Water rich in ferrous iron (Fe^{+2}) has a "metal" taste, tends to cloud water upon oxidation, and favors the growth of iron bacteria. Iron precipitates stain bath fixtures and laundry, encrust well screens, and clog pipes (Driscoll and others, 1986).

Although the chemical behavior of manganese resembles iron, its concentration in Fillmore County aquifers differs from that of iron. The upper carbonate, Franconia-Ironton-Galesville, and Mt. Simon aquifers have slightly higher manganese concentrations (averaging 0.02 mg/L) than the St. Peter-Prairie du Chien-Jordan aquifer (average of 0.01 mg/L). Manganese concentrations in most of the samples was below the secondary drinking water standard of 0.05 mg/L.

GROUND WATER-RESIDENCE TIME

A major effort in this study was to determine the residence time of ground waters in Fillmore County. The amounst of radioactive isotopes of hydrogen and carbon were determined in selected samples to estimate how long it has been since the water left the atmosphere and entered the ground-water system. This information allows recent, possibly human-affected recharge water to be separated from older recharge water, allowing a better evaluation of how long it might take contaminants to reach an aquifer from surface sources.

The results of 102 tritium samples (Table 1) show that all 11 samples from the upper carbonate aquifer were "recent water," having entered the ground after 1953 (see sidebar). Figure 4 shows the distribution across Fillmore County of tritium levels in the St. Peter-

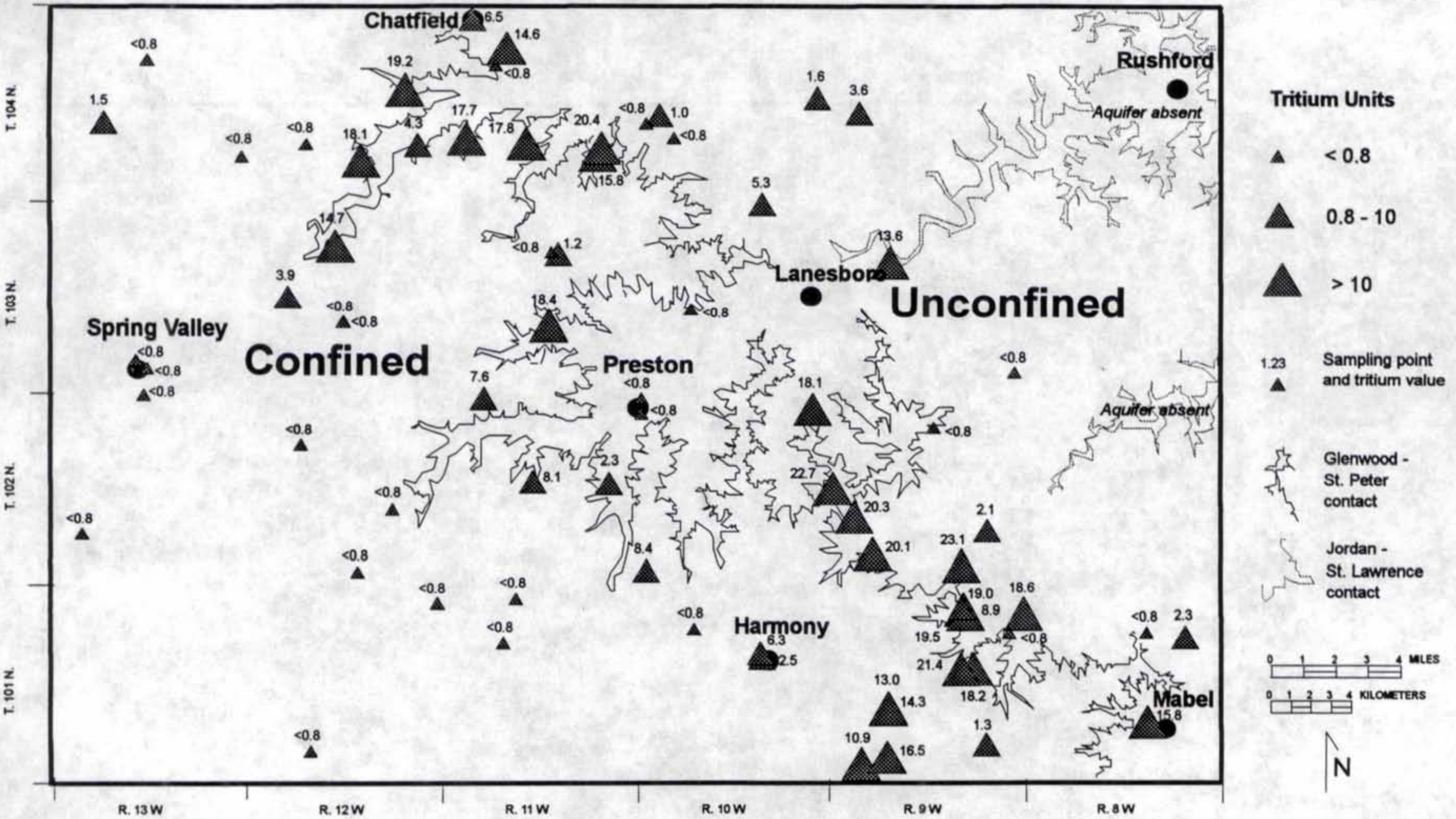


Figure 4. Distribution of tritium in the St. Peter-Praìrie du Chien-Jordan aquifer in Fillmore County. Confined portion of the aquifer is west and south of the Glenwood-St. Peter contact. Aquifer absent north and east of the Jordan-St. Lawrence contact where it is eroded below the base of the Jordan.

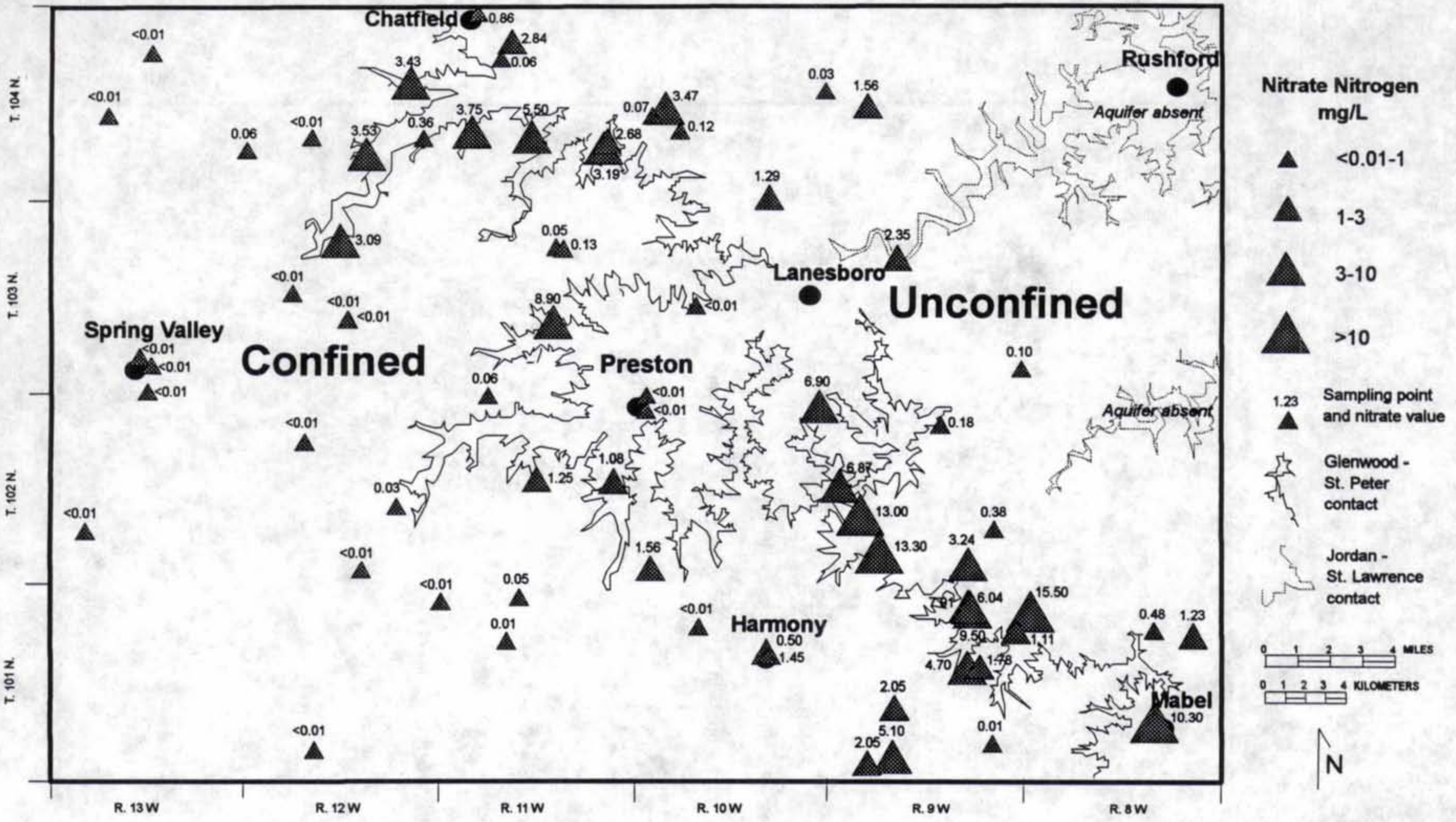


Figure 5. Distribution of nitrate-nitrogen in the St. Peter-Prairie du Chien-Jordan aquifer in Fillmore County. Confined portion of the aquifer is west and south of the Glenwood-St. Peter contact. Aquifer absent north and east of the Jordan-St. Lawrence contact where it is eroded below the base of the Jordan.

Prairie du Chien-Jordan aquifer. Tritium concentrations in the St. Peter-Prairie du Chien-Jordan aquifer show the influence of the presence or absence of the overlying Decorah Shale. Higher tritium levels are concentrated in a band along and east of the subcrop of the Decorah-Platteville-Glenwood confining unit. Tritium was generally below 0.8 TU where the aquifer is overlain by the confinng unit. Where the Decorah Shale is absent and the St. Peter-Prairie du Chien-Jordan aquifer is directly recharged from precipitation, tritium values as high as 23 TU were recorded. These high tritium levels also broadly correspond to the elevated levels of nitrate in the St. Peter-Prairie du Chien-Jordan aquifer shown in Figure 5. Waters in the Franconia-Ironton-Galesville aquifer are generally "vintage" except for some wells in the main Root River valley, where erosion has exposed the aquifer and surface water appears to be recharging what would normally be a more protected aquifer. The Mt. Simon aquifer had the lowest average tritium concentrations.

In areas where ground waters are "vintage," it is possible to obtain more information about residence times by analyzing another radioactive isotope produced in the atmosphere, carbon-14. Analyses of 23 ^{14}C samples indicate that the oldest ground waters in Fillmore County are more than 35,000 years old. These samples were from the Franconia-Ironton-Galesville and the Mt. Simon aquifers in the eastern part of the county, and from the St. Peter-Prairie du Chien-Jordan aquifer in the western part of the county. These old ages imply that recharge to those aquifers from surface sources occurred long ago and there is less chance of them becoming contaminated by surface pollutants. However, if these old waters do become contaminated, such as via poorly constructed wells, they could remain contaminated for a long time.

Table 2 compares the ground-water chemistry for the four aquifers sorted by residence time. Figure 6 displays the differences of water chemistry in the recent, mixed, and vintage waters for the upper three aquifers. The table shows that some chemical parameters within the St. Peter-Prairie du Chien-Jordan aquifer vary by tritium class. Recently recharged waters, characterized by tritium concentrations >10 TU, are higher in Ca^{+2}, Mg^{+2}, Na^{+}, Cl^{-}, and NO_3^{-}-N compared to the older waters.

DISTRIBUTION OF SOME CHEMICAL COMPONENTS IN THE ST. PETER-PRAIRIE DU CHIEN-JORDAN AQUIFER

The major dissolved components of ground water in the St. Peter-Prairie du Chien-Jordan aquifer can be grouped into three categories: Group I (calcium, magnesium, and bicarbonate), Group II (nitrate and tritium), and Group III (manganese, iron, and sulfate). These groups are based on chemical, geological, and cultural factors. Chemical factors include processes such as rock and mineral dissolution. The presence or absence of the Decorah Shale above the St. Peter-Prairie du Chien-Jordan aquifer is one important geological factor. Recent human activity has produced a measurable change in the chemistry of Fillmore County ground water. The groups combine these factors in different relative proportions.

Group I (Ca^{+2}, Mg^{+2}, HCO_3^{-}) includes ions that result primarily from the dissolution of carbonate minerals, although other natural geochemical processes, as well as human activities such as agriculture, affect the distribution of the components of this group. In addition, the presence or absence of the Decorah Shale has some effect on the distribution of the components of this

Tritium and Carbon-14

Tritium is a radioactive isotope of hydrogen that is generated naturally by nuclear reactions in the upper atmosphere. Tritium was also created by atmospheric nuclear testing between 1953 and 1963. Once created, tritium decays with a half-life of 12.43 years. The amount of tritium measured in a sample of ground water can indicate its age. Tritium concentration or activity is reported in tritium units (TU). A tritium unit is the equivalent to an atom ratio of 1 tritium atom in 10^{18} hydrogen atoms. Ground water in Minnesota has been classified into three age categories from measured tritium levels (Alexander and Alexander, 1989). Waters with tritium levels of 10 TU or higher are "recent waters" and entered into ground water after 1953, when large-scale atmospheric testing of nuclear weapons began. Waters with less than 0.8 TU of tritium are classified as "vintage waters" that entered the ground water prior to 1953. Waters with 0.8 to 10 TU tritium are "mixed waters" of the previous two.

Carbon-14 is a radioactive isotope of carbon with a half-life of 5730 years. It can be used to establish ground water residence times as old as 35,000 years. Similar to tritium, ^{14}C is produced in the earth's upper atmosphere and enters the ground-water system with precipitation. The amount of ^{14}C measured in a sample of ground water provides an estimate of how long the water has been isolated from the atmosphere.

Table 2. Summary of ground-water chemistry by aquifer for three residence time groups.

	Well Depth	Temp	pH	Conductivity	Eh	Dissolved Oxygen	Ca	Mg	Na	K	Fe	Mn	Sr	Ba	Si	Alkalinity	Cl	Br	NO3-N	SO4	HCO3	Hardness	TDS	Tritium	^{14}C	$D^{13}C$
units	feet	°C	pH unit	µS/cm	mV	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	TU	%modern	per mil
Tritium < 0.8 TU																										
Upper Carbonate Aquifer (no records this tritium range)																										
St. Peter-Prairie du Chien-Jordan Aquifer																										
Min	166	6.2	7.25	280	-165	0.0	43.1	15.4	1.47	0.55	0.01	0.001	0.035	0.009	4.0	177.0	0.15	0.01	0.01	12.5	215.9	204.8	326.2	<0.8	0.3	-12.6
Max	1030	11.8	7.77	930	352	5.6	60.5	27.6	3.46	2.94	7.31	0.047	0.146	0.149	6.6	271.0	3.79	0.01	1.11	46.6	330.6	289.6	456.6	<0.8	63.0	-9.3
Average	517	9.5	7.53	443	50	1.1	53.2	22.8	2.24	1.47	0.86	0.017	0.098	0.040	6.0	227.1	1.27	0.01	0.09	24.0	277.1	251.7	399.2	<0.8	32.7	-10.8
Count	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	15	15
St. Dev	231	0.7	0.14	122	116	1.8	9.7	2.8	0.51	0.60	1.59	0.013	0.026	0.026	1.6	29.7	1.01	0.00	0.22	9.4	36.2	25.5	41.0	-	26.2	0.9
Franconia-Ironton-Galesville Aquifer																										
Min	245	8.6	7.14	320	-132	0.0	52.4	21.7	1.44	0.63	0.24	0.014	0.047	0.014	4.6	213.0	0.39	0.01	0.01	15.4	259.9	233.9	369.5	<0.8	28.7	-13.6
Max	730	11.4	7.93	910	609	4.9	69.0	32.5	2.97	5.31	7.09	0.037	0.615	0.086	6.9	267.0	1.11	0.01	0.12	27.6	325.7	289.3	461.3	<0.8	28.7	-13.6
Average	536	9.8	7.53	477	16	1.5	61.7	25.9	2.27	2.57	1.57	0.024	0.212	0.059	5.9	240.3	0.57	0.01	0.02	21.2	293.1	260.5	415.1	<0.8	28.7	-13.6
Count	10	11	11	11	10	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	1	1
St. Dev	129	0.9	0.21	165	221	2.0	5.0	3.1	0.50	1.69	2.02	0.008	0.193	0.027	0.9	16.6	0.20	0.00	0.03	4.2	20.3	16.5	26.5	-	-	-
Mt. Simon Aquifer																										
Min	366	10.2	7.54	555	-113	0.1	56.8	20.2	17.12	3.61	0.31	0.019	0.308	0.037	3.3	210.0	6.46	0.01	0.00	31.2	256.2	226.1	409.5	<0.8	0.2	-11.9
Max	1070	10.8	7.68	1140	18	1.3	76.9	30.4	121.50	8.20	0.63	0.033	0.959	0.203	5.4	240.0	175.00	0.63	0.02	95.0	292.8	294.8	790.4	<0.8	0.8	-11.5
Average	702	10.5	7.60	639	-63	0.4	64.8	24.0	53.73	6.14	0.51	0.025	0.686	0.092	4.3	224.5	71.88	0.17	0.01	52.9	273.9	260.4	553.1	<0.8	0.5	-11.7
Count	4	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2
St. Dev	290	0.3	0.06	250	71	0.6	8.6	4.8	48.52	1.90	0.14	0.006	0.273	0.075	0.9	13.9	74.15	0.31	0.01	29.7	16.9	33.2	174.8	-	0.4	0.3
Tritium 0.8-10 TU																										
Upper Carbonate Aquifer (no records this tritium range)																										
St. Peter-Prairie du Chien-Jordan Aquifer																										
Min	80	8.0	7.26	268	-117	0.0	53.0	17.8	1.66	0.55	0.00	0.001	0.050	0.011	0.0	199.0	0.95	0.01	0.01	9.8	242.8	221.9	344.3	1	63.4	-11.7
Max	1222	12.0	7.64	570	718	11.2	94.2	30.3	5.32	2.57	2.00	0.047	0.150	0.075	10.2	273.0	11.81	0.01	7.91	51.6	333.1	324.1	496.2	6.9	68.5	-11.2
Average	462	9.5	7.44	450	148	3.9	73.3	22.8	2.45	1.13	0.29	0.014	0.088	0.039	7.2	250.8	2.68	0.01	1.22	20.7	306.0	276.8	438.0	4.1	66.0	-11.5
Count	15	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	2	2
St. Dev	273	0.8	0.11	97	190	3.6	11.6	3.3	0.82	0.54	0.51	0.012	0.023	0.017	2.2	20.0	2.65	0.00	1.83	9.4	24.4	26.3	39.0	2.7	3.6	0.4
Franconia-Ironton-Galesville Aquifer																										
Min	270	8.0	7.46	310	-194	0.0	55.1	17.0	1.99	0.64	0.01	0.012	0.052	0.016	6.1	232.0	1.03	0.01	0.01	12.6	263.0	243.5	369.6	1.3	51.6	-8.9
Max	580	10.0	7.71	510	21	13.0	81.6	30.6	2.59	1.78	3.79	0.072	0.098	0.033	7.7	264.0	3.47	0.01	1.04	23.7	322.1	280.0	443.7	5.9	58.5	-8.8
Average	451	9.3	7.59	375	-85	3.3	64.7	25.5	2.30	1.24	1.12	0.029	0.065	0.027	7.2	243.3	1.99	0.01	0.44	18.7	298.8	266.4	420.1	2.8	55.1	-8.9
Count	4	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	2	2
St. Dev	140	0.9	0.11	91	114	6.4	11.6	6.0	0.30	0.49	1.80	0.029	0.021	0.008	0.7	14.9	1.13	0.00	0.50	4.9	16.1	16.0	24.9	2.2	4.9	0.1

Table 2. (continued)

Mt. Simon Aquifer																										
Min	582	10.3	7.53	490	30	0.3	56.8	29.1	5.69	1.83	0.19	0.020	0.106	0.037	6.0	235.0	7.44	0.01	0.04	19.1	286.7	281.3	413.1	0.9	-	-
Max	582	10.3	7.53	490	30	0.3	56.8	29.1	5.89	1.83	0.19	0.020	0.106	0.037	6.0	235.0	7.44	0.01	0.04	19.1	286.7	261.3	413.1	0.9	-	-
Average	582	10.3	7.53	490	30	0.3	56.8	29.1	5.69	1.83	0.19	0.020	0.106	0.037	6.0	235.0	7.44	0.01	0.04	19.1	286.7	261.3	413.1	0.9	-	-
Count	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
St. Dev	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tritium > 10 TU																										
Upper Carbonate Aquifer																										
Min	50	7.4	7.08	310	140	0.0	55.1	14.3	2.72	0.62	0.02	0.001	0.039	0.062	3.9	196.0	2.11	0.01	0.02	14.9	239.1	212.6	349.6	11.6	-	-
Max	283	10.4	7.77	1010	324	10.5	135.8	57.8	41.70	6.70	1.00	0.111	0.272	0.168	14.3	351.0	70.70	0.13	31.20	68.3	428.2	576.5	816.5	25.0	-	-
Average	131	9.3	7.34	703	220	4.9	92.5	30.8	12.71	2.21	0.25	0.025	0.139	0.111	8.6	279.5	31.68	0.04	8.46	31.8	340.9	357.7	560.2	16.7	-	-
Count	6	11	11	11	8	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	0	0
St. Dev	86	0.8	0.19	240	69	4.4	30.4	13.0	12.49	2.00	0.32	0.038	0.083	0.039	3.6	63.7	25.93	0.04	6.98	17.1	77.7	119.5	169.6	3.9	-	-
St. Peter-Prairie du Chien-Jordan Aquifer																										
Min	68	8.9	7.13	550	160	2.7	76.5	14.9	2.31	0.47	0.00	0.000	0.081	0.043	7.6	240.0	3.72	0.01	1.10	13.6	292.8	294.3	456.4	10.9	-	-
Max	575	12.4	7.57	1140	658	12.7	117.6	37.7	16.01	5.47	1.66	0.042	0.153	0.143	13.3	329.0	60.95	0.07	15.50	38.1	401.4	418.2	855.6	23.1	-	-
Average	292	9.9	7.38	857	250	6.6	94.1	23.3	4.95	1.48	0.16	0.005	0.112	0.080	9.9	279.2	12.23	0.02	5.83	21.1	340.6	330.7	513.8	17.7	-	-
Count	24	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	0	0
St. Dev	150	0.8	0.12	135	97	2.6	10.4	5.7	3.56	1.14	0.37	0.009	0.017	0.025	1.5	23.8	11.97	0.01	3.99	5.3	29.0	38.6	56.8	3.0	-	-
Franconia-Ironton-Galesville Aquifer																										
Min	-	7.8	7.50	700	-	9.9	60.8	28.1	2.53	0.95	0.04	0.005	0.084	0.040	6.3	252.0	3.41	0.01	2.33	13.6	307.4	287.2	425.6	19.4	77.2	-14.3
Max	-	7.8	7.50	700	-	9.9	60.8	28.1	2.53	0.95	0.04	0.005	0.084	0.040	6.3	252.0	3.41	0.01	2.33	13.6	307.4	287.2	425.6	19.4	77.2	-14.3
Average	-	7.8	7.50	700	-	9.9	60.8	28.1	2.53	0.95	0.04	0.005	0.084	0.040	6.3	252.0	3.41	0.01	2.33	13.6	307.4	287.2	425.6	19.4	77.2	-14.3
Count	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
St. Dev	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mt. Simon Aquifer (no records this tritium range)																										

Note: See Table 1 for explenation of units.

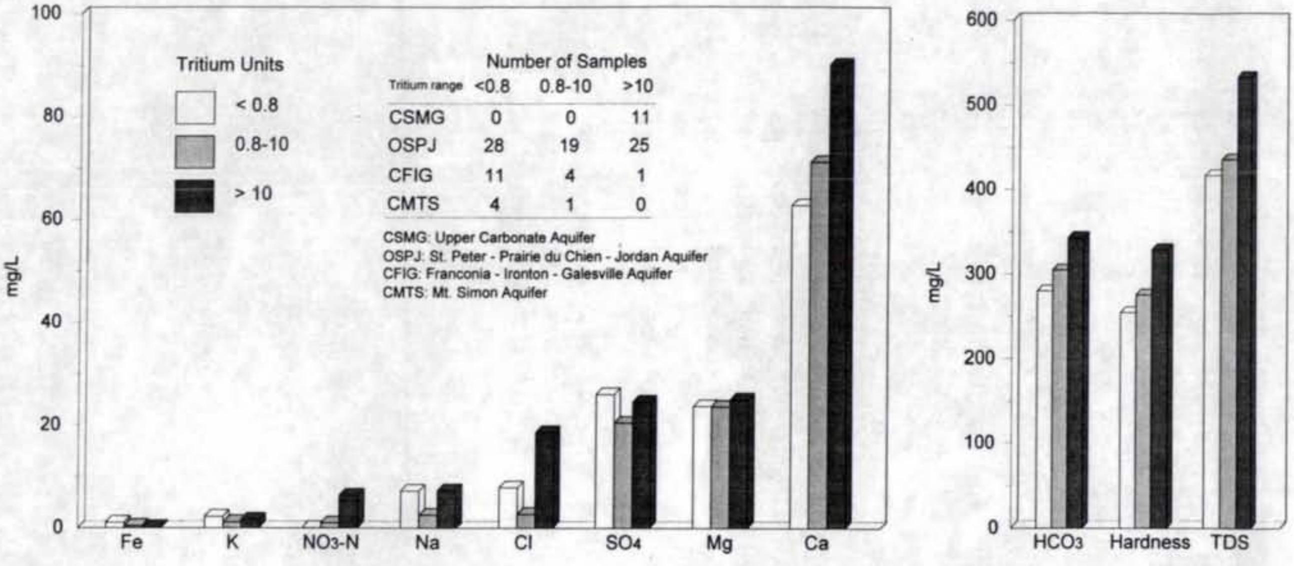


Figure 6. Comparison of major chemical parameters by residence time.

group, but the effect is seen more strongly in Group II, discussed below. As discussed earlier, all ground water in the St. Peter-Prairie du Chien-Jordan aquifer contains at least 4 to 6 meq/L of these ions, but somewhat higher levels of calcium (70-100 mg/L Ca^{+2}) and bicarbonate (300-380 mg/L HCO_3^-) occur in a broad zone that includes Chatfield, Fountain, Preston, Lanesboro, Harmony, and Canton. Slightly lower concentrations of Ca^{+2} (<60 mg/L) and HCO_3^- (<280 mg/L) are found in the southwestern part of the county where the aquifer is both confined and deep. Magnesium ions also show higher concentrations (25-35 mg/L) in less confined portions of the aquifer, but the elevated zone is less continuous than that of Ca^{+2} and HCO_3^-. The amount of Ca^{+2} and Mg^{+2}, as mentioned in the previous section, contributes to water hardness. As a result, water hardness is also higher in the zone where Ca^{+2} and Mg^{+2} concentrations are elevated. Water softeners remove calcium and magnesium to produce softened water.

Group II contains the components nitrate and tritium. They are introduced into the aquifer from the land surface, almost entirely because of human activity. The distribution of these highly soluble components clearly reflects the protective influence of the overlying Decorah Shale. Figure 5 shows a zone of elevated nitrate concentrations occurring roughly northwest to southeast through the county along the Decorah Shale boundary. Beneath the confined areas of the St. Peter-Prairie du Chien-Jordan aquifer to the west and south of the Decorah Shale boundary, nitrate was generally undetected. Where it is intact, the Decorah Shale confining unit effectively prevents nitrate from moving downward from the upper carbonate aquifer into the underlying aquifer. The component tritium also shows this general distribution pattern. Figure 4 shows a zone of elevated tritium concentrations similar to that of nitrate. The confined parts of the aquifer generally show tritium concentrations of <0.8 TU, although some deeper wells northeast of the Decorah Shale boundary also show very low tritium concentrations.

Group III (Fe, Mn, and SO_4^{-2}) ions have distributions that are mostly controlled by geochemical processes, such as the dissolution of non-carbonate minerals or the oxidation state of the ground water, although human activity may be contributing in some places to elevated concentrations. The highest sulfate concentrations (up to 50 mg/L) in the St. Peter-Prairie du Chien-Jordan aquifer occur in the northwestern corner of the county where the aquifer is deep and confined. However, elevated sulfate concentrations are also found in the unconfined, shallow portion of the aquifer in the eastern part of the county between Rushford and Mabel. Iron and manganese also have elevated zones in both the confined and unconfined areas. Dissolved iron concentrations in most areas of the St. Peter-Prairie du Chien-Jordan aquifer are below 1 mg/L, except for areas between Fountain and Pilot Mound, Canton and Mabel, Wykoff and Granger, and northwest of Washington where they are higher. Manganese shows a similar pattern to iron but at much lower concentrations (average 0.012 mg/L). As discussed earlier, higher concentrations of Fe and Mn are often related to reducing (low oxygen) conditions which can allow Fe- and Mn-bearing minerals to dissolve.

SUMMARY

Ground water in Fillmore County is relatively hard. Dissolution of aquifer rock at the earth's surface results in elevated concentrations of calcium, magnesium, and bicarbonate ions. In addition, human activities at the land surface have resulted in elevated concentrations of calcium, magnesium, bicarbonate, sodium, chloride, nitrate, and sulfate in some shallow ground water. Water-quality concerns include elevated nitrate concentrations in shallow aquifers and locally elevated iron concentrations in deep aquifers. Based on their distribution in the St. Peter-Prairie du Chien-Jordan aquifer, some dissolved components can be classified into three groups reflecting chemical, geological, and cultural factors. The distribution of tritium and nitrate shows that the Decorah Shale provides protection to the St. Peter-Prairie du Chien-Jordan aquifer from surface contamination.

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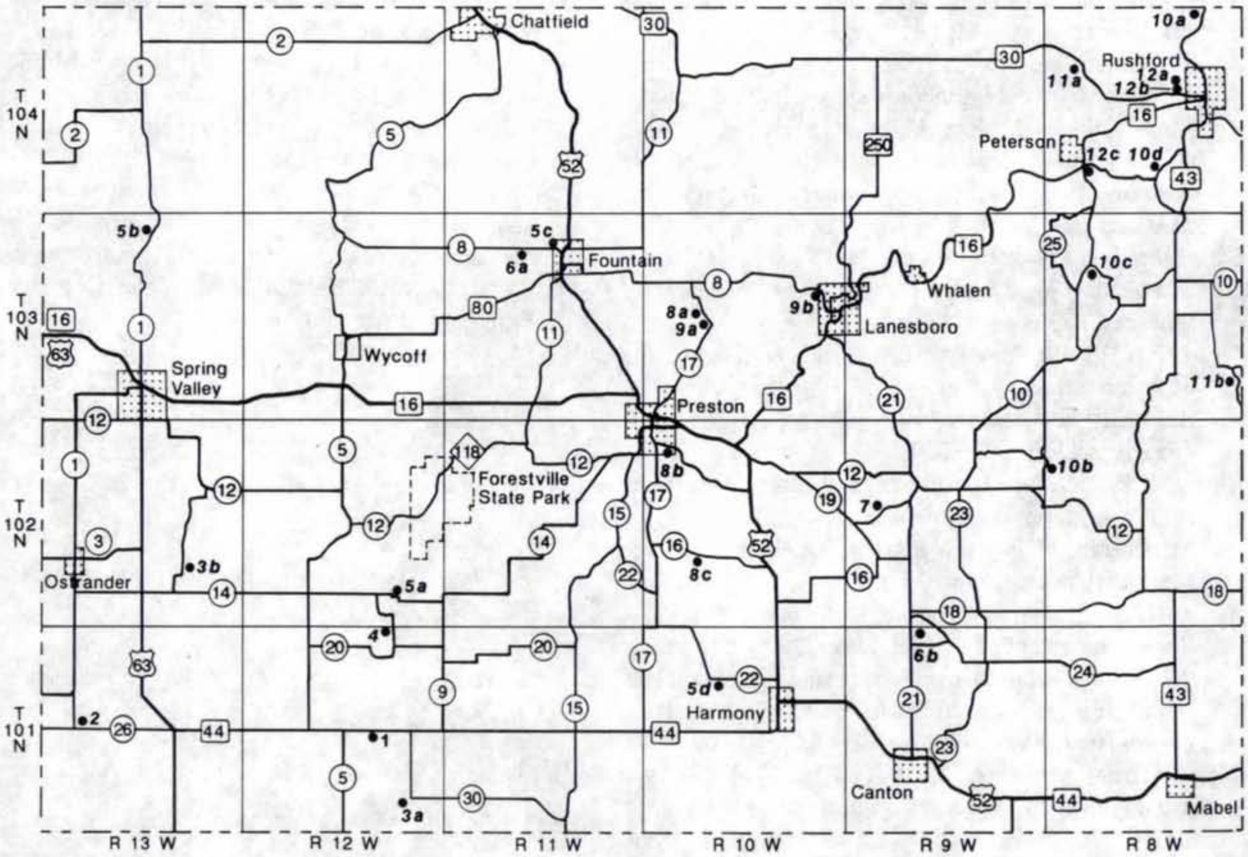
APPENDIX 1. GUIDE TO REPRESENTATIVE OUTCROPS

By

John H. Mossler

The following outcrops are representative of the bedrock formations in Fillmore County that can be visited today, but some are in quarries that are on private property and require permission of the owner for entry. Outcrops, especially exposures in active quarries, can change or disappear with time. The stratigraphic column (Plate 2) includes brief lithologic descriptions of the geologic units. Outcrop locations (numbered dots) are shown on the map below; U.S. public land survey locations, together with names of 7.5-minute topographic quadrangles, are given with the outcrop descriptions.



Map of Fillmore County showing locations of representative outcrops (numbered dots). Most major highways are shown, plus township roads that are adjacent to outcrops.

CRETACEOUS

1. One place where it is possible to see iron ore and Ostrander gravel is in a small borrow pit at the northeast corner of sec. 22, T. 101 N., R. 12 W. (Greenleafton quad). The gravel is composed of quartz and chert grains with the polished surfaces typical of the Ostrander Member. The ore is massive, earthy, red-brown goethite hematite. Just to the north there are additional exposures in a reclaimed strip mine that is now farmland in E1/2SE1/4 sec. 15, T. 101 N., R. 12 W. (Cherry Grove quad). This exposure includes an outcrop of Devonian Spillville Formation, the host rock for the ore. These outcrops are covered by vegetation during the summer.

DEVONIAN

Little Cedar Formation (Cedar Valley Group)

2. Low outcrops along County Highways 26 and 109, SW1/4SW1/4 sec. 17, T. 101 N., R. 13 W. (Ostrander quad), and adjoining sections, expose the Little Cedar Formation, a dense, buff to gray, unfossiliferous dolostone. It was used to construct the house in the SE1/4 sec. 18.

Spillville Formation (Wapsipinicon Group)

3a, 3b. Inactive quarries on township roads in the NW1/4NE1/4NE1/4 sec. 35, T. 101 N., R. 12 W. (Greenleafton quad) and in SE1/4NW1/4 sec. 26, T. 102 N., R. 13 W. (Cherry Grove quad) expose low outcrops of Spillville Formation, buff, vuggy, fossiliferous dolostone.

ORDOVICIAN

Maquoketa and Dubuque Formations

4. Roadcut along the township road in the NE1/4 NE1/4 NW1/4 sec. 2, T. 101 N., R. 12 W. (Greenleafton quad) in "Wubbels Ravine." Fifty-eight to 60 feet of light-gray, to brownish-gray, argillaceous, fossiliferous (brachiopods, graptolites, echinoderm debris) limestone of the Maquoketa Formation. Also visible is the contact between the Maquoketa and the interbedded limestone and shale of the Dubuque Formation which extends below the contact for approximately 30 feet. About 12 feet of dolomitic limestone of Stewartville Formation is exposed at the base of the roadcut below the Dubuque. It is yellowish brown and color mottled; bedding is thin to medium and crinkly. The Dubuque Formation and basal Maquoketa are also exposed in roadcuts along bends in County Highway 14 in NW1/4 NE1/4 and NE1/4 NW1/4 sec. 35, T. 102 N., R. 12 W. (Greenleafton quad), near location 5a.

Galena Group

5a. The Rifle Hill quarry in the NE1/4 NE1/4 NW1/4 sec. 35, T. 102 N., R. 12 W. (Greeleafton quad). Exposes the top 43 feet of Prosser Limestone, the Stewartville Formation (75 feet thick), and also the Dubuque Formation (about 20 feet thick). About 22 or 23 feet of the lower part of the Maquoketa Formation is visible at top of quarry and in the stripped area above it. The limestone of the Maquoketa is thin to medium (2 to 15 inches) bedded, yellowish gray to olive gray, fossiliferous (echinoderm debris, trilobites, brachiopods), and contains scattered thin (3 to 9 inches) beds of olive-gray shale. The limestone of the Dubuque is thin to medium (5 to 12 inches) bedded, yellowish gray, and regularly interbedded with olive-gray fossiliferous (brachiopods, trilobites, echinoderms), calcareous shale. It is inaccessible in the quarry, but can be seen from the second ledge. The dolomitic limestone of the Stewartville is thin to thick (2 inches to more than 6 feet) bedded, light olive gray to yellowish gray and orange gray, and color mottled. It is sparsely fossiliferous with *Fisherites*, a green algae, plus gastropods. There are more fossils, particularly brachiopods, in the lower part. Bedding in the Prosser Limestone is thin to thick (4 to 31 inches) and crinkly; the rock is yellowish gray to olive gray, and fossiliferous. Fossils generally occur in thin streaks that are chiefly fragmented fossil remains, but are rare at this locality. There are minor light-gray chert nodules. See detailed description in Sloan (1987, p. 208-211).

5b. Bly quarry in NE1/4 SW1/4 sec. 3, T. 103 N., R. 13 W. (Stewartville quad). Twenty-five feet of the Dubuque Formation overlying about 50 feet of the Stewartville Formation. The limestone of the Dubuque is thin to medium (5 to 13 inches) bedded, yellowish gray to olive gray, and fossiliferous with regularly interbedded layers of olive-gray, fossiliferous shale. Fossils are mainly echinoderm fragments and brachiopods. The dolomitic limestone of the Stewartville is mainly thin to thick (5 to 64 inches) bedded, yellowish gray to light olive gray, and color mottled. It is much less fossiliferous than the Dubuque but contains *Fisherites* and gastropods, as well as echinoderm debris near the top of the formation.

5c. Larson quarry in SW1/4 SW1/4 sec. 3, T. 103 N., R. 11 W. (Fountain quad). Much of the Prosser Limestone (55 to 60 feet) and the top of the underlying Cummingsville Formation. The limestone of the Prosser is thin bedded, light gray to yellowish gray, with thin fossiliferous bands (brachiopods, echinoderm fragments). It has scattered thin, olive-gray shale beds. The very shaly limestone of the Cummingsville is thin bedded, light gray, and regularly interbedded with medium-gray to gray-green shale beds. Good exposures of the Cummingsville (about 60 feet) can be found uphill from the large springs north of the quarry along the township road in the NW1/4 SW1/4 sec. 3, T. 103 N., R. 11 W. (Chatfield quad).

5d. Big Spring quarry in SW1/4 sec. 9, T. 101 N., R. 10 W. (Harmony quad). Stratigraphic interval similar to that at the Larson quarry (5c). Springs can be seen flowing from the top of the Cummingsville along County Highway 22 in the NE1/4 sec. 8, as well as from strata within the quarry. The springs are controlled by shale beds in the Cummingsville which act as confining layers.

Decorah Shale

6a. Road ditch along County Highway 8 in NE1/4 NW1/4 sec. 9, T. 103 N., R. 11 W. (Fountain quad). Low outcrop of blocky greenish-gray Decorah Shale and contact with overlying limestone of the Galena Group.

6b. Inactive limestone quarry (Hoag quarry) in SE1/4 NW1/4 sec. 4, T. 101 N., R. 9 W. (Canton quad). Lower part of the Decorah Shale above Platteville Formation limestone.

Platteville Formation

7. Inactive quarry (Sorum quarry) in the NW1/4 SW1/4 sec. 17, T. 102 N., R. 9 W. (Lanesboro quad). The top 4.25 feet is medium-bedded, brown to gray limestone with shaly layers about an inch thick. A K-bentonite bed, an altered volcanic ash (grayish-orange, soft clay), is about 6 inches above the base of this unit. Below the top unit is about 15 feet of thin- to medium- and crinkly-bedded, gray to yellowish-gray limestone that contains numerous shaly partings especially in the top 6 feet.

Platteville Formation—Glenwood Formation—St. Peter Sandstone

8a. Roadcuts on County Highway 17 in NE1/4 sec. 20, T.103 N., R.10 W., and SE1/4 sec. 17, (Preston quad). Eighteen to 19 feet of massive, light-gray, fine-grained, quartzose St. Peter Sandstone overlain by 8 to 8.5 feet of silty, fine-grained sandstone with thin shale partings (earlier workers put this into the Glenwood Formation). This is overlain by 1.25 feet of sandy, grayish-green shale of the Glenwood Formation and by 23 feet of limestone and interbedded limestone and shale of the Platteville Formation. There is a thin K-bentonite about 4.25 feet below the top of the Platteville.

8b, 8c. Several sand pits in the county expose the St. Peter Sandstone. Examples are in NE1/4 SE1/4 sec. 6, T.102 N., R.10 W. (Preston quad) and in SW1/4 SE1/4 sec. 20, T.102 N., R.10 W. (Harmony quad). The Glenwood and Platteville Formations commonly crop out at the tops of the exposures in the sand pits.

Shakopee Formation

9a. A roadcut on County Highway 17 in NW1/4 NW1/4 sec. 21, T.103 N., R.10 W. (Preston quad) exposes 23 feet of sandstone of the New Richmond Member. This is overlain with a visible contact by 54 feet of dolostone of the Willow River Member of the Shakopee Formation. The New Richmond Sandstone is light gray, fine grained, and quartzose with low-angle cross-bedding. The Willow River dolostone is thin to thick bedded, buff to gray, and stromatolitic. The top of it contains minor siliceous oolites and intraclasts. This locality is just down the hill from locality 8a.

9b. Roadcuts near Lanesboro on County Highway 8 in SE1/4 NW1/4 and NE1/4 SW1/4 sec. 13, T.103 N, R.10 W. (Lanesboro quad); 57 feet of the Oneota Dolomite overlain by 54 feet of the New Richmond Member of the Shakopee Formation and about 42 feet of the Willow River Member. The Oneota is medium-bedded to massive, gray dolostone with chert layers and nodules and coarse calcite spar. It is brecciated at the top. The New Richmond is white to grayish-orange, fine- to medium-grained (coarse at base), quartzose sandstone with low-angle cross-bedding. The basal 6 feet of sandstone is dolomitic. The Willow River is thin-bedded, yellowish-gray to gray, stromatolitic, intraclastic dolostone.

Oneota Dolomite

10a. Active quarry (Eggert quarry) in the NE1/4 sec. 2, T.104 N., R. 8 W. (Rushford quad) and roadcuts on Minnesota Highway 43; 60 to 65 feet of the Hager City Member of the Oneota, overlying a 35-foot interval of the Coon Valley Member, which can be seen in the roadcut along the highway just below the quarry. The Coon Valley is a grayish-orange to yellowish-gray, thin-bedded quartzose sandstone with dolomitic cement, interbedded with sandy dolostone. It contains stromatolites, oolites, and minor chert. The upper part of the Oneota is massive to medium-bedded, yellowish-gray dolostone with scattered chert nodules and sparry calcite-filled vugs. Farther down the hill along the highway there are outcrops of the quartzose facies of Jordan Sandstone and thin-bedded dolomitic siltstone of the upper part of the St. Lawrence Formation, which is just uphill from the bridge over the small creek.

10b. Quarry in SW1/4 NW1/4 sec. 7, T. 102 N., R. 8 W. (Bratsberg quad). Upper part of Oneota Dolomite possesses minor Upper Mississippi Valley-type sulfide mineralization in breccia (minor sphalerite, galena, marcasite, and abundant pyrite). The 40- to 45-foot interval of Oneota dolostone is overlain by a 10- to 15-foot interval of New Richmond Sandstone at the top of quarry. The Oneota here contains both digital and hemispherical stromatolites and also contains thick brecciated zones. See Runkel and others (1993) for fuller description.

10c, 10d. Several other quarries in the county including those in SW1/4 sec. 8, T. 103 N., R. 8 W. (Bratsburg quad) and SE1/4 SW1/4 sec. 27, T. 104 N., R. 8 W. (Rushford West quad) expose large Oneota sections.

Jordan Sandstone

11a. Roadcuts on Minnesota Highway 30 in SW1/4 sec. 8, T. 104 N., R. 8 W. (Rushford West quad). Coarse-grained quartzose Jordan Sandstone unconformably overlain by the Coon Valley Member of the Oneota Dolomite. Contact of sandy dolostone of Coon Valley and purer dolostone of upper Oneota Hager City Member can be seen uphill in the next outcrops. See Runkel (1994b) for discussion.

11b. Roadcut at the bend in the township road in NE1/4 NE1/4 NE1/4 sec. 36, T. 103 N., R. 8 W. (Yucatan quad). Interbedded fine-grained, feldspathic sandstone and coarser grained, quartzose Jordan Sandstone.

St. Lawrence and Franconia Formations

12a. SW1/4 SW1/4 NW1/4 sec. 14, T. 104 N., R. 8 W. (Rushford West quad): Thin-bedded dolomitic siltstone of the St. Lawrence Formation is exposed in low outcrops along curves in the road into Magelssen Park next to a private driveway. Glauconitic fine-grained sandstone of the Reno Member of the Franconia is exposed just downslope south of small ravine.

12b. Borrow pit by Magelssen Park on Minnesota Highway 30, in the NE1/4 SW1/4 sec. 14, T. 104 N., R. 8 W. (Rushford West quad). Outcrops of Franconia Formation (Reno Member).

12c. Franconia Formation (Reno Member) exposure behind buildings on U.S. Highway 16 in the NE1/4 SW1/4 sec. 29, T. 104 N., R. 8 W. (Rushford West quad). Basal St. Lawrence Formation is exposed uphill in a roadcut and borrow pit along the township road (to southeast of buildings). It is thin-bedded, tan to buff, silty dolostone with thin green shale partings.

APPENDIX 2. MANAGEMENT OF PRIVATE WATER WELLS

By

E. Calvin Alexander, Jr.

If household water is obtained from a municipal system, part of the utility fee is used to monitor the water quality. If however, the water supply is obtained from a private well, it is the well owner's responsibility to monitor the quality of drinking water. Owners of private water-supply wells should maintain a file on well construction and water quality and keep it along with other records such as deeds and insurance policies. The county environmental staff can, upon request, advise how to proceed with such monitoring, but the primary responsibility for doing water-quality monitoring rests with the private system's owner.

The block diagrams illustrate some of the problems which may affect a well in karst terrains. Although pollution from distant sources is possible in karst aquifers, many well-contamination problems result from nearby land uses. Common contamination sources include feedlots, septic systems, and back siphoning of pesticides or nutrients from mixing tanks. Improper well construction can allow contaminated water to enter the well or enter another geologically protected aquifer. If a well is contaminated, the source of contamination is likely visible to someone standing next to the well.

Management of a private water-supply well requires information on its construction, depth, and the aquifer(s) which it pumps. Several parts of this atlas can help supply the necessary information.

Ground-water pollution and unprotected—improperly constructed—well. Artwork by Ramesh Venkatakrishnan.

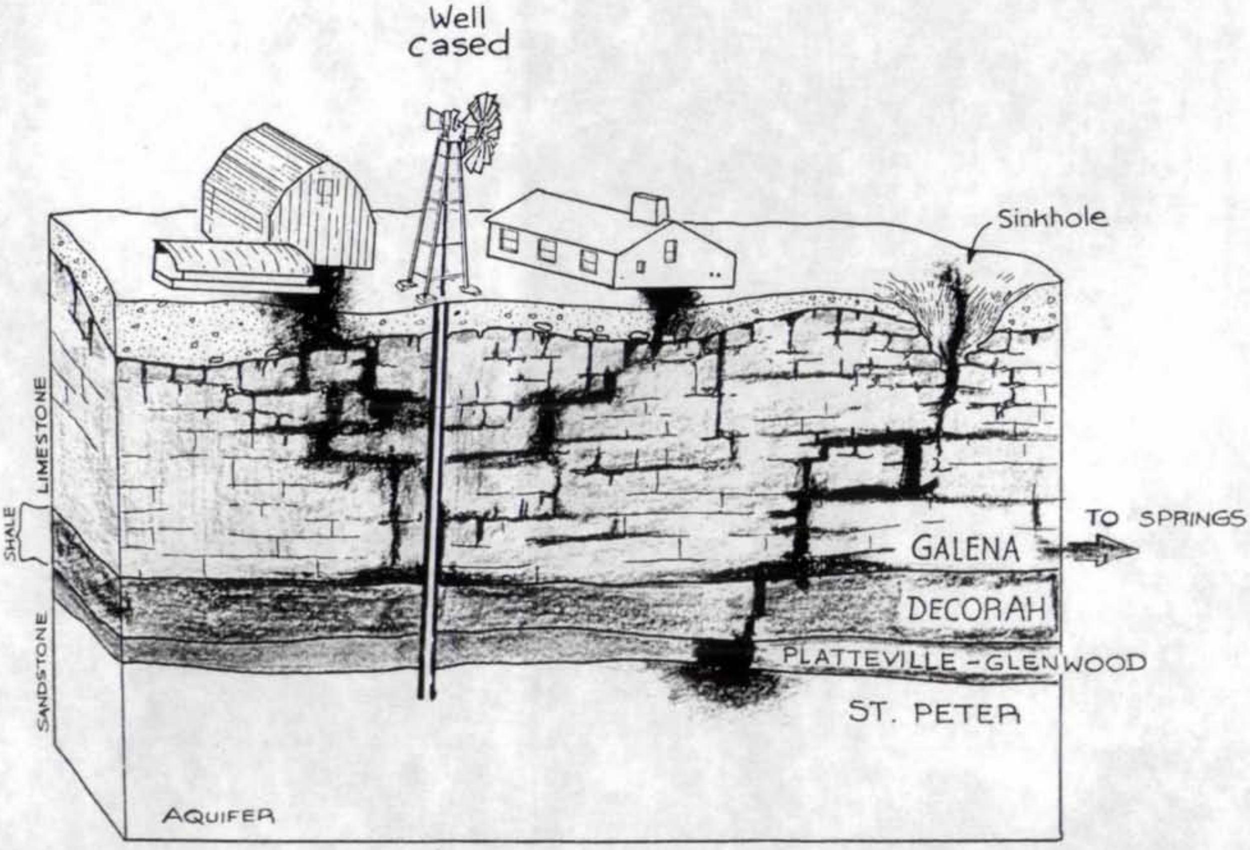
Step 1: Determine if a well record exists for the well. The well record is the well driller's description of the drilling and construction of the well. If the well was drilled since 1975, a construction log should be on file with the Minnesota Department of Health and the Minnesota Geologic Survey (MGS). Logs used in this atlas program were field located and geologically interpreted and are available through the county or the MGS County Well Index data base (see Plate 1).

Although efforts were made to place each well log at the correct geographic location, the system is not perfect. Changes in ownership, common surnames, and mislocations of wells may exist in the data base. If a well was drilled before 1975, a driller's construction log may not exist, and the construction of the well may not be up to modern well-code standards. The original well owners may be able to remember details about the well's construction. Also, information on wells may be available from well-repair services if the well pump was ever repaired or replaced.

Step 2: The atlas can be used to identify the producing aquifers(s) of the well, if its depth, location, and construction are known. The county staff is available to assist with this determination or refer the owner to the Minnesota Geological Survey if necessary. Identification of the aquifer is an important step in managing a private well, because the sensitivity of any aquifer to pollution varies greatly with location. Even aquifers which exhibit a low pollution sensitivity can be adversely affected by improper well construction or management or via contamination through nearby wells in the same aquifer.

Step 3: The next step is to check for indications that surface pollutants are entering a well. There are a number of simple indicators that may already have been noted. Does water from a well turn cloudy or muddy after recharge events such as snow melt or heavy rains? Does surface water run into the well after heavy rains? Does the water quality (taste, odor, color, etc.) ever change abruptly? Are there unusual losses of young animals? Any of these are danger signals indicating that surface water and accompanying pollutants are in the water pumped from the well. Such contamination may be due to either faulty well construction or to contamination of the aquifer itself.

Step 4: Consult with the county staff and begin a program of periodic water testing. Keep the results as part of your permanent file on the well. Compare your results to the relevant Drinking Water Standards, available



Ground-water pollution and properly constructed-well. Artwork by Ramesh Venkatakrishnan.

from the county or the Minnesota Department of Health, and watch for changes over time. Nitrate-nitrogen and coliform bacteria are the most common water-quality tests. If the nitrate-nitrogen level is above about 1 ppm nitrate-nitrogen or any coliform bacteria are present, the well water is showing signs of contamination by surface pollutants. How often these tests should be repeated is a trade-off between economics and safety. If the simple indicators of surface pollutants are not present and all of the well information indicates that it was properly constructed and producing from a protected aquifer, and if the first water-quality results are good, a test every few years may be adequate. With the presence of pollution indicators, poor well-construction and maintenance records, water-quality problems, or problems with nearby wells in the same aquifer, it may be prudent to test much more frequently. Annual testing may be appropriate, but it has been shown repeatedly that water quality in the near-surface aquifers in Fillmore County can and does change dramatically on time-scales as short as hours.

Detailed remediation suggestions are beyond the scope of this appendix. If the problem results from specific management practices that create contamination around the wellhead, or allow contaminants to enter via the wellhead, it can sometimes be remedied. If the problem is a more basic issue of improper well construction or contamination of the aquifer itself, the best option may be to properly seal the existing well and drill a new one, or seek an alternative, safe water supply. Consultation with county staff or water-supply professionals can be helpful in reaching a decision.

APPENDIX 3. RADON IN FILLMORE COUNTY

By

R.S. Lively

Radon is a naturally occurring radioactive gas. Exposure to this gas and its decay products, which also are radioactive, has received considerable media and public health attention because long-term exposure to high concentrations of them has been linked to an increased risk of lung cancer. As an outcome of risk analysis, the U.S. Environmental Protection Agency (EPA) is recommending that radon levels in home living spaces not exceed 4 picoCuries per liter of air (pCi/L). For information on testing procedures, follow-up measurements, and how to reduce indoor radon levels, homeowners should contact the local or Minnesota Department of Health.

The radon found inside homes comes primarily from the radioactive elements uranium, thorium, and radium in the soil and sediments that surround the foundation or basement. All soils and rocks in the county normally contain these radioactive materials in small concentrations, and therefore they also contain some radon in proportion to the concentration of uranium, thorium, and radium. Indoor radon concentrations may be proportional to the concentration of radon in the surrounding soil, but can also be highly variable depending upon how much soil air can enter the building and how much ventilation from outdoors replaces the indoor air.

Most radon in Fillmore County is associated with the unconsolidated glacial sediments around and underneath basements. The limestone, shale, and sandstone bedrocks of Fillmore County can also be sources of radon. Caves and fractures in the limestone bedrock are known to have radon levels that reach several hundred pCi/L periodically during the year. Though visiting caves does not involve significant risk for tourists, basements in direct contact with large open joints or that use air from them in a ventilation system could introduce high levels of radon into a house. Limestone blocks used in basement walls do not create a radon problem, because there is not enough radioactive material in that small volume of rock to produce significant levels of radon. Residual sediments produced in place by weathering of the limestone bedrock can also be potential sources of indoor radon, but these sediments are not common in Fillmore County and if formed, have been mostly eroded away. In all instances, it is necessary that the home be in contact with geologic material producing radon in order for it to migrate indoors.

Predicting levels of indoor radon in individual homes is virtually impossible, although regional predictions may be made with resonable confidence. Almost no data are available on radon levels in sediments or rocks in Fillmore County. The interactions between the ground, the house, and the atmosphere introduce so many variables that predictions based on any single factor are useless. That is why agencies recommend that home owners conduct tests, rather than rely on regional estimates. Less than 50 measurements are available from Fillmore County homes; they average about 9 pCi/L and range from 4 to 17. These levels are fairly common in Minnesota, much of which is covered by glacial materials similar to those in Fillmore County.. None of the indoor radon in Fillmore County and very little around the state is associated with granitic or other types of crystalline bedrock.

C-8 PART C