RELAY RAMP STRUCTURES AND THEIR INFLUENCE ON GROUNDWATER FLOW IN THE EDWARDS AND TRINITY AQUIFERS, HAYS AND TRAVIS COUNTIES, CENTRAL TEXAS

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Abstract
The Cretaceous Edwards and Middle Trinity Aquifers of central Texas are critical groundwater resources for human and ecological needs. These two major karst aquifers are stratigraphically stacked (Edwards over Trinity) and structurally juxtaposed (normal faulting) in the Balcones Fault Zone (BFZ). Studies have long recognized the importance of faulting on the development of the karstic Edwards Aquifer. However, the influence of these structures on groundwater flow is unclear as groundwater flow appears to cross some faults, but not others. This study combines structural and hydrological data to help characterize the potential influence of faults and relay ramps on groundwater flow within the karstic Edwards and Middle Trinity Aquifers. Detailed structure contour maps of the top of Walnut Formation in the study area were created from a geologic database (n=380) comprised of primarily geophysical and driller’s logs. The data were then contoured in Surfer® (Kriging) with no faults. Structure contour surfaces revealed detailed structural geometries including linear zones of steep gradients (interpreted as faults) with northeast dipping zones of low gradients (interpreted to be ramps) between faults. Hydrologic data (heads, dye trace, geochemistry) were overlaid onto the structure contour maps in GIS. Results for the Middle Trinity Aquifer suggest relay ramps provide a mechanism for lateral continuity of geologic units and therefore groundwater flow from the Hill Country (recharge area) eastward into the BFZ. Faults with significant displacement (>100 m) can provide a barrier to groundwater flow by the juxtaposition of contrasting permeabilities, yet flow continues across fault zones where ramps exist, or where permeable units are juxtaposed with other permeable units. In the Barton Springs segment of the Edwards Aquifer the primary flow path defined by dye tracing and heads is coincident with the Onion Creek relay ramp dipping to the northeast. This work addresses the lateral continuity (intra-aquifer flow) of the Edwards and Trinity Aquifer systems, which has importance for conceptual models and ultimately resource management.

Introduction
The Cretaceous Edwards and Middle Trinity Aquifers of central Texas are critical groundwater resources for human and ecological needs (Figure 1). These two major karst aquifers are stratigraphically stacked and structurally juxtaposed in the Balcones Fault Zone (BFZ) (Figure 2). However, the role of faulting and related structures on groundwater flow is not clearly understood due to the stratigraphic and structural complexity.

The purpose of this paper is to describe the influence of faults and related structures called relay ramps on
Figure 1. Simplified geologic map with potentiometric surfaces of the Middle Trinity and Edwards Aquifers. Two major faults, the Mount Bonnell and the San Marcos faults, are shown with the relay ramp structure proposed by Grimshaw and Woodruff (1986) and Collins and Hovorka (1997). Figure modified from Smith et al. (2015).
groundwater flow within the Edwards and Trinity Aquifers in a portion of the BFZ in central Texas.

Studies have long recognized the importance of faulting for the development of the Edwards Aquifer (Hill and Vaughan, 1898; DeCook, 1963; Sharp, 1990). More recently, studies have addressed the hydrologic connection within the Edwards and Trinity Aquifers (Smith and Hunt, 2010; Gary et al., 2011; Wong et al., 2014; Smith et al., 2015) with some studies focusing on structure (Ferrill et al., 2008). However, the influence of faults and the related “relay ramp” structures on groundwater flow have not been fully characterized. Cross sections through the BFZ generally show vertical offset and suggest lateral discontinuity, which may or may not occur in three dimensions (Figure 2). Yet recent studies of groundwater flow suggest lateral continuity of flow across or around faults in the BFZ (Figures 1 and 2; Hauwert et al., 2004; Smith et al., 2015). This paper will explore the mechanism for lateral continuity of flow in a karst setting with complex structures. Implications of this work address the lateral continuity of units and therefore intra-aquifer flow. This has great importance for conceptual models and ultimately, resource management.

**Structural Setting**

A series of complex tectonic cycles have strongly influenced the hydrogeology of central Texas. The tectonic events or cycles are described in detail in Ewing (1991), and are composed of the Grenville (pre-Cambrian), Ouachita (late Paleozoic), and Gulfian (Triassic to present) cycles. The Llano Uplift is a structural dome in central Texas which is related to the formation of the San Marcos Arch. These features influenced Cretaceous deposition and subsequent structures, such as the BFZ (Figure 1).

![Geologic cross section along the Blanco River showing the geologic and hydrogeologic units. The faults shown are normal faults of the BFZ. Note the Edwards and Trinity Aquifer are both stratigraphically stacked and structurally juxtaposed. Groundwater flow is schematically shown to move across faults. Line of section A to A' is down the Blanco River in Figure 1. Figure modified from Smith et al. (2015). Vertical Exaggeration is ~100x.](image)

**Figure 2.** Geologic cross section along the Blanco River showing the geologic and hydrogeologic units. The faults shown are normal faults of the BFZ. Note the Edwards and Trinity Aquifer are both stratigraphically stacked and structurally juxtaposed. Groundwater flow is schematically shown to move across faults. Line of section A to A’ is down the Blanco River in Figure 1. Figure modified from Smith et al. (2015). Vertical Exaggeration is ~100x.
**Balcones Fault Zone: A Review**

The BFZ produces the prominent physiographic feature known as the Balcones Escarpment in central Texas. The BFZ is a dominant structural feature extending in an arcuate pattern from Del Rio along the border with Mexico, toward Dallas in north Texas. The BFZ trend changes from W to NNE (Figure 1). The BFZ is a fault system consisting of numerous normal faults with hanging walls generally dropping down toward the Gulf of Mexico with displacements ranging from 30 to 260 meters. There are up to 365 meters of total displacement across the BFZ. Faults are generally steeply dipping (45-85 degrees) with stratigraphy a fundamental control on the geometries and dips (Ferrill and Morris, 2007). Faults generally trend to the NE (N40 to 70 E) and dip to the southeast (Collins and Hovorka, 1997). The faults are described as “en echelon,” which indicates closely-spaced, overlapping and subparallel. Depending on location, the faults can occur at oblique angles to the overall regional structural trend. The BFZ is characterized by numerous structures including horsts, grabens, and relay ramps (the focus of this paper). The BFZ generally follows the strike of the Cretaceous units and the trend of the Paleozoic-age Ouachita front (Sellards and Baker, 1934; Grimshaw and Woodruff, 1986; Ewing, 1991; Barker and Ardis, 1996; Collins and Hovorka, 1997; Collins 2004). The faults extend down into the Ouachita rocks and may also pass into extensionally reactivated Ouachita faults (Ewing, 1991); but they may also have listric geometries that terminate or sole out into shales at depth (Collins and Hovorka, 1997).

The BFZ is Tertiary in age, but the exact period or epoch of faulting is uncertain—the youngest sediments to be faulted are late Paleogene (Eocene-age ~55 Ma; Sellards and Baker, 1934). However, most of the fault movement is thought to have occurred during the early Neogene (late Oligocene ~30 Ma or early Miocene ~15 Ma). This timing is also coincident with regional uplift centered on the Colorado Plateau and extensional Basin and Range province which extends into west Texas. Although the BFZ is located at the boundary between the uplifting plateau area and the subsiding Gulf Coast Basin, it is unknown if the uplift and extension of the Basin and Range is related to the BFZ (Ewing, 1991; Collins, 2004). Instead, the BFZ may have formed as a result of the sedimentary loading and extension of the Gulf Coastal Plain toward the Gulf of Mexico Basin (Collins, 2004). Ewing (2004) describes the formation of the BFZ as the differential subsidence and slippage along the old Ouachita lines of weakness.

**Relay Ramps**

Normal faults are inclined dip-slip faults in which the hanging wall moves down compared to the footwall. They generally have steep dips of 60 degrees or greater, depending upon the stratigraphic unit (Ferrill and Morris, 2007). Where the offset along a fault decreases along its strike to zero, the extension is taken up by adjacent sub-parallel (en echelon) faults. Between these faults (that dip in the same direction) there is often a “transfer zone” where deformation is accommodated by folding, faulting, and fracturing (Twiss and Moores, 1992). These are the structures described as “relay ramps” (Figure 3; Grimshaw and Woodruff, 1986; Collins and Hovorka, 1997).

Relay ramps of different scales are described as occurring in the BFZ (Collins, 1995; Collins, 2004). Grimshaw and Woodruff (1986) describe two en echelon faults and an associated relay ramp structure in the San Marcos area that they hypothesize influenced the geomorphology and groundwater flow—namely the location of the Blanco River and San Marcos Springs. This same structure (Figure 1) is also mapped by Collins and Hovorka (1997).
**Hydrogeology and the Balcones Fault Zone**

The Trinity Aquifer is a sole-source supply for much of the central Texas Hill Country—its springs (Jacob’s Well and Pleasant Valley Springs, among others) provide baseflows that ultimately recharge the Edwards Aquifer down gradient (Figure 2; Smith et al., 2015). The Edwards Aquifer is also a significant sole-source supply for hundreds of thousands of people in central Texas and its renowned springs such as Comal, San Marcos, and Barton Springs provide habitat for a variety of endangered species.

The BFZ was critical to the hydrogeologic evolution of the Edwards and Middle Trinity Aquifers. Faulting provided the hydrogeologic architecture (e.g. recharge areas vs. confined aquifers) and the initiation point for karst processes (DeCook, 1963; Slade et al., 1986; Sharp, 1990; Ferrill et al., 2004). Structures such as joints and fractures influence the location and development of karst recharge features. These features often are located within stream channels and are capable of high rates of groundwater recharge (up to about 3,000 liters per second, or 100 cubic feet per second). Antioch Cave in Onion Creek which recharges the Edwards Aquifer and Saunder’s Swallet in the Blanco River which recharges the Middle Trinity Aquifer are examples of such features (Figure 1).

Both aquifer systems contain joint-controlled conduits that transmit large amounts of water. The conduits are documented by cave maps, dye tracing, aquifer tests, and potentiometric surfaces (Wierman et al., 2010 and references therein). The structural influence on flow is more pronounced in the Edwards Aquifer at the regional scale as the aquifer is located entirely within the BFZ, while only the eastern portion of the Trinity is strongly influenced by the BFZ. However, major springs in both the Edwards and Trinity Aquifer systems are strongly influenced by structure as evidenced by faults at Barton Springs in the Edwards Aquifer and visible fractures or faults at Pleasant Valley Spring and Jacob’s Well Spring in the Middle Trinity Aquifer.

**Approach**

The approach to evaluate the influence of relay ramp structures on groundwater flow was to construct a detailed geologic contour surface in the BFZ (Figures 4 and 5). Different types of hydrologic data from the Edwards and also the Middle Trinity Aquifers were overlain onto this structure contour map.

The Walnut Formation (also known as the Basal Nodular Member) below the Edwards Group was the stratigraphic layer selected as the primary contour mapping horizon. The formation’s subsurface characteristics based on geophysical logs of wells are described in Hunt et al. (2011). It was selected as the primary mapping horizon for the following reasons: 1) The relative ease in identifying it in outcrop and geophysical logs (fossil assemblages and lithology in outcrop, high gamma ray signature on geophysical logs), 2) it represents the base of the Edwards Aquifer and, as such, many wells penetrate it, and 3) it has relatively consistent thickness through the study area. Geologic data used to construct the detailed structure contour surfaces were derived from an unpublished database maintained at the Barton Springs/Edwards Aquifer Conservation District. The database consists of well information and the tops of geologic formations or units primarily based upon geophysical logs plus driller’s logs, outcrops, and cuttings. A few contacts were derived from published geologic maps to fill in data gaps. Data for the top of the Walnut Formation were gridded and contoured in Surfer® using a Kriging algorithm—no faults were used in the gridding process. A total of 379 data points were used consisting of 45% geophysical logs, 42% driller’s logs, and 13% outcrops.

The gridded and contoured structural data was intentionally done without reference to faulting or structural domains. The authors believe the data reflect the overall geometry of the unit, without introducing the bias of mapped faults that in fact represent a spectrum of geometries from wide zones of dipping beds, to discrete offsets with variable throw. This approach is an obvious simplification of the structural surface, but allows for the significant geometries (major faults, and ramps) to be highlighted.

Simplified faults were drawn over the contour map from the Geologic Atlas of Texas (Stoeser, 2005) where gradients were steep and supported the presence of significant relatively discrete faults. These faults generally fall into two classes, those that have greater than 150 m displacement, such as the Mount Bonnell and the San Marcos Faults, and those with intermediate displacements up to 60 m. It is assumed that the structures mapped in the Walnut Formation persist at depth into the Middle Trinity Aquifer, about 150 m below the Walnut Formation.

Hydrogeologic data used in this evaluation are potentiometric data from Hunt and Gary (2014) consisting of a synoptic event during drought conditions (February-March 2009) in both the Edwards and Middle Trinity Aquifers (Figures 1, 5 and 6); dye-tracing data during low-flow conditions were summarized from the work of Hauwert et al., 2004 and Johnson et al., 2012 (Figure 5); geochemical data compiled from the Texas Water Development Board database and modified data from Wierman et al., 2010 (Figure 6).
Figure 4. Structure contour map of the top of the Walnut Formation—the base of the Edwards Aquifer. Two relay ramp structures are drawn where gradients flatten out between large faults. The two ramps are named Onion Creek Ramp (OCR) and the Kyle Ramp (KR). Contouring was done without faults in Surfer®. To illustrate the geometry of the relay ramp, faults were drawn where contouring supported their presence—these generally coincide with faults mapped in the Geologic Atlas of Texas (Stoeser, 2005).
Aquifer permeability is reported to generally be enhanced parallel to faults and decreases perpendicular to faults in the Edwards Aquifer (Ferrill et al., 2004; Ferrill et al., 2008). However, is it possible that other structures such as relay ramps may also influence groundwater flow? These types of structures have been attributed to control groundwater flow paths in other parts of the Edwards Aquifer, such as the Knippa Gap west of San Antonio (Clark et al., 2013). We know that the fractures associated with faulting can be as significant as the faults themselves in terms of influencing groundwater recharge, flow, and discharge. We hypothesize that the structural dip, and associated faulting and fracturing in a relay ramp could be a significant factor in influencing groundwater flow.

Groundwater flow from the Blanco Watershed eastward into the BFZ must flow “across” some faults with significant displacements. In fact, relay ramps provide a mechanism or pathway for groundwater to flow around faults, as the head and geochemical data in Figure 6 suggest. Where displacements are minimal or where permeable units are juxtaposed against each other, flow can actually be across the faults. In addition, head data also suggest that faults with significant displacements are indeed barriers to flow as shown by the NE-trending flow along the Mount Bonnell Fault (Figures 1 and 6).

Groundwater flow paths in the Barton Springs segment of the Edwards Aquifer have been conceptualized to be focused along solutioned (karstic) NE-trending fractures (Hunt et al., 2005). The primary flow path in the Barton Springs segment of the Edwards Aquifer, determined from potentiometric maps and dye tracing, is called the Manchaca Flow route (labeled “MF” on Figure 5; Hauwert et al., 2004). This flow route generally coincides with faults (in part) and the Onion Creek ramp structure of this study. The wide potentiometric trough and circuitous dye trace paths within the Onion Creek ramp suggest a wide area of elevated permeability, instead of a single discrete flow path along a single fault zone. Dye tracer tests have demonstrated that during high-flow conditions in Onion Creek, groundwater flow can reverse directions and flow to the SE (up structural dip) toward San Marcos Springs (Smith et al., 2012).

A zone of highly permeable Edwards Aquifer is inferred from an area of very low hydraulic gradient extending south of San Marcos Springs along the saline zone, to the north toward Kyle (Land et al., 2010). This area is coincident with the Kyle ramp structure, an area bound by a significant fault on the northwest and the saline zone boundary to the east (Figure 5). Where the Kyle ramp ends, the high permeability zone appears to also

**Figure 5.** Map showing low-flow hydrologic data relative to the ramp structures. Major flow paths (Manchaca Flow Path, “MF” on map) defined by potentiometric troughs and dye tracing are coincident with the Onion Creek Ramp (OCR) structure. Note the Kyle Ramp (KR) is coincident with a flat hydraulic gradient (Land et al., 2010). Saline boundary from Hunt et al., 2014. Potentiometric data from Hunt and Gary, 2014. Dye tracing results summarized from Hauwert et al., 2004 and Johnson et al., 2012.

**Results**

Figure 4 presents the results of the structure contour map of the top of the Walnut Formation. The map contains generalized faults where the contour gradients suggest their presence and also interpreted ramp structures.

Hydrologic data in the Edwards (Figure 5) and Middle Trinity (Figure 6) are overlain on the major faults and the interpreted ramp structures for comparison.

**Discussion**

Structure is an important control on the location of recharge, flow paths, and spring discharge locations in carbonate aquifers (Sasowsky, 1999), and for the Edwards and Trinity Aquifers (Ferrill et al., 2004). Faults have generally been the primary structure cited in the literature to influence groundwater flow (Maclay and Small, 1986; Hunt et al., 2005).
Figure 6. Map showing hydrologic data (potentiometric and geochemistry) relative to the ramp structures and major faults. Flow paths of the Middle Trinity defined by potentiometric heads and the “tongue” of low TDS appear to flow to the east along the Onion Creek ramp. Note the flow to the northeast indicating the fault may be a barrier to flow in that area. Potentiometric data from Hunt and Gary, 2014. TDS data modified from Wierman et al., 2010.
Groundwater flow appears to be strongly influenced by faults and by the fault-bound ramp structures. This essentially agrees with previous hypotheses of Grimshaw and Woodruff (1986) and Collins and Hovorka (1997). Detailed structural data and hydrologic data presented in this study support those hypotheses. However, instead of one large single ramp structure (Figure 1), the data supports a more complex system of at least two smaller structures (Figure 4). The practical application of mapping relay ramp structures is that it provides a mechanism for predicting lateral continuity of geologic units, and therefore lateral groundwater flow paths. A better understanding of these flow paths will provide a better understanding of the connection between recharge areas and the deeper portions of these aquifers that are being used more extensively for water supply.

Conclusions
Groundwater flow appears to be strongly influenced by faults and by the fault-bound ramp structures first proposed by Grimshaw and Woodruff (1986). Conclusions from this study include:

- Relay ramps provide a continuity of geologic units for lateral groundwater flow within the Middle Trinity Aquifer from the Hill Country eastward into the BFZ. At least two relay ramps (Onion Creek Ramp and Kyle Ramp) were identified in the study area based on detailed structure contours of the Walnut Formation.
- Relay ramps may influence groundwater flow in the Barton Springs segment of the Edwards Aquifer due to their northeast structural dip superimposed with solution along fractures and faults.
- Faults with significant displacements (Mount Bonnell) can provide a barrier to flow and force flow around faults and along relay ramps. Flow across moderate to minor faults can occur due to the juxtaposition of permeable units.

These conclusions should be incorporated into conceptual models of the Edwards and Trinity Aquifers—and considered in the management of aquifers that span structural and political regions.

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