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PETROLOGY OF THE GRADATIONAL INTRUSIVE CONTACT BETWEEN THE
PACKSADDLE SCHIST AND THE TOWN MOUNTAIN GRANITE, ENCHANTED
ROCK STATE NATURAL AREA, LLANO UPLIFT, CENTRAL TEXAS

By

TRAVIS GALLE, Bachelor of Science

Presented to the Faculty of the Graduate School of

Stephen F. Austin State University

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Master of Science

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PETROLOGY OF THE GRADATIONAL INTRUSIVE CONTACT BETWEEN THE
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TRAVIS GALLE, Bachelor of Science

APPROVED:

Dr. Liane Stevens, Thesis Director

Dr. Melinda Faulkner, Committee Member

Dr. Joseph Musser, Committee Member

Dr. R. LaRell Nielson, Committee Member

Pauline, M. Sampson, Ph. D.
Dean of Research and Graduate Studies

ABSTRACT

The Mesoproterozoic intrusive contact between the ~1.1 Ga anorogenic Town Mountain Granite and the ~1.3 Ga Packsaddle Schist is a gradational contact exhumed within the Llano uplift. This contact is exposed along the southeastern margin of the Enchanted Rock batholith in central Texas. Field observations, hand sample and thin section petrography, and handheld X-ray fluorescence analysis of hand samples were used to characterize the gradational nature of this contact at multiple scales. The style of gradation between the Town Mountain Granite and Packsaddle Schist varies throughout the study area, containing both injection and permeation. The complex relationships observed at the contact possibly resulted from variations in temperature conditions along the contact at different stages of the emplacement.

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TABLE OF CONTENTS

I. Abstract	i
II. Acknowledgments	ii
III. Table of Contents	iii
IV. List of Figures	v
V. List of Tables	vii
VI. Introduction	1
VII. Geologic History	3
1. Proterozoic History	5
2. Paleozoic History	11
3. Mesozoic History	13
4. Mesoproterozoic Lithology	13
i. Packsaddle Schist	14
ii. Valley Spring Gneiss	16
iii. Town Mountain Granite	16
iv. Enchanted Rock Batholith	17
v. Intrusive Igneous Relationships	19
VIII. Study Area	22
IX. Methods	24

X.Results	27
1. Field Observations	27
2. Petrography	33
i. Packsaddle Schist	36
ii. Town Mountain Granite	41
3. hXRF Data	50
XI.Discussion	53
XII. Conclusions	59
XIII. References	61
XIV. Appendices	65
XV. Vita	76

LIST OF FIGURES

Figure 1. A geologic map of the Llano uplift in Central Texas.	4
Figure 2. Rodinia and the Grenville orogenic belt.	6
Figure 3. The lithotectonic domains of the Llano uplift.	9
Figure 4. A cross-sectional computer model of the prowedge and retrowedge.	10
Figure 5. A tectonic model for the evolution of the Llano during the Grenville orogeny.	12
Figure 6. A geologic map of the Enchanted Rock Batholith.	18
Figure 7. The styles of gradational intrusive contacts.	21
Figure 8. Geologic map of the study area.	23
Figure 9. Elements analyzed by hXRF for this study.	26
Figure 10. The four types of granitoids of the Town Mountain Granite observed in the study area.	28
Figure 11. Contact relationships between Town Mountain Granite and Packsaddle Schist.	29
Figure 12. Stereonets of plotted structural measurements.	31
Figure 13. Stereonets of planar features by sites.	32
Figure 14. Photomicrographs of the contact between Town Mountain Granite and Packsaddle Schist.	37
Figure 15. Photomicrograph of contact between the TMG and Packsaddle Schist.	39

Figure 16. Photomicrograph of equigranular quartz and feldspar grains within the Packsaddle Schist.	40
Figure 17. Photomicrograph of micas within the Packsaddle Schist.	42
Figure 18. Photomicrograph of an aluminosilicate grain within the Packsaddle Schist.	43
Figure 19. IUGS igneous rock classification ternary diagram showing the classification of TMG granitoids (circles).	45
Figure 20. Photomicrograph of exsolution lamellae in K-feldspar.	46
Figure 21. Myrmekitic textures within the Town Mountain Granite.	47
Figure 22. ACF diagram of hXRF analyses.	52

LIST OF TABLES

Table 1. Compilation of structural measurements from the study area.	30
Table 2. A table of all samples collected.	34
Table 3. Chart of hXRF data collected from Town Mountain Granite samples and Packsaddle Schist.	51

INTRODUCTION

The nature of the geologic contacts between intrusive igneous bodies and the country rock that they intrude can be indicative of the temperature and depth of emplacement and the rate of crystallization. Intrusion of the anorogenic Mesoproterozoic Town Mountain Granite into the Mesoproterozoic metamorphic basement rocks of the Llano uplift followed the ~1.3-0.9 Ga Grenville orogeny (Karlstrom et al., 1998; Mosher et al., 2008). While the general pressure-temperature (P - T) conditions associated with the emplacement of the Town Mountain Granite are known, this research aims to investigate the gradational contact at multiple scales. This study focuses on the contact between the Town Mountain Granite and the Packsaddle Schist, which outcrops along the southeastern margin of the Enchanted Rock batholith, and is exposed in Enchanted Rock State Natural Area (ERSNA), 17 miles north of Fredericksburg, Texas.

Previous studies have examined geochemical, mineralogical, and structural features of both the Town Mountain Granite and Packsaddle Schist (Hutchinson, 1956; Nelis et al., 1986; Wilkerson et al., 1988; Smith et al., 2010). Hutchinson (1956) noted that the contact between the two along the southern margin of the

batholith is concordant. In this study, the style of the gradational nature of this contact will be the focus.

Through field work, petrography, and handheld X-ray fluorescence (hXRF), analysis, this work aims to characterize the mineralogy, bulk geochemistry, and structural features of both the Packsaddle Schist and the Town Mountain Granite along the segment of the contact exposed in the ERSNA in order to interpret conditions along the contact at the time of the intrusion. This work describes this intrusive boundary in the context of the tectonic history of the Llano uplift, and interprets general P - T conditions along the contact at the time of the intrusion. The results of this study will pave the way for more detailed future studies regarding the metamorphism and deformation along this contact.

GEOLOGIC HISTORY

The Llano uplift is a structural dome in central Texas that exposes Mesoproterozoic metamorphic and igneous rocks that are overlain by Paleozoic and Mesozoic sedimentary rocks (Figure 1). The Mesoproterozoic Grenville orogeny resulted in multiple stages of deformation and metamorphism, followed by anorogenic magmatism (Mosher et al., 2008; Smith et al., 2010). Transgressive and regressive marine cycles throughout the Paleozoic contributed to erosion of the crystalline basement and deposition of the sedimentary cover (Barnes and Bell, 1977). The Ouachita orogeny of the late Paleozoic led to another stage of uplift and mountain building and was followed by further marine erosion and deposition in the Cretaceous (Barnes and Bell, 1977; Corrigan et al., 1998).

Figure 1. A geologic map of the Llano uplift in Central Texas. The uplift roughly corresponds to the patterned, pink Precambrian units and is surrounded by blue Permian units and green Cretaceous units. The black star indicates the location of the study area (Map modified from USGS-Pocket Texas Geology, accessed March, 2019).

Proterozoic History

The supercontinent Rodinia existed between ~1.3 Ga, when its final stage of assembly began, and ~0.9 Ga (Whitmeyer and Karlstrom, 2007). During the assembly of Rodinia, the southern margin of Laurentia was involved in the Grenville orogeny, a collision with an unknown “Southern continent” (Whitmeyer and Karlstrom, 2007; Mosher et al., 2008). Most Grenville-aged North American rocks are exposed discontinuously from southeastern Canada and along the Appalachian Mountains to Van Horn, Texas (Figure 2). The Llano uplift and the Van Horn locality in West Texas expose the only Grenvillian rocks in the southern United States (Whitmeyer and Karlstrom, 2007; Walker et al., 1992; Mosher et al., 2008). During the Grenville orogeny, the southern margin of Laurentia was subducted beneath the Southern continent (Grimes and Copeland, 2004; Mosher et al., 2008).

Grenville-aged rocks in the Llano uplift are divided into three lithotectonic domains based on their original areas of deposition along the orogenic belt: the Packsaddle Domain, the Valley Spring Domain, and the Coal Creek Domain (Mosher et al., 2008). The Packsaddle and Valley Spring domains originated as siliciclastic rocks and mafic volcanic sequences that were deposited in intracratonic rift basins along the southern margin of Laurentia. (Whitmeyer and Karlstrom, 2007). The Valley Spring Domain is interpreted as continental margin

volcanic arc deposits and the Packsaddle Domain is interpreted as part of the adjacent forearc basin (Mosher et al., 2008). The Coal Creek Domain represents an exotic arc terrane on the overriding Southern continent and contains tonalitic to dioritic igneous rocks and ophiolitic rocks (Mosher et al., 2008).

Early high- P (up to 15 kbar) eclogite facies metamorphism occurred within the Valley Spring domain during the initial stages of the subduction of Laurentia (Wilkerson et al., 1988). Evidence for this high- P metamorphism is confined to boudins of mafic eclogite in felsic gneisses, suggesting conditions of 610-775 °C and 14-24 kbar. (Carlson et al., 2007). Further evidence recorded in the western, northern, and south-central parts of the Llano uplift also indicate high- P metamorphism (Carlson, 1998). This suggests early, steep, southwestward subduction of Laurentia, followed by buoyancy-driven uplift (Carlson et al., 2007).

The early high- P metamorphism was followed by moderate- P , middle amphibolite facies metamorphism that overprinted remnants of the eclogite facies metamorphism (Carlson et al., 2007). Evidence for amphibolite facies metamorphism in the south-central uplift includes relict Mg-rich garnet and pyroxenes (Carlson, 1998). A rare staurolite inclusion in garnet in the Packsaddle Schist within the Packsaddle Domain provides a P - T estimate of 650-750 °C and 6-11 kbar (Wilkerson et al., 1988; Nelis et al., 1989, Carlson et al., 2007). These conditions are similar to P - T conditions elsewhere along the Grenville deformation front (Carlson and Nelis, 1986).

As continental collision continued, the Llano uplift developed distinct eastern and western regimes (Figure 3; Reese et al., 2000). The eastern uplift contains the older Coal Creek Domain atop the Valley Spring Domain, which sits atop the older Packsaddle Domain (Mosher et al., 2008). The western uplift, however, does not contain the Coal Creek Domain, and the older Packsaddle Domain sits atop the Valley Spring Domain (Mosher et al., 2008). The lack of Coal Creek Domain in the western uplift is likely due to its origin in the overriding Southern continent, and the different stacking and vergence patterns relate to the opposing dip direction of the units in the west after thrust imbrication (Mosher et al., 2008). Rocks in the western uplift experienced a higher degree of partial melting than those in the eastern uplift (Levine and Mosher, 2010). These differences in melting, stratigraphic stacking, and vergence are interpreted to reflect distinct parts of the subduction zone, the retrowedge and the prowedge (Figure 4). The retrowedge was positioned deeper within the orogen, experienced a greater volume of melting, and was associated with the overriding plate (back-arc), as was observed in the western uplift (Levine and Mosher, 2010). The prowedge was the shallow portion of the subduction zone with a lesser volume of melting and was associated with the subducting plate (forearc), which corresponds to observations in the eastern uplift. (Levine and Mosher, 2010).

Figure 3. The lithotectonic domains of the Llano uplift (Mosher et al., 2008). The three regions of the Llano uplift are also shown.

Figure 4. A cross-sectional computer model of the prowedge and retrowedge. Compare the relative depths, orogenic stacking, and opposite sense of vergence in the prowedge and the retrowedge (Levine and Mosher, 2010).

The metamorphosed rocks were exhumed via extension and erosion at ~1120-1070 Ma, induced by post-collisional extension of the orogen (Mosher et al., 2008). Exhumation was initiated by the buoyancy of the subducted continental crust (Mosher et al., 2008, Figure 5). The breakoff of the subducted slab produced upwelling of the asthenosphere (Mosher et al., 2008; Figure 5). Subsequent underplating and heating of the continental crust led to the intrusion of the juvenile, post-tectonic Town Mountain Granite (Mosher et al., 2008; Smith et al., 2010). The magma was primarily derived from partial melting of tonalitic to granodioritic crust, with the participation of mantle-derived basaltic magma (Smith et al., 2010). This model is consistent with the intrusion of the undeformed or weakly deformed Town Mountain Granite into the deformed and metamorphosed Packsaddle and Valley Spring domains. (Smith et al., 2010). The widespread intrusion of the Town Mountain Granite coincided with a final metamorphic event: static, fluid-rich, low-*P*, middle amphibolite facies metamorphism (3 kbar, 525-625 °C), (Carlson, 1998; Mosher et al., 2008).

Paleozoic History

A mantle superplume initiated the breakup of Rodinia between 830 Ma and 650 Ma (Bogdanova et al., 2009), resulting in the uplift and exhumation of the Mesoproterozoic units within the Llano uplift. Erosion of these units occurred

Figure 5. A tectonic model for the evolution of the Llano uplift during the Grenville orogeny. A: The positions of the lithotectonic domains as Laurentia began to subduct beneath the Southern continent. B: The lithotectonic domains were juxtaposed during collision, resulting in early high-pressure metamorphism. C: As orogenic thickening continued, the retrowedge formed. D: Exhumation was followed by slab-breakoff, the upwelling of the asthenosphere, underplating of basaltic magmas, and intrusion of juvenile granites E: Younger granites intruded as collision continued along strike in West Texas (Mosher et al., 2008).

throughout the Neoproterozoic and into the Middle Cambrian (~510 Ma), when a transgressive sea from the southeast buried the region in marine sediments (Barnes and Bell, 1977). A shallow-water carbonate platform developed in the Lower Ordovician (~480 Ma) and was then sub-aerially exposed (Barnes and Bell, 1977). The region was submerged beneath the Rheic Ocean in Pennsylvanian time (prior to 318 Ma), when carbonates and fine-grained siliciclastic sediments indicative of a shelf environment were deposited (Barnes and Bell, 1977).

Shortly after the Pennsylvanian transgression, the Ouachita orogeny tilted both the crystalline basement and sedimentary layers of the Llano uplift (Barnes and Bell, 1977). The Ouachita orogeny was a continental collision between Laurentia and South America; the Llano uplift was in the foreland of the deformation front (Heron et al., 2018).

Mesozoic History

Erosion after the Ouachita orogeny is estimated to have been on the order of 10-20 m/m.y. (Corrigan et al., 1998). This erosion continued through the Triassic and Jurassic, followed by the mid-Cretaceous development of the Western Interior Seaway, and deposition of shelf carbonates over the sediments of Ouachita affinity (Atchley et al. 2001). The Llano uplift and much of central

Texas was buried under Cretaceous carbonates, which include the Glen Rose, Comanche Peak, and Edwards formations. Regression of the Cretaceous seas by the Cenozoic led to erosion of the overlying limestones and the sediments that buried the Mesoproterozoic crystalline rocks, allowing for the island-like exposure of the relic Grenvillian units in a sea of Phanerozoic sediments (Barnes et al., 1972).

Mesoproterozoic Lithology

The Town Mountain Granite intrudes the Packsaddle and Valley Spring domains in the Llano uplift (Mosher et al., 2008). The Packsaddle Domain contains the Packsaddle Schist and the Red Mountain Gneiss (Mosher et al., 2008). The Valley Spring Domain contains the Valley Spring Gneiss (Mosher et al., 2008). The Packsaddle Schist and Valley Spring Gneiss are the metasedimentary and metavolcanic equivalents of continental arc and forearc basin deposits on the Laurentian margin (Mosher et al., 2008).

Packsaddle Schist

The Packsaddle Schist has both sedimentary (siliciclastic and calcareous) and extrusive igneous protoliths. The metamorphic assemblage of the Packsaddle Schist is quartz + biotite + muscovite + hornblende + plagioclase ±

andalusite $\pm$ sillimanite $\pm$ garnet $\pm$ staurolite $\pm$ K-feldspar $\pm$ cordierite. This assemblage is consistent with moderate-*P* amphibolite facies metamorphism (Carlson and Nelis, 1986).

The Packsaddle Schist has a total thickness of ~22,300 feet, and includes, from its base, the Honey, Sandy, Rough Ridge, and Click formations (USGS, 2019). The Click Formation (~7,800 ft) is mostly hornblende schist, underlain by quartz-feldspar-mica schist (Barnes, 1952; USGS, 2019). The Rough Ridge Formation (~5,200 ft) contains quartz-feldspar-mica schist, biotite-cordierite gneiss, biotite schist, and biotite-microcline gneiss (Barnes, 1952; USGS, 2019). The Sandy Formation (~2,100 ft) is made up of alternating units of hornblende schist and quartz-feldspar-mica schist (Barnes, 1952; USGS, 2019). Finally, the Honey Formation (~7,800 ft) contains a highly heterogeneous assortment of graphite schist, hornblende schist, marble, and muscovite schist (Barnes, 1952; USGS, 2019).

A multi-grain zircon fraction from metavolcanic rocks sampled at two localities within the Packsaddle Schist yielded upper intercept U-Pb ages of 1243 $\pm$ 2 Ma and 1247 $\pm$ 8/-6 Ma, which are interpreted as the timing of volcanism (Walker et al., 1992). The protoliths of the Packsaddle Schist were subsequently intruded by the granitic protolith of the Red Mountain Gneiss, which has a zircon multi-grain fraction U-Pb upper intercept age of 1239 $\pm$ 5/-3 Ma (Walker et al., 1992).

Valley Spring Gneiss

Following the intrusion of the Red Mountain Gneiss protolith, the rhyolitic protolith of the Valley Spring Gneiss was deposited. The Valley Spring Gneiss is primarily microcline-plagioclase-quartz-biotite gneiss, but also includes calc-silicates, marble, amphibolite, and quartzite (Barnes et al., 1988; USGS, 2019). Five abraded, multi-grain zircon fractions define a U-Pb upper intercept of 1232 ± 4 Ma, which is interpreted as the crystallization age (Walker et al., 1992).

Town Mountain Granite

The Town Mountain Granite is a coarse-grained, partly porphyritic, felsic to intermediate granite, primarily composed of quartz, plagioclase, and microcline in nearly equal proportions, as well as biotite and hornblende, and accessory minerals such as magnetite, apatite, fluorite, zircon, and pyrite (Barnes et al., 1954; Smith et al., 2010). Microcline megacrysts are up to 4 cm long, and weakly zoned gray-green to white plagioclase crystals are up to 2 cm long (Smith et al., 2010).

Upper intercepts of U-Pb isotope ratios of zircon data from plutons of the Town Mountain Granite suggest that the Town Mountain Granite intruded the Packsaddle and Valley Spring domains at ~ 1116 -1070 Ma (Walker et al., 1992).

The oldest intrusions (1119-1118 Ma) were folded by the last stage of deformation in the central uplift and cut by shear zones in the eastern uplift, while plutons younger than 1093 Ma are undeformed (Mosher et al., 2008).

Enchanted Rock Batholith

The Enchanted Rock batholith is one of the many plutons and batholiths within the Llano uplift that are composed of the Town Mountain Granite (Walker et al., 1992; Figure 6). From its outer rim inward, the batholith is divided into four zones based on texture and composition: 1) medium to coarse-grained leucogranite; 2) medium to coarse-grained granite to quartz monzonite; 3) coarse-grained quartz monzonite to alkalic granodiorite; and 4) fine to medium-grained leuco-quartz monzonite and leucogranite (Hutchinson, 1956). The granitoids in each of these zones have an approximate normalized 1:1:1 ratio of albite, orthoclase, and quartz (Hutchinson, 1956).

The 45-mile perimeter of the Enchanted Rock batholith, including the southern contact zone at Enchanted Rock State Natural Area, is largely concordant (Hutchinson, 1956). Along the southern contact of the Enchanted Rock batholith, Hutchinson (1956) reports porphyritic granite, leuco-quartz monzonite, and granodiorite. Hutchinson (1956) identified a chilled border zone with a width of 10-20 feet between the outer zone of the Enchanted Rock

Figure 6. A geologic map of the Enchanted Rock Batholith. The batholith is the large, teardrop-shaped area of Town Mountain Granite (pCtm, light pink), surrounded by Packsaddle Schist (pCps) and Valley Spring Gneiss (pCvs). The study area is located at the black star, straddling both the contact between the Packsaddle Schist and the Town Mountain Granite and the border between Llano and Gillespie counties. (Map modified from USGS- Pocket Texas Geology, accessed March, 2019).

batholith and the metamorphic country rock, with narrow apophyses of porphyritic leuco-granite monzonite intruding the Packsaddle Schist.

Intrusive Igneous Relationships

Some of the features of an igneous intrusion may be correlated to depth of emplacement, including the nature of the contact (sharp or gradational), the degree of concordance between the intrusion and the country rock, the shape of the intrusion, and igneous textures and microstructures.

Intrusive igneous contacts can be classified as concordant (intrusion does not cross-cut country rock), discordant (intrusion cross-cuts country rock), or complex (intrusion displays characteristics of both concordant and discordant contacts) (Winter, 2013 p. 78). Emplacement within the epizone (depths < 8 km, and temperatures < 300 °C) typically results in discordant contacts.

Emplacement within the mesozone (depths of 5 to 15 km, 300 to 500 °C) typically produces complex contacts. The contacts of intrusions emplaced within the catazone (> 10 km, 450 to 600 °C) are typically concordant (Buddington, 1959; Winter, 2013, p. 80).

The shapes of plutonic bodies are also related to depth of emplacement. Horizontal-tabular intrusions (laccoliths) and wedge-shaped plutons occur in the

catazone, near the brittle-ductile transition. Tabular, sheeted, and blobby plutons occur in the magma ascent conduit at shallower depths (<10 km) (Brown, 2013).

Sharp intrusive contacts result in heating and recrystallization of the colder country rock, with the grain size and degree of recrystallization of the country rock decreasing away from the contact. The recrystallization process can result in a contact metamorphic aureole (Winter, 2013, p. 78). Fine-grained chill zones typically occur on the plutonic side of a sharp contact as a result from rapid cooling in contact with the colder, stationary country rock (Winter, p. 78).

Gradational intrusive contacts vary between injected and permeated end members (Winter, 2013, p. 78; Figure 7). Injection is the purely mechanical emplacement of magma into the host rock. An injected contact can be identified by observing injected dikes in the country rock and xenoliths of the country rock within the intrusive igneous matrix (Winter, 2013, p. 78). Permeation occurs when silicic plutonic bodies that are highly saturated in fluids alter or partially melt the country rock (Winter, 2013, p. 78). A permeated contact typically appears as an indistinct boundary with the igneous rock gradually transitioning into the country rock (Figure 7).

Figure 7. The styles of gradational intrusive contacts. Gradational contacts have two end member styles, injected and permeated, or a combination thereof. The country rock is black while the intrusive body is white. a. An example of an injected intrusive contact. b: An example of a permeated intrusive contact. c: An example of a combination of both injection and permeation. From Winter (2013, p. 78).

STUDY AREA

The Enchanted Rock State Natural Area (ERSNA) is located along the southeastern margin of the Enchanted Rock batholith, on the boundary between Gillespie and Llano counties. The park contains a short section of the contact between the intrusive Town Mountain Granite and the Packsaddle Schist, which is exposed at the base of the Enchanted Rock exfoliation dome. Sandy Creek approximately follows the contact for a short distance within ERSNA and can be accessed by following the Loop Trail and the Buzzard's Roost Trail (Figure 8). ERSNA granted permission for field work and limited sampling in this area.

The study area includes nine sites that were selected based on good outcrop exposure of the contact and lithologies (Figure 8). Site 1 is located farthest to the northeast, while Site 9 is located at the southwestern end of the study area, near the ERSNA parking lot.

Figure 8. Geologic map of the study area. The Enchanted Rock State Natural Area is outlined in black. The map is overlain on satellite imagery. The map shows the contact between the Packsaddle Schist (pCps, red) and the Town Mountain Granite (pCtm, pink), as well as the locations of the Enchanted Rock exfoliation dome, Sandy Creek, and Texas Ranch Road 965. The approximate study area is marked by the 9 field sites along Sandy Creek (Map modified from USGS- Pocket Texas Geology, accessed March, 2019).

METHODS

Mineralogy, rock types, igneous and metamorphic textures, and geologic structures along the contact were observed at nine sites in the study area (Figure 9). Samples collected from the study area were petrographically described in hand sample and in thin section. The bulk chemistry of hand samples was determined using hXRF.

Field work at ERSNA was conducted over the summer months of 2019. Each study site was documented through field notes and photography. A Brunton compass was used to measure the strike and dip of planar features (such as bedding planes and mineral foliations) and the trend and plunge of linear features (such as mineral lineations and dikes) at each site. Twenty samples that were representative of contact lithologies and relationships were collected from the study area.

Eight thin sections were produced from the samples with the most representative lithologies, textures, and/or contact relationships. Hand samples were cut into billets, and then sent to Spectrum Petrographics in Vancouver, Washington, for standard thin section production.

Thin sections were observed using a Labomed Lx POL petrographic microscope in plane polarized light (PPL) and cross polarized light (XPL).

Photomicrographs in both PPL and XPL were used to document minerals, mineral relationships, microtextures, and small-scale contact features.

An hXRF was used to determine the bulk chemical composition of the lithologies in the hand samples. A handheld Thermo Niton XRF spectrometer was used for this non-destructive analysis. While the hXRF analyzes elements from Mg through U on the periodic table with near-laboratory accuracy and precision, only major elements, transition metals, and lanthanides that were relevant to understanding bulk rock geochemistry were analyzed (Figure 9). Several 3 mm diameter spots on each sample were analyzed for 180 seconds. These spots were chosen as representative points on differing and distinct lithologies in each sample. The hXRF data was reduced and plotted on ACF chemographic diagrams.

The Periodic Table of Elements

1 1A																	18 18A	
1 H																	2 He	
3 Li	4 Be	ATOMIC NUMBER - 1 SYMBOL - H NAME - Hydrogen										13 B	14 C	15 N	16 O	17 F	18 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	
LANTHANIDES		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
ACTINIDES		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

Figure 9. Elements analyzed by hXRF for this study. Periodic table of the elements with the elements analyzed by the hXRF for this study shaded in blue.

RESULTS

Field Observations

The study area is composed of low, knobby, discontinuous outcrops along Sandy Creek that contain a complex contact without a distinct boundary between the Town Mountain Granite and Packsaddle Schist. Four basic igneous rock types were identified in the field by texture and composition as part of the Town Mountain Granite: 1) a fine-grained pink granitoid, 2) a coarse-grained intermediate granitoid, 3) a coarse-grained pink granitoid, and 4) a pegmatitic granitoid (Figure 10). Metamorphic rocks from the Packsaddle Schist vary from darkly colored and strongly foliated schists and gneisses, to fine-grained, weakly foliated, gray schists (Figure 11).

The Packsaddle Schist is strongly folded and deformed throughout the study area, while the Town Mountain Granite generally cross cuts the metamorphosed units as dikes. Foliations and lineations observed at the study site include contact surfaces, metamorphic foliation surfaces, and intrusive dikes. (Table 1, Figure 12, Figure 13).

Figure 10. The four types of granitoids of the Town Mountain Granite observed in the study area. (A) Fine-grained pink granitoid (granite). (B) Coarse-grained intermediate granitoid. (C) Coarse-grained pink granitoid (granite) (D). Pegmatitic granitoid (granite).

Figure 11. Contact relationships between Town Mountain Granite and Packsaddle Schist. (A) A visually sharp contact (arrow) between a strongly foliated Packsaddle Schist (left) and the Town Mountain Granite at Site 1 (right). (B) A sharp contact (yellow arrow) between the strongly foliated Packsaddle Schist (left) and Town Mountain Granite (right) (Site 1). Granitoid lenses are present in the schist (white arrow). (C) A permeated gradational contact (arrow) lacks a distinct contact between the TMG and the Packsaddle Schist. Small lenses of granite (box) are also present within the schist. (D) A primarily injected gradational contact, lacking a distinct boundary between the TMG and Packsaddle Schist (Site 3). (E) Faults and fractures (arrow) overprint the contact between the migmatitic Packsaddle Schist and a permeated zone. (Site 5). (F) Evidence for a combination of permeation (lower, yellow arrow) and injection (upper, white arrow) processes along the gradational contact with a weakly-foliated schist. The granite here is pegmatitic.

Table 1. Compilation of structural measurements from the study area. All measurements are strike and dip of measurements of planar features, with the exception of the granodiorite dike, a linear feature with a trend and plunge measurement.

Site	Feature	Measurement
1	PS Foliation	N 21 W/ 78 SE
1	PS Foliation	N 18 W/ 72 SE
1	Contact Plane	N 12 E/ 52 SW
2	Contact Plane	N 46 W/ 18 SE
2	Contact Plane	S 41 E/ 42 NW
2	PS Foliation	S 10 W/ 16 NE
3	PS Foliation	N 50 E/ 26 SW
3	Contact Plane	N 37 E/ 22 SW
3	Granodiorite Dike	N 18 W/ 20 SE
3	PS Foliation	N 38 W/ 52 SE
3	PS Foliation	N 21 E/ 69 SW
3	Contact Plane	N 76 E/ 64 SW
3	Contact Plane	S 44 W/ 40 NE
3	PS Foliation	S 17 W/ 40 NE
4	PS Foliation	N 18 E/ 58 SW
4	PS Foliation	S 18 W/ 48 NE
5	Contact Plane	S 15 E/ 25 NW
5	PS Foliation	N 16 E/ 58 SW
5	PS Foliation	S 66 W/ 68 N
5	PS Foliation	N 12 E/ 25 SW
7	Contact Plane	N 06 E/ 70 SW
8	Contact Plane	S 25 W/ 27 NE
8	PS Foliation	N 19 E/ 29 SW
8	Contact Plane	NN 43 E/ 30 SW

Figure 12. Stereonets of structural measurements. (A). Plotted schist foliations and poles (B). Plotted contact planes and poles.

Figure 13. Stereonets of planar features for selected sites. Schist foliations are in blue, contact planes in red. (A). Plotted planar features at Site 1. (B). Plotted planar features at Site 2. (C). Plotted planar at Site 5. (D). Plotted planar features at Site 8.

The contact relationships between the igneous and metamorphic lithologies vary. There are some parts of the observable contact, particularly at the northeast, where the contact is sharp (Figure 11A), in which a clear boundary between the Town Mountain Granite and Packsaddle Schist is apparent, with little to no intermixing between the igneous material and country rock. The Packsaddle Schist may contain granitic lenses (Figure 11B).

In other places the contact was characterized by gradational features. Permeated contacts zones were observed wherein the igneous rock blends into the country rock (Figure 11C). These usually appear as a gradual transition of granitic rock within the Packsaddle Schist. Injected contacts are also present (Figure 11D), usually as granitoid interlayered with the schist. Complex gradational contacts containing evidence of both permeation and injection (Figures 11E, 11F) are observed in several outcrops in the study area, most prominently in the southwest portion of the study area.

Faults and fractures cross-cutting these gradational contact points are observed throughout the study area. Several of these fractures contained a significant amount of epidote, as observed in the field.

Petrography

Thirteen samples of Packsaddle Schist and 14 samples of Town Mountain Granite were collected as a representative sample suite (Table 2). Eight samples

Table 2. A table of all samples collected. The site and formations they are from, rock-types classified, descriptions, and whether a thin section was prepared are recorded.

Sample Site	Unit	Rock Type	Description	Thin Section
ER101 Site 1	Packsaddle Schist	Coarse-grained schist	Blue to gray, high schistosity and foliation. Slight gneissic texture.	--
ER102 Site 1	Packsaddle Schist and Town Mountain Granite	Coarse-grained schist and quartz-rich granitoid	Blue to gray, highly foliated schist. White to pink, fine grained granitoid.	--
ER103 Site 1	Packsaddle Schist	Coarse-grained schist	Highly schistose. Slight gneissic texture.	--
ER201 Site 2	Packsaddle Schist and Town Mountain Granite	Fine-grained schist and quartz-rich granitoid	Fine-grained, low amounts of foliation, Fine-grained granite. Sharp contact.	Yes
ER202 Site 2	Packsaddle Schist	Fine-grained schist	Fine-grained, weakly foliated. Gray in color.	--
ER301 Site 3	Town Mountain Granite	Granite	Fine-grained, pink, rich in K-spar.	Yes
ER302 Site 3	Town Mountain Granite	Granodiorite	Coarse-grained, intermediate. Plagioclase-rich	--
ER304 Site 3	Packsaddle Schist and Town Mountain Granite	Coarse-grained schist and quartz-rich granitoid	Strongly foliated schist. White to pink granitoid. Sharp contact.	--
ER305 Site 3	Packsaddle Schist and Town Mountain Granite	Coarse-grained schist and granite	Highly foliated and gneissic schist. K-spar-rich granitoid	Yes
ER306 Site 3	Packsaddle Schist and Town Mountain Granite	Coarse-grained schist and granite	Gneissic schist with moderate foliation. Fine-grained pink granitoid.	--

Table 2 (continued).

Sample Site	Unit	Rock Type	Description	Thin Section
ER401 Site 4	Packsaddle Schist and Town Mountain Granite	Fine-grained schist and granite	Gray to black schist. Coarse-grained granitoid.	--
ER402 Site 4	Town Mountain Granite	Granodiorite	White to gray, coarse-grained granitoid.	Yes
ER403 Site 4	Packsaddle Schist	Fine-grained schist	Weak foliation and schistosity.	Yes
ER501 Site 5	Packsaddle Schist and Town Mountain Granite	Fine-grained schist and quartz rich granitoid	Low foliation and dark in color schist. Coarse-grained pink granitoid.	--
ER502 Site 5	Town Mountain Granite	Granodiorite	Intermediate in composition, coarse-grained.	--
ER503 Site 5	Town Mountain Granite	Granite	Coarse-grained, alkaline granitoid.	--
ER504 Site 5	Packsaddle Schist	Fine-grained schist	Poorly foliated, gray to brown.	--
ER701 Site 7	Town Mountain Granite	Granite	Pegmatitic granitoid, pink to white in color.	Yes
ER802 Site 8	Packsaddle Schist and Town Mountain Granite	Fine-grained schist and granite	Poorly foliated gray schist. Weak schistosity, pegmatitic granitoid.	Yes
ER803 Site 8	Town Mountain Granite	Granite	Pegmatitic granitoid. Pink to white in color	--

straddled the contact between both units. Eight thin sections were prepared from 7 of the samples. These hand samples and thin sections are described below.

Packsaddle Schist

Sample ER201

Sample ER201 features the contact between fine-grained Packsaddle Schist and the fine-grained pink granitoid. The schist is gray to black, fine grained, and is folded and injected by thin, concordant layers of more fine-grained pink granitoid. The schist is in sharp contact with the Town Mountain Granite, with little to no intermixing between the igneous and metamorphic material. There are some fine-grained pink granitoid lenses in the schist.

In thin section the schist contains quartz (70%), biotite (15%), and hornblende (15%). The grains are subhedral to anhedral.

The equigranular quartz grains have polygonal grain boundaries (Figure 14). The biotite and hornblende grains form a strong foliation (Figure 14). The thin section is cut along the contact between the Packsaddle Schist and Town Mountain Granite, with the smaller metamorphic quartz and biotite grains in a distinct boundary with the larger igneous plagioclase grains (Figure 14).

Figure 14. Photomicrographs of the contact between Town Mountain Granite and Packsaddle Schist. The contact between plagioclase-rich TMG (left) and biotite-rich Packsaddle Schist (right) is indicated by the arrow. Taken from sample ER201 (A) PPL, 4x. (B) XPL, 4x.

Sample ER305

The hand sample of sample ER305 features the contact between fine-grained Packsaddle Schist and the fine-grained pink granitoid (Figure 11C). The schist is gray to black. The biotite and muscovite make up a strong foliation, and is somewhat gneissic. The contact with the granitoid appears sharp with small amounts of igneous rock permeating the schist (Figure 11C).

In thin section the schist contains anhedral quartz (72%); the biotite (20%) and muscovite (8%) are euhedral to subhedral. The grain boundaries of the quartz are highly polygonal (Figure 15).

Sample ER403

Sample ER403 is a fine-grained, Packsaddle Schist sample with strongly-foliated biotite. In thin section, the quartz (45%) is euhedral, the plagioclase (5%) is subhedral, and the biotite (18%) and muscovite (30%) are anhedral. The quartz grain boundaries are highly polygonal (Figure 16). This sample also contains opaque minerals (2%).

Figure 15. Photomicrograph of the contact between the TMG and Packsaddle Schist. Taken from sample ER305. XPL, 4x.

Figure 16. Photomicrographs of equigranular quartz and feldspar grains within the Packsaddle Schist. A triple junction of polygonal grain boundaries is indicated in red. Taken from sample ER403. (A). PPL, 4x. (B). XPL, 4x.

Sample ER802

Sample ER802 is fine-grained Packsaddle Schist with small dikes of Town Mountain Granite. The schist is gray in color and weakly foliated. The sample contains quartz (70%), plagioclase (18%), chlorite (14%), biotite (14%), and an aluminosilicate (5%).

In thin section, the schist contains subhedral to anhedral quartz, anhedral muscovite, and subhedral to anhedral biotite. The micas form the schist's weak foliation (Figure 17). A porphyroblastic aluminosilicate grain (possibly andalusite) is surrounded by chlorite (Figure 18).

Town Mountain Granite

Sample ER201

This coarse-grained pink Town Mountain Granite is pink to white in color, with fine-grained quartz and biotite and medium-grained K-feldspar and plagioclase. In thin section, the quartz, biotite, and microcline are subhedral to anhedral, and plagioclase is euhedral to subhedral. The grain boundaries between quartz and plagioclase grains in the granite are interlobate. The estimated modes from the granitoid in thin section are 63% quartz, 13% biotite,

Figure 17. Photomicrographs of micas within the Packsaddle Schist. Micas include well-aligned biotite grains in the lower portion of the image, and non-foliated chlorite and muscovite grains in the upper portion. Taken from sample ER803. (A). PPL, 4x. (B). XPL, 4x.

Figure 18. Photomicrograph of a possible aluminosilicate porphyroblast in the Packsaddle Schist. The porphyroblast is surrounded by chlorite. Taken from sample ER803. (A). PPL, 4x. (B). XPL, 4x.

13% microcline, and 11% plagioclase. This sample plots as a quartz-rich granitoid on the IUGS classification diagram (Figure 19).

Sample ER301

Sample ER301 is fine-grained, pink Town Mountain Granite. The granite is gray, pink, and black on a fresh surface, and white to brown on a weathered surface.

In thin section, the quartz grains are subhedral to euhedral, microcline is subhedral, plagioclase is subhedral, and biotite is elongate. Some K-feldspars grains contain exsolution lamellae and display twinning (Figure 20), and there are examples of myrmekitic intergrowths of quartz and plagioclase (Figure 21). The grain boundaries between the feldspar and quartz are largely interlobate. The estimated modes for this thin section are 60% quartz, 23% microcline, 10% plagioclase, 2% zircons, 5% biotite. This sample plots as a granite on the IUGS classification diagram (Figure 19).

Figure 19. The Town Mountain granitoids plotted on an IUGS igneous rock classification diagram (circles).

Figure 20. Photomicrograph of exsolution lamellae in K-feldspar. This is taken from sample (ER301). (A) PPL, 4x. (B) XPL, 4x.

Figure 21. A region of myrmekitic texture (red arrow) within the Town Mountain Granite is surrounded by interlobate grains (ER301). (A). PPL, 10x. (B). XPL, 10x.

Sample ER305

This sample of fine-grained pink Town Mountain Granite contains very-fine-grained quartz, fine-grained and medium-grained alkali-feldspar, fine-grained plagioclase, and fine biotite. In thin section, the igneous quartz and plagioclase are subhedral, and biotite grains anhedral. The grain boundaries between the granite minerals are interlobate (Figure 15). The estimated modes within the granite are 58% quartz, 26% plagioclase, and 16% microcline. This sample plots as a granite on the IUGS classification diagram (Figure 19).

Sample ER402

Sample ER402 is coarse-grained, white coarse-grained intermediate Town Mountain Granite. The sample is fine- to medium-grained with quartz, plagioclase, biotite, and amphibole.

In thin section, the quartz (50%) is subhedral to anhedral, the plagioclase (40%) is subhedral, and the biotite grains (10%) are anhedral. The quartz and plagioclase grain boundaries are interlobate. This sample plots as a granodiorite on the IUGS classification diagram (Figure 19).

Sample ER701

Sample ER701 is pegmatitic Town Mountain Granite. The sample is white to pink in color, and medium- to coarse-grained. In thin section, quartz grains are anhedral, plagioclase grains are anhedral to subhedral, microcline grains are anhedral, and biotite grains are elongate. The biotite grains, which are only observed in thin section, are inclusions within the quartz and plagioclase. The grain boundaries are primarily interlobate. The estimated mineral modes within the granite are 50 % quartz, 16% plagioclase, 10 % microcline, 7% muscovite, 10 % biotite, 2% zircon, 5% opaque minerals. This sample plots as granite on the IUGS classification diagram (Figure 19).

Sample ER802

This medium-grained Town Mountain Granite is pink to white in color. In thin section, the igneous quartz grains are subhedral, and the plagioclase and microcline grains are subhedral to euhedral. The grain boundaries within the porphyritic igneous matrix are primarily interlobate. The sample contains 72% quartz, 16% microcline, and 12% plagioclase. This sample plots as granite on the IUGS classification diagram (Figure 19).

hXRF Data

Thirty-nine hXRF analyses of 16 hand samples provide an indication of bulk composition for the igneous and metamorphic rocks (Appendices A-I). Thirteen points were analyzed on igneous rock, and 17 points were analyzed on the metamorphic rock (Table 3).

The hXRF data was plotted on an ACF ternary diagram with A representing Al_2O_3 , C representing CaO , and F representing FeO plus MgO . Both rock types plot over a range of compositions (Figure 22). Igneous samples classified as granodiorite plot within the basic compositional field, while the granite and quartz-rich granitoid rocks plot in both the quartzofeldspathic and pelitic ranges (Figure 22). Most Packsaddle Schist samples plot within the basic field, with five points plotting close to the quartzofeldspathic range (Figure 22).

Table 3. Chart of hXRF data collected from Town Mountain Granite samples and Packsaddle Schist. Major element compositions are recorded in parts per million.

Site	Sample	Fe	Ca	K	Al	P	Si	Mg
1	ER102	48074.71	21242.03	12458.1	12310.54	260.21	149430.94	5242.8
1	ER102	16002.64	61782.59	30289.69	138840.17	14394.77	547954	59569.14
1	ER101	80158.83	2908.05	32591.88	30853.8	1800.4	124289.61	0
1	ER101	106408.23	4302.06	29684.73	26057.25	1740.13	128368.62	12918.41
2	ER201	13454.09	27313.93	6454.89	39527.34	5325.09	145835.11	11217.52
2	ER201	35105.98	28793.74	12510.21	74802.49	3204.93	230171.44	8951.93
3	ER305	10748.94	9652.7	4843.55	45245	6416.06	318643.81	8833.43
3	ER301	1171.38	8881.57	12213.3	53768.59	11193.4	352256.81	0
3	ER301	732.32	3504.74	7343.91	42181.6	12609.86	317602.19	0
3	ER304	103187.9	4425.35	8830.67	43856.32	249.98	167602.09	7090.15
3	ER304	75011.89	1039.06	19702.5	63875.39	0	325895.22	18973.37
3	ER304	87805.94	4077.05	26124.42	141694.67	1943.9	261636.3	13940.12
4	ER402	24124.71	29030.77	11245.09	67620.63	2392.49	321819.81	12368.53
4	ER402	21412.34	14671.68	22540.09	28221.74	2081.59	200519.02	12074.45
4	ER403	42319.77	16442.85	30552.63	103684.48	1609.81	231426.98	15545.3
4	ER403	126413.43	9904.99	17900.9	68260.15	15603.56	161358.53	27269.65
4	ER401	32233.49	14918.35	11551.41	17454.37	2442.26	143207.34	7170.85
4	ER401	37196.48	4775.15	13768.21	17117.57	571.75	121886.84	0
4	ER401	92555.36	13184.84	28016.7	27325.66	737.59	137986.95	0
5	ER502	85132.04	16086.93	21749.2	31944.48	1156.15	117067.6	9797.82
5	ER501	124469.12	12301.08	10420.71	80308.78	7909.47	214712.38	40470.03
7	ER701	5514.82	14671.49	10429.42	64133.59	3960.98	472230.47	0
8	ER802	105762.54	13471.72	22859.74	76774.83	0	209895.36	22653.3
8	ER802	39987.98	10887.35	11027.98	27019.91	0	279105.47	0
8	ER802	90269.16	3511.04	12837.41	47608.84	4696.76	127386.49	26396.95
8	ER803	2151.02	10067.37	3636	33760.49	0	371401.97	0
8	ER803	5593.26	7792.84	6491.61	38315.71	1145.98	307646.63	8384.78
9	ER902	42870.51	21565.45	22885.27	37310.41	714.66	193869.33	0
9	ER902	5912.62	4300.71	33077.05	38622.18	0	432026.09	7693.94
9	ER901	3769.98	626.3	34344.23	15468.17	0	123127.98	0

Figure 22. ACF diagram of hXRF analyses. Packsaddle Schist points are represented by the purple squares, Town Mountain Granite points are represented by pink circles. Compositions include calcareous (yellow), mafic (blue), quartzofeldspathic (orange), and pelitic (purple) protoliths.

DISCUSSION

The variation in dip of the foliation in the Packsaddle Schist from a southeast to northwest dip is consistent with broad folding (Figure 12), which has been observed in the metamorphic country rock near ERSNA (Hutchinson, 1956). A lack of consistency in the orientation of schist foliation is expected in an area that has been subjected to multiple deformation events (Mosher et al., 2008).

The surfaces of the discordant contacts between the Town Mountain Granite and Packsaddle Schist within each site also vary from a southeast dip to a northeast dip. Contacts tend to strike at an angle to the schist foliation at each site (Table 1, Figure 12). This suggests that, at certain scales, the Town Mountain Granite cross cuts the established foliations of the country-rock in a discordant manner. This could suggest a relatively shallow emplacement (<10 km, <3 kbar) of the intruding body into the Packsaddle Schist at these sites.

Small granitic lenses within the Packsaddle Schist have a similar appearance to the Town Mountain granitoids, but they are folded and deformed concordantly with the schist, suggesting that they are possibly pre-tectonic or

syntectonic migmatites (Figure 11B). A post-tectonic granitic intrusion is expected to be undeformed or weakly deformed. It is possible, but unlikely, that these are lenses of the post-tectonic Town Mountain Granite intrusion that intruded concordantly into previously deformed portions of the Packsaddle Schist. Another possibility is that these granitic stringers represent the oldest stage of Town Mountain Granite intrusion (1119-1118 Ma), which were deformed in the final stages of orogenesis (Mosher et al., 2008).

Most sites within the study area show evidence of contact gradation. The observation of injection at multiple sites (Figure 11D, Figure 11F) suggests mechanical intrusion of magma into the country rock at brittle conditions. Evidence of permeation throughout the study area (Figure 11C, Figure 11E, Figure 11F) suggests magmas intruded at more ductile conditions (Winter, 2013, p. 78). Evidence for both gradational styles could be indicative of variable emplacement depths of the Enchanted Rock Batholith. It is more likely that P - T conditions varied during emplacement of the batholith; an initial shallow intrusion (<10km) injected the schist at brittle conditions, but the boundary became hotter after subsequent shallow intrusions, resulting in permeation.

The three types of granitoids described in this study (quartz-rich granitoid, granodiorite, and granite) are consistent with a previous map of the Enchanted Rock batholith that identified similar rock-types in the southeast corner of the batholith; Hutchinson (1956) referred to what this study classifies as “granite” in

some localities as both monzogranite and leucogranite. The different magma compositions observed in this area may have been produced through fractional crystallization of the same magma, or from multiple intrusions of magmas of different compositions representing different degrees of partial melting and/or multiple sources. Both explanations are compatible with previous interpretations of the Town Mountain Granite magma deriving from the partial melting of older, juvenile tonalitic-granodioritic crust with depleted mantle contamination (Smith et al., 2010).

The variation of metamorphic minerals and textures in the Packsaddle Schist is consistent with multiple metamorphic events, as suggested by prior studies of the Llano uplift (Mosher et al., 2008, Carlson et al., 1986, Carlson et al., 2007). The presence of biotite throughout the metamorphic rocks is indicative of the widespread amphibolite-facies metamorphic event, while the presence of chlorite in some samples suggests lower P - T conditions, consistent with contact metamorphism. The differences in degree of foliation observed in hand sample is most likely due to differences in bulk composition of the metamorphic protoliths.

In thin section, the Packsaddle Schist typically displays strong foliation (Figure 14, Figure 17, Figure 18); one sample displays both a biotite foliation and non-foliated chlorite (Figure 19). This is consistent with the low- P static recrystallization overprint event associated with the Town Mountain Granite intrusion. An aluminosilicate porphyroblast surrounded by chlorite (Figure 20)

appears in the same sample. This porphyroblast could be an andalusite grain, which would indicate low- P metamorphism, or a kyanite from the early high or moderate- P regional metamorphism that has undergone retrograde metamorphism. The chlorite rim on the porphyroblast most likely formed during the static recrystallization of biotite and the aluminosilicate.

Microstructures within both the Town Mountain Granite and country rock reveal information about the rocks' cooling histories. The Packsaddle Schist contains equigranular and polygonal quartz grain boundaries, which is suggestive of a long period of annealing at high temperatures following deformation and metamorphism (Holness et al., 2011). These samples appear to have reached textural equilibrium, wherein crystals annealed at high temperatures over long periods of time, giving rise to polygonal grains and quartz grain boundaries that meet at triple junctions with dihedral angles of $\sim 120^\circ$ (Holness et al., 2011). This may have been achieved by heating from the intrusion without any significant deformation allowing for uniform recrystallization of the country rock. By contrast, petrographic analyses of the Town Mountain Granite reveal interlobate grains, suggesting very little annealing after crystallization. The granite was not able to attain textural equilibrium, suggesting that it did not spend an extended period at high temperatures (Holness et al. 2011).

Myrmekite is a wormy intergrowth of quartz in plagioclase. It can form during the late stages of crystallization during the simultaneous growth of quartz and plagioclase with a volatile phase, or myrmekite can develop from the metasomatic replacement of an alkali feldspar (Abart et al., 2014). It is possible that the Town Mountain Granite was exhumed shortly after its intrusion into the Packsaddle Schist, leading to cooling which coincided with metasomatism of the feldspars leading to the textures described above. The metasomatism may have been caused by fluids present within subsequent intrusions into the igneous grains, or by the release of volatiles from the metamorphic rocks in contact with the heat of intrusion.

XRF analysis indicates that the Packsaddle Schist samples likely have mafic protoliths, as they plot closely to the F corner of the ACF diagram (Figure 22). The more strongly foliated Packsaddle Schist samples are slightly more mafic in composition, while the weakly foliated samples are more aluminum-rich. This compositional variation may explain the differences in foliation observed in the Packsaddle Schist.

The Town Mountain Granite plots across the fields associated with pelitic, quartzofeldspathic, and mafic protoliths. The samples classified as granodiorite (ER401, ER501, ER502) plot more closely to the F corner of the ACF diagram (Figure 22), which is consistent with granodiorites containing more Fe and Mg than the average granitoid. Three samples classified as granite and quartz-rich

granitoid plot within the quartzofeldspathic field, as is expected with felsic igneous rocks. However, six samples of granite and quartz-rich granitoid plot near the pelitic field (Figure 22), which is not expected for granitoids. The high Al recorded in these samples could have to do with selective measuring of spots along alkali feldspar grains in these granitoids samples.

CONCLUSION

Within the study area, the exposed gradational contact between the Town Mountain Granite and Packsaddle Schist contains evidence of injection, permeation, and a combination of the two. The three styles of gradational contacts observed suggests a complex emplacement history, possibly related to changing temperature conditions during the intrusion period.

The study area was subjected to early high-*P* regional metamorphism that formed the primary foliation observed in the schist. The equilibrium textures observed in the Packsaddle Schist suggest a relatively long annealing time after the initial metamorphism prior to and/or during the intrusion of the Town Mountain Granite. When the Town Mountain Granite was emplaced, it was accompanied by static metamorphism, as indicated by non-foliated chlorite overprinting the well-aligned micas, and by the presence of an andalusite or retrograded kyanite porphyroblast. Myrmeketic textures suggest metasomatism of the feldspars within the granite shortly after the intrusion, possibly related to the release of volatiles from the country rock due to the heat from the intrusion, or volatiles from the intrusion itself. The poor textural equilibrium and microstructures present within the Town Mountain Granite suggest a short annealing time for the igneous minerals post-intrusion. This could be the result of

exhumation of the Enchanted Rock Batholith shortly after intrusion, possibly due to uplift and erosion.

Future thermochronologic studies of the batholith could further understanding of the timing of exhumation following the intrusion into the Llano uplift basement rock. More descriptions and analysis of the entire contact and the gradational style between the Enchanted Rock Batholith and the surrounding metamorphic formations could also help determine if the entire emplacement of the batholith features both injection and permeation. Further petrographic analysis of the microstructures within the Town Mountain Granite at other parts of the batholith could reveal more information about the conditions of the melt at the time of intrusion, such as the degree of annealing based on textural maturity. Geochronologic analyses of the deformed granitic lenses observed within the Packsaddle Schist could also verify whether they are partial melt of the schist, or later granitoids concordantly intruding in previously deformed rocks.

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APPENDICES

Appendix A. Table of hXRF data of major elements without errors from all samples used for analysis in parts per million.

Site	Sample	Fe	Ca	K	Al	P	Si	Mg
1	ER102	48074.71	21242.03	12458.1	12310.54	260.21	149430.94	5242.8
1	ER102	16002.64	61782.59	30289.69	138840.17	14394.77	547954	59569.14
1	ER101	80158.83	2908.05	32591.88	30853.8	1800.4	124289.61	0
1	ER101	106408.23	4302.06	29684.73	26057.25	1740.13	128368.62	12918.41
2	ER201	13454.09	27313.93	6454.89	39527.34	5325.09	145835.11	11217.52
2	ER201	35105.98	28793.74	12510.21	74802.49	3204.93	230171.44	8951.93
3	ER305	10748.94	9652.7	4843.55	45245	6416.06	318643.81	8833.43
3	ER301	1171.38	8881.57	12213.3	53768.59	11193.4	352256.81	0
3	ER301	732.32	3504.74	7343.91	42181.6	12609.86	317602.19	0
3	ER304	103187.9	4425.35	8830.67	43856.32	249.98	167602.09	7090.15
3	ER304	75011.89	1039.06	19702.5	63875.39	0	325895.22	18973.37
3	ER304	87805.94	4077.05	26124.42	141694.67	1943.9	261636.3	13940.12
4	ER402	24124.71	29030.77	11245.09	67620.63	2392.49	321819.81	12368.53
4	ER402	21412.34	14671.68	22540.09	28221.74	2081.59	200519.02	12074.45
4	ER403	42319.77	16442.85	30552.63	103684.48	1609.81	231426.98	15545.3
4	ER403	126413.43	9904.99	17900.9	68260.15	15603.56	161358.53	27269.65
4	ER401	32233.49	14918.35	11551.41	17454.37	2442.26	143207.34	7170.85
4	ER401	37196.48	4775.15	13768.21	17117.57	571.75	121886.84	0
4	ER401	92555.36	13184.84	28016.7	27325.66	737.59	137986.95	0
5	ER502	85132.04	16086.93	21749.2	31944.48	1156.15	117067.6	9797.82
5	ER501	124469.12	12301.08	10420.71	80308.78	7909.47	214712.38	40470.03
7	ER701	5514.82	14671.49	10429.42	64133.59	3960.98	472230.47	0
8	ER802	105762.54	13471.72	22859.74	76774.83	0	209895.36	22653.3
8	ER802	39987.98	10887.35	11027.98	27019.91	0	279105.47	0
8	ER802	90269.16	3511.04	12837.41	47608.84	4696.76	127386.49	26396.95
8	ER803	2151.02	10067.37	3636	33760.49	0	371401.97	0
8	ER803	5593.26	7792.84	6491.61	38315.71	1145.98	307646.63	8384.78
9	ER902	42870.51	21565.45	22885.27	37310.41	714.66	193869.33	0
9	ER902	5912.62	4300.71	33077.05	38622.18	0	432026.09	7693.94
9	ER901	3769.98	626.3	34344.23	15468.17	0	123127.98	0

Appendix B. Table of hXRF data from all samples of elements Mo, Zr, Sr, U, Rb, and Th in parts per million.

Sample	Mo	Mo Error	Zr	Zr Error	Sr	Sr Error	U	U Error	Rb	Rb Error	Th	Th Error
ER101	0	1.9	149.21	2.43	155.73	2.28	<LOD	4.14	73.26	1.94	<LOD	2.3
ER101	5.16	2.18	347.68	5.25	172.4	3.39	<LOD	300000	68.63	1.66	<LOD	300000
EE101	3.3	1.72	327.63	4.07	65.36	1.74	<LOD	4.55	87.2	1.53	<LOD	9.8
ER102	0	2.27	236.22	2.99	288.62	3.03	5.52	3.03	96.59	2.2	<LOD	7.95
ER102	0	2.22	158.65	2.54	153.53	2.31	<LOD	3.61	49.52	1.69	3.38	1.52
ER102	0	300000	<LOD	300000	643.45	9.99	12342.25	128.28	<LOD	300000	<LOD	300000
ER201	0	2.53	225.39	3.46	580.23	4.61	79.14	4.99	38.55	1.02	88.51	7.35
ER201	0	2.29	74.58	2.77	742.39	5.13	69.6	4.76	18.65	1.57	53.94	7.04
ER201	0	2.53	124.92	3.06	574.13	4.77	126.94	5.96	34.08	1.06	127.96	8.15
ER201	0	2.29	166.41	2.98	586.02	4.35	75.47	4.59	65.24	2.11	89.18	6.87
ER301	0	1.95	160.21	2.31	218.7	2.41	28.62	2.99	28.51	1.3	53.23	5.27
ER301	0	2.42	322.6	3.4	151.13	2.32	24.94	3.28	24.93	1.42	105.42	6.69
ER304	0	2.67	356.37	4.39	89.07	2.05	<LOD	5.27	34.2	1.01	18.5	6.66
ER304	0	1.5	218.33	3.05	113.19	2.03	<LOD	3.37	13.7	1	<LOD	7.32
ER304	0	2.02	186.3	2.75	152.1	2.35	<LOD	3.93	62.57	1.91	5.89	1.83
ER304	0	2.28	180.97	2.6	72.81	1.67	<LOD	3.75	56.75	1.81	<LOD	7.53
ER304	0	1.69	3.19	1.06	99.21	1.61	<LOD	3.17	2.32	0.68	3.41	1.17
ER304	2.4	1.44	241.38	3.12	76.07	1.82	<LOD	4.26	73.17	2.14	<LOD	2.83
ER305	0	2.5	192.57	3	157.69	2.57	14.97	3.35	53.28	1.97	33.55	6.1
ER305	0	1.76	71.75	1.6	104	1.63	10.76	2.33	17.02	1	18.51	4.38
ER401	4.1	1.67	317.65	3.5	298.14	3.21	9.66	3.15	51.56	1.78	10.38	1.8
ER401	0	2.35	190.81	2.98	364.15	3.56	5.55	3.19	65.3	1.96	6.07	1.74
ER401	0	2.93	472.27	4.57	299.68	3.57	<LOD	5.59	53.55	1.15	25.21	6.57
ER402	0	2.07	152.83	2.7	554.02	3.98	19.12	3.27	39.03	1.52	18.11	5.57
ER402	0	2.25	135.11	2.75	467.36	3.97	13.52	3.37	45.87	1.72	<LOD	2.21
ER403	0	2.14	180.58	2.66	265.17	2.86	30.73	3.39	56.32	1.8	60.08	5.82
ER403	0	2.03	502.92	5.38	238.49	3.31	13.29	4.15	60.46	1.29	61.48	7.55
ER501	0	1.5	93.07	2.17	64.12	1.6	8.28	3.32	35.91	1	16.05	5.62
ER502	0	300000	217.32	3.62	228.54	3.36	11.91	4.17	55.64	1.29	25.88	7.04
ER701	0	2.04	214.32	2.56	189.97	2.27	13.35	2.7	47.7	1.51	13.95	1.6
ER802	4.98	1.62	357.38	3.93	115.06	2.06	<LOD	6.63	95.33	1.46	20.59	5.97
ER802	2.41	1.13	126.28	2.14	102.96	1.6	<LOD	3.62	59.62	1.69	8.25	4.5
ER802	0	300000	207.23	3.57	36.9	1.49	96.37	6.03	55.03	1.4	141.09	8.8
ER802	0	2.71	364.65	3.72	88.17	1.93	47.32	4.26	69.88	1.26	75.3	6.53
ER803	0	1.83	163.04	2.07	74.61	1.39	13.05	2.31	7.5	0.83	20.36	1.57
ER803	0	2.1	337.59	2.92	52.42	1.26	18.5	1.94	5.28	0.89	26.57	1.79
ER901	0	300000	204.63	3.57	69.25	1.99	<LOD	300000	92.93	1.77	<LOD	300000

Appendix B (continued).

Sample	Mo	Mo Error	Zr	Zr Error	Sr	Sr Error	U	U Error	Rb	Rb Error	Th	Th Error
ER902	0	3.49	213.5	3.46	270.93	3.69	533.3	11.56	348.24	5.82	380.71	7.79
ER902	2.15	1.24	261.24	2.73	126.39	1.89	7.49	2.66	97.55	2.01	10.19	1.56

Appendix C. Table of hXRF data from all samples of elements Pb, Au, Se, As, Hg, and Zn in parts per million.

Sample	Pb	Pb Error	Au	Au Error	Se	Se Error	As	As Error	Hg	Hg Error	Zn	Zn Error
ER101	18.58	2.52	<LOD	2.28	<LOD	1.98	3.04	1.86	<LOD	4.99	68.38	4.91
ER101	11.67	5.69	<LOD	300000	<LOD	300000	7.9	4.79	<LOD	300000	137.97	11.19
EE101	<LOD	5.85	<LOD	5.96	<LOD	2.14	11.92	3.54	<LOD	300000	234.26	10.27
ER102	13.2	2.35	<LOD	2.29	<LOD	1.97	<LOD	4.14	<LOD	5.01	100.96	5.5
ER102	6.09	2.1	<LOD	2.34	<LOD	2.01	<LOD	2.37	<LOD	5.26	59.65	4.88
ER102	1799.73	41.94	897.47	51.67	997.16	21.13	283.85	38.05	<LOD	300000	3192.98	60.6
ER201	31.01	3.21	<LOD	2.66	<LOD	2.27	10.44	3.72	13	4.06	112.7	6.31
ER201	16.52	2.62	<LOD	2.49	<LOD	2.1	<LOD	2.86	<LOD	5.5	32.18	4.43
ER201	23.98	3.11	<LOD	2.87	<LOD	2.4	11.47	3.72	24.87	4.4	82.35	5.96
ER201	26.41	2.85	<LOD	2.42	<LOD	2.02	7.24	3.31	12.53	3.64	78.85	5.22
ER301	25.34	2.44	<LOD	1.99	<LOD	1.7	<LOD	2.6	8.77	2.91	16.15	3.2
ER301	20.18	2.68	<LOD	2.41	<LOD	2.06	<LOD	4.94	6.89	3.57	13.62	3.77
ER304	20.98	5.09	<LOD	6.23	<LOD	2.3	19.63	4.5	<LOD	300000	160.18	9.24
ER304	<LOD	5.96	<LOD	5	<LOD	1.62	13.13	3.4	<LOD	5.88	148.94	7.86
ER304	56.89	3.71	<LOD	2.49	<LOD	2.09	15.05	4.32	7.02	3.69	83.58	5.48
ER304	24.65	2.8	<LOD	2.42	<LOD	2.09	6.38	3.29	7.5	3.58	104.64	5.78
ER304	18.7	2.11	<LOD	1.88	<LOD	1.55	<LOD	2.28	<LOD	4.01	11.49	2.93
ER304	63.65	4.09	<LOD	2.66	<LOD	2.33	20.95	4.69	7.48	4.02	132.3	6.76
ER305	19.11	2.86	<LOD	2.75	<LOD	2.34	<LOD	5.04	14.82	4.33	78.54	5.89
ER305	11.82	1.9	<LOD	1.86	<LOD	1.54	<LOD	2.1	7.1	2.73	29.71	3.34
ER401	21.17	2.72	<LOD	2.4	<LOD	2.05	<LOD	2.98	<LOD	5.39	52.74	4.82
ER401	25.87	2.88	<LOD	2.4	<LOD	2.04	<LOD	3.13	<LOD	5.44	68.6	5.18
ER401	29.73	3.4	3.62	1.96	<LOD	2.47	9.32	3.77	<LOD	6.39	173.45	7.88
ER402	17.23	2.35	2.28	1.48	<LOD	1.86	<LOD	2.58	5.17	3.12	34.69	3.91
ER402	26.03	2.83	<LOD	2.39	<LOD	2.02	<LOD	3	5.47	3.48	24.15	4.07
ER403	18.6	2.48	<LOD	2.23	<LOD	1.88	<LOD	2.64	11.76	3.36	76.26	4.92
ER403	15.64	5	<LOD	5.79	<LOD	2.05	20.26	4.25	13.23	4.81	183.63	9.34
ER501	<LOD	9.15	<LOD	5.04	<LOD	1.75	16.74	3.58	12.03	4.21	229.02	9.43
ER502	<LOD	300000	<LOD	300000	<LOD	300000	9	3.59	<LOD	300000	143.83	9.14

Appendix C (continued).

Sample	Pb	Pb Error	Au	Au Error	Se	Se Error	As	As Error	Hg	Hg Error	Zn	Zn Error
ER701	24.94	2.46	<LOD	2.02	<LOD	1.71	<LOD	2.64	5.82	2.92	19.29	3.31
ER802	<LOD	6.16	<LOD	4.75	<LOD	1.5	11.89	3.3	<LOD	6.64	160.38	8.16
ER802	16.38	2.29	2.77	1.46	<LOD	1.8	4.14	2.62	<LOD	4.62	60.02	4.45
ER802	8.72	5.13	<LOD	300000	<LOD	300000	17.85	4.18	<LOD	300000	170.15	10.03
ER802	11.42	2.6	<LOD	2.63	<LOD	2.23	13.74	3.12	16.07	4.14	130.25	6.67
ER803	22.9	2.23	<LOD	1.78	<LOD	1.53	<LOD	2.4	<LOD	3.79	8.32	2.72
ER803	27.24	2.47	<LOD	1.92	<LOD	1.64	<LOD	2.64	6.02	2.74	15.35	3.08
ER901	21.33	4.92	<LOD	300000	<LOD	300000	<LOD	300000	<LOD	300000	<LOD	10.89
ER902	462.02	12.44	253.22	13.16	139.32	5.05	41.59	7.2	205.95	10.1	557.27	15.48
ER902	21.24	2.38	<LOD	2.08	<LOD	1.75	<LOD	2.57	8.99	2.98	31.02	3.62

Appendix D. Table of hXRF data from all samples of elements W, Cu, Ni, Co, Fe, and Mn in parts per million.

Sample	W	W Error	Cu	Cu Error	Ni	Ni Error	Co	Co Error	Fe	Fe Error	Mn	Mn Error
ER101	<LOD	22.03	12.33	7.26	58.55	9.12	<LOD	80.63	42601.98	618.22	609.96	33.19
ER101	<LOD	300000	<LOD	300000	134.79	51.26	<LOD	300000	80158.83	1243.12	<LOD	300000
EE101	<LOD	42.4	<LOD	22.37	<LOD	97.01	<LOD	179.94	106408.23	1190.17	<LOD	5480.34
ER102	<LOD	21.72	<LOD	10.44	65.45	9.02	<LOD	85.49	48074.71	733.76	1274.09	41.81
ER102	<LOD	22.85	41.03	8.06	60.27	9.35	<LOD	73.05	34578.69	617.14	939.88	38.34
ER102	4271.21	192.78	5155.48	85.97	1480.62	74.04	2252.89	185.44	16002.64	1286.87	<LOD	300000
ER201	<LOD	25.86	15.52	8.45	119.16	11.18	519.97	63.98	46397.56	833.35	1272.35	45.64
ER201	<LOD	23.49	<LOD	12.07	<LOD	13.68	139.72	32.2	13454.09	619.85	384.57	30.14
ER201	<LOD	26.32	33.8	9.35	67.44	11.58	1334.78	63.25	36362.74	861.55	1093.32	44.56
ER201	<LOD	22.79	15.8	7.49	84.5	9.83	624.98	52.47	35105.98	708.13	812.53	36.52
ER301	<LOD	17.79	11.6	5.92	10.97	7.07	65.39	13.15	1171.38	28.21	187.83	21.77
ER301	<LOD	22.34	<LOD	11.17	<LOD	12.55	64.66	13.91	732.32	27.33	169.6	24.61
ER304	<LOD	43.27	<LOD	34.42	72.45	40.94	<LOD	183.88	103762.24	924.57	<LOD	3449.15
ER304	<LOD	34.33	22.16	12.63	<LOD	72.98	<LOD	154.83	103187.9	955.84	<LOD	4260.3
ER304	<LOD	23.72	16.92	7.83	77.92	9.93	<LOD	99.15	56445.49	734.93	1013.65	40.91
ER304	<LOD	23.05	21.42	7.55	112.67	10.05	<LOD	116.37	75011.89	821.04	1031.52	41.48
ER304	18.8	11.43	8.79	5.47	50.79	7.01	35.96	12.69	1401.99	29.15	176.79	20.77
ER304	<LOD	26.22	<LOD	12.71	118.74	11.34	<LOD	138.11	87805.94	951.85	1637.96	52.11
ER305	<LOD	27.49	19.22	9.09	135.52	11.76	387.37	59.54	38734.82	838.3	537.74	36.62
ER305	<LOD	17.02	<LOD	8.15	50.02	7.07	127.35	23.26	10748.94	499.6	212.04	21.39
ER401	<LOD	23.38	12.45	7.8	17.3	9.19	<LOD	71.19	32233.49	607.24	576.79	33.34

Appendix D (continued).

Sample	W	W Error	Cu	Cu Error	Ni	Ni Error	Co	Co Error	Fe	Fe Error	Mn	Mn Error
ER401	<LOD	23.63	12.79	7.83	54.71	9.62	<LOD	77.33	37196.48	674.76	494.96	32.75
ER401	<LOD	28.09	40.07	9.67	82.02	11.83	<LOD	151.03	92555.36	1048.84	1263.01	50.49
ER402	<LOD	19.98	18.56	6.72	75.54	8.53	<LOD	56	24124.71	591.62	453.58	28.66
ER402	<LOD	22.23	56.92	8.49	16	9	<LOD	57.12	21412.34	631.33	580.13	32.89
ER403	<LOD	29.64	18.73	6.88	101.8	9.34	557.96	54.97	42319.77	682.98	868.35	35.97
ER403	<LOD	40.8	<LOD	33.66	195.73	40.72	<LOD	179.61	126413.43	991.25	3800.92	2124.86
ER501	<LOD	36.84	75.85	13.5	213.61	34.38	<LOD	155.61	124469.12	792.58	<LOD	2496.5
ER502	<LOD	300000	<LOD	300000	151.35	41.77	<LOD	300000	85132.04	1189.21	<LOD	300000
ER701	<LOD	18.4	10.52	6.02	46.75	7.58	59.34	21.51	5514.82	56.44	255.18	23.45
ER802	<LOD	36.88	31.27	14	109.97	38.07	250.54	116.92	105762.54	916.59	<LOD	3560.39
ER802	<LOD	19.96	22.39	6.71	56.53	8.31	<LOD	73.05	39987.98	612.12	601.25	31.29
ER802	<LOD	300000	<LOD	300000	536.19	49.1	2932.87	138.06	90269.16	963.03	6637.29	2530.99
ER802	44.98	23.3	21.03	8.44	202.43	12.43	1055.95	94.87	86089.86	775.05	2244.61	58.39
ER803	<LOD	15.91	<LOD	7.79	38.31	6.7	<LOD	20.63	2151.02	34.26	152.2	19.8
ER803	<LOD	17.19	22.64	5.89	64.4	7.38	<LOD	29.97	5593.26	55.72	173.54	21.46
ER901	<LOD	300000	<LOD	300000	<LOD	300000	<LOD	300000	3769.98	901.86	<LOD	300000
ER902	649.11	33.19	697.34	19.82	341.67	15.91	877.74	73.83	42870.51	816.03	1360.17	54.38
ER902	<LOD	18.45	16.83	6.25	56.91	7.79	50.52	22.2	5912.62	58.79	243.84	23.32

Appendix E. Table of hXRF data from all samples of elements Nd, Pr, Ce, La, Ba, and Sb in parts per million.

Sample	Nd	Nd Error	Pr	Pr Error	Ce	Ce Error	La	La Error	Ba	Ba Error	Sb	Sb Error
ER101	812.21	80.48	491	59.38	338.33	50.79	339.06	49.05	960.22	31.26	52.83	8.86
ER101	1704.34	167.28	973.36	120.31	705.96	103.39	695.71	97.19	1778.43	59.63	68.01	14.95
EE101	986.96	100.82	614.92	74.29	395.5	63.12	370.83	60.28	1019.85	50.74	<LOD	24.05
ER102	749.76	65.5	417.37	47.89	284.26	41.15	282.78	39.58	865.97	33.39	66.99	9.88
ER102	1190.09	102.11	748.93	75.19	452.27	63.62	497.61	61.74	672.19	25.31	42.21	7.54
ER102	5182.99	508.4	3498.43	367.37	2215.43	303.9	2083.37	287.32	2525.89	217.28	<LOD	86
ER201	1032.37	91.55	621.16	67.09	404.48	56.81	431.44	54.61	1653.07	39.72	53.82	9.85
ER201	547.27	85.88	320.41	63.78	211.37	54.14	243.37	53.29	1148.31	39.26	68.75	10.98
ER201	588.37	96.44	291.16	71.36	257.23	59.65	232.43	57.99	3792.2	59.22	63.26	11.43
ER201	852.43	80.23	571.1	59.53	366.1	50.65	360.07	48.61	1150.92	34.13	66	9.47
ER301	558.78	64.14	371.7	47.95	255.65	40.93	287.09	40.07	899.76	26.5	53.84	7.62
ER301	589.3	91.81	408.78	68.8	243.87	58.13	259.69	57.16	922.75	31.97	73.46	9.43
ER304	1213.03	109.42	726.04	79.86	525.23	68.43	535.19	64.75	1625.63	58.23	<LOD	19.84

Appendix E (continued).

		Nd			Ce			Ba			Sb	
Sample	Nd	Error	Pr	Pr Error	Ce	Error	La	La Error	Ba	Error	Sb	Error
ER304	1054.68	94.41	677.07	69.7	424.26	59.41	444.14	57.3	388.16	42.92	<LOD	18.19
ER304	660.36	81.91	479.07	61.55	281.28	51.06	294.51	49.66	2656.11	45.75	54.74	9.84
ER304	775.04	79.02	483.79	58.7	341.01	49.56	333.76	47.83	2123.81	36.88	35.33	8.22
ER304	606.25	57.27	404.61	42.74	242.08	36.37	251.76	35.54	458.78	21.27	47.04	6.79
ER304	1188.32	103.79	751.25	76.4	501.26	64.87	533.34	62.27	1401.18	34.58	43.14	8.8
ER305	1423.59	122.89	940.38	90.55	532.09	75.9	540.56	73.14	833.99	28.48	53.08	8.31
ER305	547.68	52.17	371.37	38.96	226.21	33.18	230.91	32.22	579.73	24.27	26.27	7.21
ER401	532.63	80.95	373.86	60.73	254.91	51.75	269.09	50.48	996.38	34.4	37.58	9.44
ER401	578.29	67.79	367.87	50.31	227.8	42.72	230.78	41.3	1453.32	47.18	76.73	12.61
ER401	919.97	90.88	611.3	67.35	500.14	58.69	457.84	55.02	2061.42	51.09	77.36	12.38
ER402	765.91	73.25	487.53	54.31	270.18	45.7	310.86	44.75	877.91	27.71	43.38	7.87
ER402	587.68	84.74	368.75	63.17	242.23	53.24	269.98	52.24	1873.23	42.53	85.9	10.7
ER403	801.69	63.08	461.55	46.17	359.58	40.05	347.12	38.06	1233.45	32.85	43.79	8.63
ER403	1301.04	105.3	772.92	76.71	695.26	67.99	546.62	62.17	1359.16	53.53	<LOD	19.03
ER501	1112.54	91.51	690.71	67.21	356.61	56.09	406.89	54.34	912.06	44.72	<LOD	16.67
ER502	1295.27	113.28	835.4	83.02	550.28	70.5	503.65	66.05	2609.15	62.43	83.14	14.19
ER701	837.58	69.96	532.29	51.76	486.77	45.54	414.85	42.9	868.35	25.03	41.68	7.09
ER802	1152.21	96.1	698.63	70.42	535.7	61.02	455.39	57.18	1105.25	47.93	<LOD	17.76
ER802	633.44	66.76	451.66	50.02	271.23	42.43	244.69	40.96	497.12	32.46	<LOD	13.01
ER802	1322.14	120.93	812.23	88.2	467.63	74.08	484.1	70.71	1667.19	52.06	75.09	13.32
ER802	956.55	80.77	606.56	59.63	397.17	50.84	394.96	48.65	1122.95	32.26	27.9	8.46
ER803	428.6	51.74	290.86	38.86	193.67	33.28	206.73	32.72	414.89	20.4	43.41	6.55
ER803	556.67	55.28	364.87	41.25	203.36	34.95	208.28	34.29	435.56	20.84	47.03	6.67
ER901	857.09	127.86	481.42	93.58	432.35	81.43	290.07	76.55	1977.57	66.43	135.59	17.67
ER902	1314.52	126.71	791.42	92.69	501.08	78.51	506.3	75.78	768.9	29.12	50.18	8.59
ER902	685.56	68.09	445.33	50.68	370.51	43.94	348.65	42.12	1072.28	27.87	43.94	7.58

Appendix F. Table of hXRF data from all samples of elements Sn, Cd, Ag, elements with an atomic number lower than 12 (Bal), Nb, and Y in parts per million.

Sample	Sn	Sn Error	Cd	Cd Error	Ag	Ag Error	Bal	Bal Error	Nb	Nb Error	Y	Y Error
ER101	30.62	5.94	17.36	6.95	13.23	5.17	643923.81	1004.42	6.57	1.11	<LOD	1.5
ER101	59.39	10.46	31.69	11.93	16.01	8.7	690882.13	1358.71	16.8	1.89	3.51	1
EE101	<LOD	25.03	<LOD	10.09	<LOD	7.25	675592.44	1117.98	13.82	1.45	<LOD	1.5
ER102	47.87	6.75	20.54	7.68	9.99	5.57	746933	752.93	8.13	1.14	<LOD	1.5
ER102	25.04	5.05	12.45	5.93	<LOD	6.39	359260.78	1468.06	3.28	1.13	3.58	1
ER102	<LOD	90.24	<LOD	45.36	<LOD	33.35	54628.8	3325.56	<LOD	12.29	29.76	1
ER201	36.84	6.71	15.95	7.7	9.1	5.65	646743.06	1191.93	<LOD	1.76	4.87	1

Appendix F (continued).

Sample	Sn	Sn Error	Cd	Cd Error	Ag	Ag Error	Bal	Bal Error	Nb	Nb Error	Y	Y Error
ER201	51.11	7.54	28.71	8.68	15.84	6.35	744700.88	920.18	<LOD	1.5	<LOD	1.5
ER201	41.58	7.83	21.93	8.97	15.99	6.75	754991.56	868	<LOD	1.5	1.94	1
ER201	33.21	6.28	20.83	7.36	14.3	5.46	594919.81	1214.58	<LOD	1.5	4.35	1
ER301	24.64	5.02	17.75	5.97	12.84	4.43	556672.38	1146.04	<LOD	1.5	<LOD	1.5
ER301	34.81	6.2	27.46	7.37	17.61	5.45	607478.88	1233.58	<LOD	1.5	2.33	1
ER304	<LOD	20.82	<LOD	10.38	<LOD	7.48	556197	1619.54	16.73	1.55	3.04	1
ER304	<LOD	19	<LOD	9.55	<LOD	6.77	654195.5	1079.68	7.33	1.23	1.79	1
ER304	35.85	6.7	15.91	7.68	9.13	5.66	631504.81	1094.14	6.36	1.21	4.91	1
ER304	28.49	5.64	12.99	6.54	<LOD	7.15	482083.66	1360.62	9.38	1.28	12.25	1
ER304	33.62	4.6	18.92	5.39	7.26	3.86	527707.94	1043.92	<LOD	1.5	<LOD	1.5
ER304	25.54	5.92	11.52	6.89	11.77	5.18	452276.88	1693.53	10.04	1.27	3.14	1
ER305	30.3	5.56	16.05	6.5	11.94	4.81	206121.3	1864.25	3.55	1.24	<LOD	1.5
ER305	18.7	4.87	<LOD	8.54	<LOD	6.22	595532.13	1028.18	<LOD	1.5	<LOD	1.5
ER401	24.38	6.36	16.99	7.57	9.28	5.51	759050.88	789.21	6.02	1.2	2.3	1
ER401	44.83	8.47	28.39	9.86	20.76	7.4	793312.63	685.02	7.29	1.2	1.52	1
ER401	54.77	8.51	28.76	9.69	21.94	7.32	685416.19	1013.76	12.9	1.41	3.07	1
ER402	27.78	5.31	13.09	6.19	10.26	4.59	528619.38	1246.49	<LOD	1.6	<LOD	1.5
ER402	50.15	7.2	26.69	8.23	18.87	6.16	694647.5	977.12	<LOD	1.5	<LOD	1.5
ER403	29.21	5.85	<LOD	9.95	<LOD	7.43	553924.5	1315.75	<LOD	1.5	2.09	1
ER403	<LOD	24.1	<LOD	10.1	<LOD	7.08	550302	1551.67	16.44	1.57	4.26	1
ER501	<LOD	18.13	<LOD	8.92	<LOD	6.57	500302.5	1595.26	2.39	1.25	3.33	1
ER502	58.89	9.8	20.32	10.82	22.29	8.4	710308	1079	10.54	1.53	3.48	1
ER701	24.86	4.76	11.62	5.57	8.42	4.1	422415.72	1241.53	<LOD	1.5	3.34	1
ER802	<LOD	18.93	<LOD	8.97	<LOD	6.64	526888	1448.67	22.68	1.45	3.23	1
ER802	<LOD	13.84	<LOD	6.82	<LOD	4.78	620922.88	929.59	16.03	1.08	<LOD	1.5
ER802	42.92	8.98	<LOD	15.07	22.92	7.94	658759.13	1351.56	7.73	1.77	4.7	1
ER802	22.29	5.76	13.26	6.81	<LOD	7.39	392179.16	1700.46	12.32	1.4	3.55	1
ER803	26.28	4.39	15.96	5.18	9.62	3.79	576321.44	998.85	<LOD	1.5	2.36	1
ER803	25.16	4.44	12.06	5.2	8.81	3.82	621353.25	1016.34	<LOD	1.5	7.38	1
ER901	78.77	11.87	47.9	13.48	33.48	10.22	816971.75	852.51	3.35	1.51	1.71	1
ER902	38.69	5.89	19.43	6.8	13.5	5.03	669816.38	1128.44	<LOD	2.05	<LOD	1.5
ER902	27.48	5.11	14.46	5.98	10.2	4.42	469276.72	1191.83	3.17	1.04	3.95	1

Appendix G. Table of hXRF data from all samples of elements Bi, Cr, V, Ti, Ca, and K in parts per million.

Sample	Bi	Bi Error	Cr	Cr Error	V	V Error	Ti	Ti Error	Ca	Ca Error	K	K Error
ER101	<LOD	8.14	76.49	9.05	111.53	21.55	3990.24	77.9	5757.71	119.64	20308.66	446.83
ER101	<LOD	13.89	57.25	6.64	130.46	18.17	<LOD	11161.5	2908.05	81.55	32591.88	1021.88
EE101	<LOD	10.49	<LOD	1748.68	<LOD	4847.09	<LOD	9436.69	4302.06	785.47	29684.73	806.82
ER102	<LOD	8.63	83.5	8.92	89.89	20.73	4273.73	78.06	21242.03	696.43	12458.1	336.21
ER102	<LOD	8.33	90.62	8.96	91.51	19.51	3070.86	69.54	42291.27	1020.08	11391.1	286.92
ER102	3952.53	48.26	<LOD	2106.25	<LOD	6655.71	<LOD	21487.93	61782.59	2901.66	30289.69	1345.45
ER201	<LOD	12.23	74.2	9.5	109.26	25.11	4448.36	91.41	31532.26	1052.24	17282.11	476.32
ER201	<LOD	11.53	<LOD	6.39	<LOD	12.87	779.15	30.25	27313.93	681.21	6454.89	108.11
ER201	<LOD	13.56	14.26	6.05	86.96	18.78	2282.93	63.64	15994.59	788.15	25104.03	752.93
ER201	<LOD	11.28	55.53	8.61	80.89	21.85	3443.05	79.02	28793.74	847.55	12510.21	328.36
ER301	<LOD	8.6	35.89	5.37	<LOD	11.77	166.07	24.4	8881.57	96.98	12213.3	228
ER301	<LOD	11.37	33.7	3.94	<LOD	7.4	72.52	15.17	3504.74	56.57	7343.91	103.56
ER304	<LOD	11.31	<LOD	2036.9	<LOD	5809.74	<LOD	10462.49	2070.14	822.13	16219.81	540.4
ER304	<LOD	8.92	<LOD	1398.61	<LOD	3929.19	<LOD	7307.29	4425.35	604	8830.67	286.23
ER304	<LOD	9.01	67.66	8.05	100	20.63	2531.44	70.01	2054.38	79.89	19577	453.97
ER304	<LOD	8.17	151.39	15.69	239.43	42	7526.27	149.33	1039.06	111.7	19702.5	531.87
ER304	<LOD	6.48	<LOD	7.72	<LOD	11.21	108.89	22.15	7829.61	86.55	1619.6	61.13
ER304	<LOD	9	145.11	13.55	194.73	31.36	5954.52	113.59	4077.05	139.73	26124.42	814.24
ER305	<LOD	10.12	95.66	9.11	71.27	20.08	3301.28	72.99	18071.85	911.42	15089.73	565.23
ER305	<LOD	6.94	30.24	6.83	104.11	12.18	1070.92	37.74	9652.7	111.46	4843.55	110.51
ER401	<LOD	9.76	42.93	6.31	58.5	14.11	2240.83	50.5	14918.35	551.31	11551.41	273.74
ER401	<LOD	9.68	33.55	6.01	76.78	15.73	2905.37	57.31	4775.15	90.99	13768.21	326.26
ER401	<LOD	11.02	81.88	13.26	266.34	42.55	10733.79	159.43	13184.84	1030.32	28016.7	883.82
ER402	<LOD	8.91	<LOD	10.49	52.99	16.51	2231.56	59.24	29030.77	737.86	11245.09	190.75
ER402	<LOD	9.55	<LOD	7.42	38.65	13.65	1082.01	45.25	14671.68	553.27	22540.09	490.32
ER403	<LOD	9.48	72.8	14.09	228.33	39.53	7115.92	141.93	16442.85	918.53	30552.63	1004.32
ER403	<LOD	12.71	<LOD	2389.74	<LOD	6916.92	<LOD	13604.07	9904.99	1158.49	17900.9	674.44
ER501	<LOD	9.31	<LOD	1745.37	<LOD	5360.63	<LOD	8419.27	12301.08	865.83	10420.71	400.88
ER502	<LOD	11.97	82.74	9.99	126.19	27.64	5149.26	101.14	16086.93	1085.64	21749.2	866.48
ER701	<LOD	8.28	39.83	7.28	51.5	13.6	1525.41	46.54	14671.49	445.35	10429.42	235.52
ER802	<LOD	10.13	<LOD	2019.72	<LOD	5615.82	12667.36	7375.74	13471.72	1011.58	22859.74	686.32
ER802	<LOD	7.12	<LOD	742.34	<LOD	2314.55	<LOD	4682.34	10887.35	495.59	11027.98	260.76
ER802	<LOD	15.07	142.39	11.25	69.68	30.92	<LOD	11755.99	3511.04	109.35	12837.41	497.73
ER802	<LOD	11.01	360.58	20.59	195.71	48.84	9656.59	179.67	7042.61	204.52	24976.79	707.65
ER803	<LOD	7.28	<LOD	8.43	<LOD	11.09	203.83	22.7	10067.37	109.64	3636	94.77
ER803	<LOD	8.34	68.35	7.62	18.75	10.97	1036.54	37.67	7792.84	106.06	6491.61	131.49
ER901	<LOD	12.36	23.89	2.93	9.44	5.89	60.92	18.11	626.3	33.95	34344.23	948.19

Appendix G (continued).

Sample	Bi	Bi Error	Cr	Cr Error	V	V Error	Ti	Ti Error	Ca	Ca Error	K	K Error
ER902	614.5	13.55	75.08	10.46	129.51	24.46	3709.26	85.96	21565.45	1088.52	22885.27	795.99
ER902	<LOD	8.03	25.01	5.62	<LOD	15.77	875.28	36.02	4300.71	89.6	33077.05	520.22

Appendix H. Table of hXRF data from all samples of elements Al, P, Si, and Mg in parts per million.

Sample	Al	Al Error	P	P Error	Si	Si Error	Mg	Mg Error
ER101	30179.1	1084.47	1141.26	205.1	235154.08	3265	740.41	69.51
ER101	30853.8	1598.52	1800.4	253.98	124289.61	3175.54	300.79	113.64
EE101	26057.25	1188.74	1740.13	191.19	128368.62	2738.05	1708.03	90.12
ER102	12310.54	604.29	260.21	136.42	149430.94	2778.79	219.51	47.29
ER102	84102.55	2143.84	1169.47	312.66	450889.06	4584.24	<LOD	105.83
ER102	138840.17	7071.78	14394.77	938.62	547954	12129.91	2353.51	240.48
ER201	64742.62	1846.69	5723.27	255.14	151302.17	2902.36	979.23	77.64
ER201	39527.34	1308.37	5325.09	250.32	145835.11	2404.98	2186.05	98.4
ER201	26520.91	1100.64	2724	212.67	126606.12	3124.42	429.89	78.56
ER201	74802.49	1891	3204.93	237.02	230171.44	3505.28	146.2	67.05
ER301	53768.59	1281.77	11193.4	316.39	352256.81	3323.41	287.98	54.54
ER301	42181.6	1296.33	12609.86	390.08	317602.19	3671.68	268.33	79.97
ER304	92044.03	2681.69	1893.13	232.74	186121.56	4052.16	133.61	82.8
ER304	43856.32	1279.99	249.98	164.42	167602.09	2875.77	350.18	56.01
ER304	42362.76	1265.12	<LOD	277.79	230093.61	3531.04	990.38	69.31
ER304	63875.39	1685.12	<LOD	383.14	325895.22	5029.46	2223.81	84.88
ER304	17543.81	681.04	<LOD	342.05	440028.88	3689.58	1451.42	58.45
ER304	141694.67	3457.76	1943.9	253.39	261636.3	5535.5	2190.4	112.84
ER305	121530.52	4001.62	14067.3	657.41	544511.19	9109.45	1191.07	109.45
ER305	45245	1103.7	6416.06	252.09	318643.81	3377.74	504.3	50.85
ER401	17454.37	866.44	2442.26	202.82	143207.34	2170.19	217.5	72.67
ER401	17117.57	744.69	571.75	146.41	121886.84	2016.35	254.58	61.13
ER401	27325.66	1156.18	737.59	173.27	137986.95	3374.21	164.22	65.71
ER402	67620.63	1695.94	2392.49	245.02	321819.81	4159.72	1330.71	75.36
ER402	28221.74	1044.87	2081.59	208.43	200519.02	3157.1	<LOD	114.54
ER403	103684.48	2579.25	1609.81	209.47	231426.98	5538.24	567.68	69.16
ER403	68260.15	2248.76	15603.56	3003.11	161358.53	4113.39	248.84	74.15
ER501	80308.78	2293.17	7909.47	307.06	214712.38	3691.83	<LOD	112.74
ER502	31944.48	1404.94	1156.15	196.91	117067.6	3745.96	400.81	84.88

Appendix H (continued).

Sample	Al	Al Error	P	P Error	Si	Si Error	Mg	Mg Error
ER701	64133.59	1770.13	3960.98	320.47	472230.47	4441.77	471.83	64.99
ER802	76774.83	2178.35	<LOD	291.55	209895.36	4276.73	<LOD	96
ER802	27019.91	920.46	<LOD	279.08	279105.47	3386.77	<LOD	80.3
ER802	47608.84	1832.67	4696.76	273.59	127386.49	3278.09	1498.06	103.67
ER802	97239.76	2661.39	12980.25	444.97	329640.03	5495.03	1942.75	96.36
ER803	33760.49	892.63	<LOD	295.11	371401.97	3023.24	1692.78	57.75
ER803	38315.71	922.46	1145.98	181.89	307646.63	3083.39	419.32	44.66
ER901	15468.17	1079.27	<LOD	605.94	123127.98	2973.62	<LOD	186.13
ER902	37310.41	1394.15	714.66	210.53	193869.33	4942.59	<LOD	135.46
ER902	38622.18	1180.91	<LOD	596.74	432026.09	3714.89	1373.19	70.59

Appendix I. Table of hXRF data from all samples of elements Sc, Cs, Te, and Pd in parts per million.

Sample	Sc	Sc Error	Cs	Cs Error	Te	Te Error	Pd	Pd Error
ER101	<LOD	21.94	50.18	2.71	126.26	14.86	<LOD	8.84
ER101	16.87	10.01	72.76	4.69	164.58	25.17	<LOD	14.54
EE101	<LOD	20.12	64.29	3.72	161.55	20.24	<LOD	11.74
ER102	70.36	25.72	58.4	3.01	140.25	16.4	<LOD	9.71
ER102	106.18	30.47	44.36	2.31	105.94	12.67	<LOD	7.27
ER201	386.66	32.48	54.84	3.05	121.72	16.47	<LOD	9.65
ER201	205.02	16.65	53.15	3.3	152.36	18.3	<LOD	10.77
ER201	107.9	16.34	61.88	3.56	145.74	19.18	<LOD	11.2
ER201	435.72	31.62	56.92	2.88	135.24	15.68	9.88	6.28
ER301	132.42	13.4	47.24	2.31	122.1	12.71	<LOD	7.55
ER301	50.32	7.73	53.29	2.82	162.57	15.73	<LOD	9.01
ER304	<LOD	16.76	84.99	4.3	199.98	23.11	<LOD	12.74
ER304	39.98	17.28	82.67	3.18	228.13	17.58	15.25	6.86
ER304	<LOD	13.8	54.97	3.05	133.51	16.57	<LOD	9.93
ER304	<LOD	19.68	47.86	2.59	113.43	14.05	<LOD	8.28
ER304	18.47	11.45	43.16	2.05	116.2	11.38	<LOD	6.7
ER304	<LOD	24.93	45.28	2.71	100.18	14.71	<LOD	8.95
ER305	111.51	20.15	48.58	2.53	112.86	13.79	<LOD	8.21
ER305	110.49	15.69	34.33	2.22	72.82	12.1	<LOD	7.32
ER401	<LOD	21.85	38.73	2.89	107.38	15.96	<LOD	9.6
ER401	22.67	11.61	66.65	3.86	179.06	21.19	<LOD	12.04

Appendix I (continued).

Sample	Sc	Sc Error	Cs	Cs Error	Te	Te Error	Pd	Pd Error
ER401	<LOD	37.12	71.54	3.83	181.61	20.84	<LOD	12.08
ER402	158.99	28.49	44.8	2.41	114	13.27	10.03	5.38
ER402	44.93	13.23	62.06	3.21	176.96	17.74	16.23	7.16
ER403	123.83	34.9	44.78	2.66	101.29	14.44	<LOD	8.47
ER403	<LOD	44.52	58.19	3.46	127.73	18.65	<LOD	11.06
ER501	<LOD	57.5	49.15	3.05	117.25	16.62	10.75	6.76
ER502	<LOD	30.54	90.78	4.52	226.73	24.45	<LOD	13.41
ER701	89.8	18.54	43.51	2.18	100.02	11.87	<LOD	6.93
ER802	122.55	16.92	69.47	4.13	161.17	22.26	<LOD	13.05
ER802	100.54	26.73	40.64	2.64	92.54	14.38	<LOD	8.78
ER803	41.13	14.6	39.67	1.98	109.15	10.99	8.42	4.41
ER803	33.46	14.02	41.53	2.02	115.76	11.2	6.98	4.44
ER901	<LOD	4.83	95.92	5.31	308.26	29.82	<LOD	16.1
ER902	52.75	22.85	47.29	2.62	120.93	14.39	<LOD	8.57
ER902	<LOD	14.24	47.99	2.34	115.94	12.8	<LOD	7.5

VITA

After completing his work at Langham Creek High School, Houston, Texas, in 2014, Travis Galle entered the University of Texas at Austin in Austin, Texas. He received a degree of Bachelor of Science from the University of Texas at Austin in Austin in May 2018. In August 2018, he entered the Graduate School of Stephen F. Austin State University, and received the degree of Master of Science in December of 2020.

Permanent Address: 161018 Country Bend Rd.
Houston, TX 77095

Style manual designation

This thesis was typed by Travis Galle