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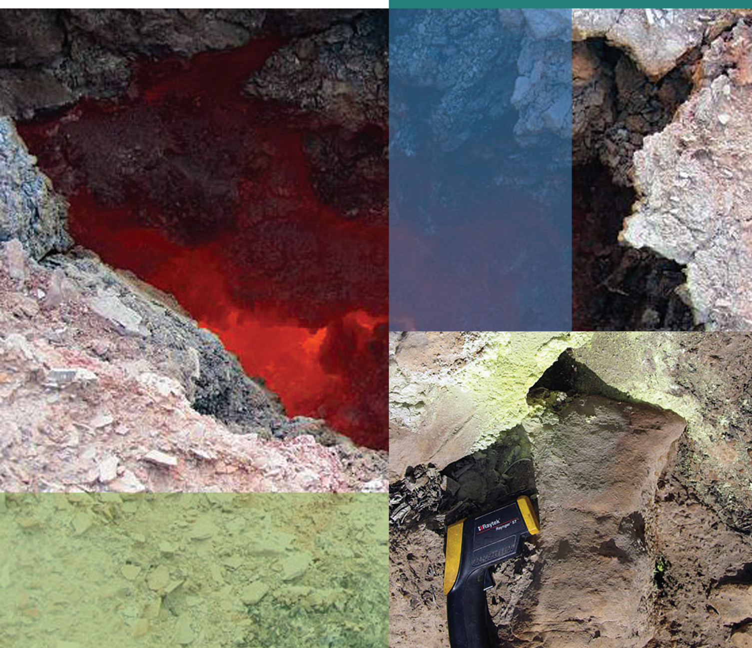
A SUMMARY OF UNDERGROUND COAL FIRES IN COLORADO



Prepared for

State of Colorado
Department of Natural Resources
Division of Reclamation Mining & Safety

Prepared by

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2013

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INTRODUCTION

There are over 30 known underground coal fires in Colorado. Extinguishing or containing these fires has been challenging, primarily because delineating the subsurface extents of these fires is difficult. This work is an extension of the Division of Reclamation, Mining and Safety's "Report on the status of fires at abandoned underground coal mines in Colorado" (**Renner, 2005**). In this report, underground fires in the state are described. The coal fires are characterized by integrating data, such as cesium-vapor magnetometer measurements, gas composition measurements, surface mapping, isotope measurements, historical mining accounts, and mine maps. These data are processed and plotted in ArcGIS. A GIS file for each coal fire site was created, and these are included with this report. These maps are designed to aid the planning of future fieldwork and/or fire control efforts.

In this study, general characteristics of underground coal fires in Colorado are described first. While the locations and the coal seams that are on fire differ, many common features are shared by the 30 plus known fires that are burning in the Colorado. Second, tools and data that were collected to characterize the fires are described. The purpose of each of the measurements is described along with their limitations. This is followed by a discussion of common fire fighting methods to combat underground fires. There is no one single method that will be applicable to control or extinguish all of the fires in Colorado.

In addition, commentaries for each of the fire characterized in this report can be viewed by navigating to http://mining.state.co.us/Pages/Home.aspx or by going to http://www.koveva.com/coal-fires.html, then clicking on a specific coal fire site.

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CHAPTER 1: GENERAL CHARACTERISTICS OF UNDERGROUND COAL FIRES IN COLORADO

Chapter 1

GENERAL CHARACTERISTICS OF UNDERGROUND COAL FIRES IN COLORADO

Although coal fires occur around the state, there are many common recurring features. Some of the common features include locations of where coal fires occur, how coal fires are ignited, and how air and combustion gases circulate through the subsurface. In this chapter, each of these features is discussed in detail.

1.1 Coal fire locations

There are nine major coal bearing regions in Colorado, and each region contains at least one underground coal fire. These regions are: San Juan River Region, Uinta Region, Green River Region, North Park Region, Middle Park Region, South Park Region, Denver Region, Canon City Region, and Raton Mesa Region. These regions are labeled and shaded green in Figure 1. There are approximately 30 known active underground fires within the state, some more active than others. All of these coal fires are located at the periphery of the coal bearing regions, where the coal crops out to the atmosphere. Figure 1 shows the spatial distribution of these fires within the state.

Figure 1: Nine different coal bearing regions in Colorado are shaded in green. Locations of the documented coal fires are depicted by green diamonds.

1.2 Ignition of coal fires

1.2.1 Ignition at the outcrop

One of the reasons why coal fires often burn near the outcrop may be because coal seams are easier to ignite when they are exposed. For example, many surface fires in Colorado can start during thunderstorms. Figure 2 is a picture of a lightning strike that was taken along the Hogback Monocline of the San Juan Basin in 2010, where a number of natural coal fires are currently active. The high frequency of thunderstorms during the summer in Colorado could be a reason why many fires in Colorado, both outcrop and abandoned mine fires, are burning along coal bearing basins. Observations at coal fire sites suggest that lightning strikes start a surface fire, which in turn ignites the coal seam below it. Coal seams that ignite at the outcrop can ignite coal in old mine workings if they are connected.

Figure 2: A lightning strike along the Hogback Monocline in the San Juan Basin, Colorado. Frequent lightning strikes in the San Juan Basin and in other coal bearing basins in Colorado may have ignited many surface fires where coal crops out.

1.2.2 Ignition by spontaneous combustion

Spontaneous combustion is another way that a coal fire can ignite. Spontaneous combustion of coal often occurs in underground mines that are poorly sealed and full of air. Although the reaction is very slow, coal is continually oxidized at ambient temperatures in the presence of oxygen. This oxidation reaction is exothermic and therefore releases heat to the surroundings. If the rate of heat generation exceeds the rate of heat removal, self-acceleration of coal oxidation takes place, thereby releasing heat at a correspondingly faster rate. The rate of coal oxidation is exponentially related to increasing temperature. Once the subsurface temperature exceeds the self-ignition temperature of coal, the coal will ignite without an external ignition source. Spontaneous combustion is more likely when the coal is crushed or pulverized, since the surface area per volume of coal is increased. A fire ignited through spontaneous ignition can continue to burn if it is able to continually access fresh air.

1.3 Circulation of air and combustion gases

Once coal is ignited, circulation of air and combustion gases must be maintained in order for the coal to continue to burn. Air can be supplied to an underground fire through one or more of the three following ways: Along outcrops, through fissures that form as a result of subsidence, or through old mine workings. Each of these mechanisms is described in detail in the three sub-sections that follow.

Unlike at active coal mine sites where air flow is regulated by ventilation systems, mechanical ventilation systems have been removed at the abandoned coal mines where fires burn today. Air and combustion gases circulate primarily due to density driven convection forces which are generated by the heat of the fire itself.

1.3.1 Air circulation near outcrops

One of the easiest locations for a coal fire to ignite and burn is along coal outcrops. Air is accessible along the outcrops, and combustion gases that are generated along the outcrops can be vented to the atmosphere.

Figure 3 illustrates how the exchange of air and combustion gases occurs near outcrops. In the absence of any subsidence, it is easier for a fire to burn along the strike of the outcrop rather than for it to burn along the dip and migrate into the formation away from the outcrop. Many outcrop fires are unable to burn far into the outcrop, and these fires often self-extinguish themselves.

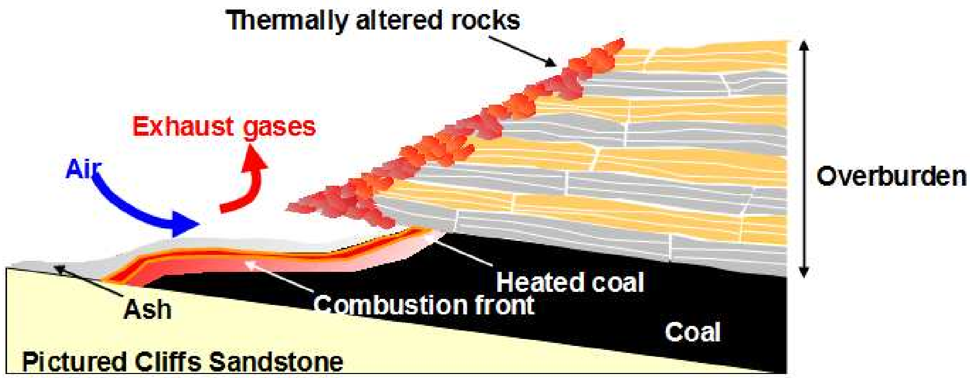

Figure 3: A conceptual diagram showing a coal fire burning near the outcrop. At fires that are contained near the outcrop, air and combustion gases are exchanged at the surface.

As the fire burns along the outcrop, overburden at the outcrop becomes thermally altered due to high temperatures. Thermally altered rocks—sometimes referred to as clinkers—which are found along outcrops are reddish and brittle; they are often found shattered into smaller pieces due to weathering and subsidence. They are indicative of either an underlying active fire or that a fire was once active in the area.

1.3.2 Circulation through fissures

Fractures can form at the surface above underground coal fires. This happens when a coal seamed that has been consumed by the fire collapses under the weight of the overburden, and the collapse exerts a tensile force on pre-existing fractures in the area causing them to widen and propagate to the ground surface. These fractures are sometimes referred to as surface fissures. Figure 4, an idealized section modeled after a coal fire burning along the Hogback Monocline in the San Juan Basin, Colorado, shows how a coal fire burning at the outcrop can advance along the dip of the seam, causing fissures to widen as the fire propagates into the sub-surface. .

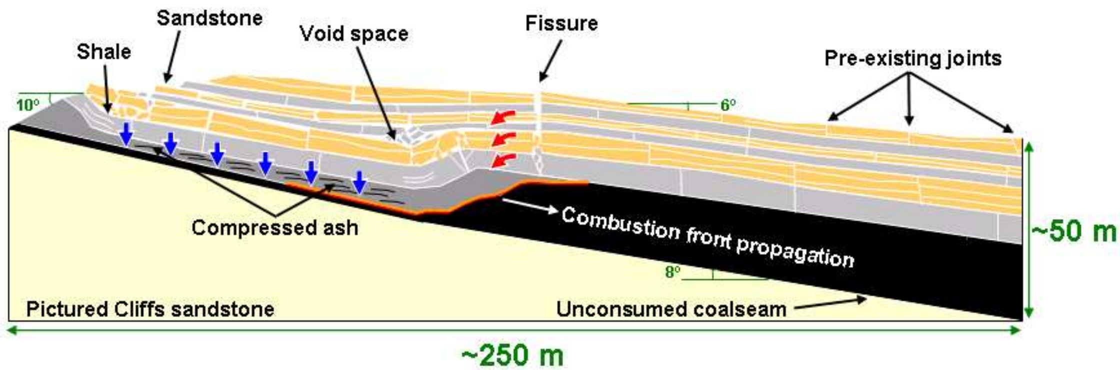

Figure 4: A conceptual diagram depicting a coal fire that has burned away from the outcrop into the formation. When the burned coal seam is no longer able to bear the weight of the overburden, subsidence occurs. This causes pre-existing fractures to widen ahead of the combustion front to form fissures.

Figure 5 illustrates fissures that have formed at the surface above a subsurface coal fire in India. The systematic nature of the fissures supports the idea that pre-existing joints in the area, which existed prior to coal fires, widened to form fissures at the surface. The same systematic nature of fissures in Figure 5 is observed at many coal fires in Colorado.

Figure 5: Fissures which have formed at the surface above a subsurface coal fire in India. The systematic nature of the fissures is also observed at fires in Colorado.

Once the coal fire burns further into the subsurface (down dip of the outcrop), its ability to exchange air and combustion gases at the outcrop is hindered. Fissures then act as conduits through which air can reach the subsurface coal seam and also allow combustion gases in the subsurface to be vented into the atmosphere. These newly formed fissures play a critical role in keeping coal fires burning in the subsurface.

The following sequence in Figure 6 illustrates how fissures typically develop over many coal fires in Colorado.

Figure 6: An evolution of a surface fissure is tracked over time from left to right. Initially, a line of moisture appears on the ground. This is followed by precipitation of sulfur (yellow crystals in the second picture), then tar (black line in the third picture), then ammonium chloride (white crystals in the fourth picture). A fissure finally appears, and hot combustion gases are released.

Sequence in the development of fissures at the surface overlying subsurface coal fires:

- Steam/moisture travels from the subsurface to the surface through pre-existing fractures and outlines the locations where fissure will form.
- Sulfur (yellow) begins to appear around the fissures.
- Tar-like materials are found along the inner-walls of the newly formed fissure.
- Ammonium chloride (white) appears around the fissures.
- Fissure opens at the surface and begins to exhaust hot combustion gases.

Figure 7, below, depicts a coal fire after it has moved sufficiently far from the outcrop so that it obtains most of its air (and thus oxygen) from cooler, chimney-like inlet fissures instead of from the outcrop. Fissures that form near the advancing combustion front provide a pathway for hot combustion product gases to escape. As the combustion front advances past these fissures, they are converted to fissures through which air is drawn into the subsurface. New fissures form ahead of the moving combustion zone to release combustion gases to the surface.

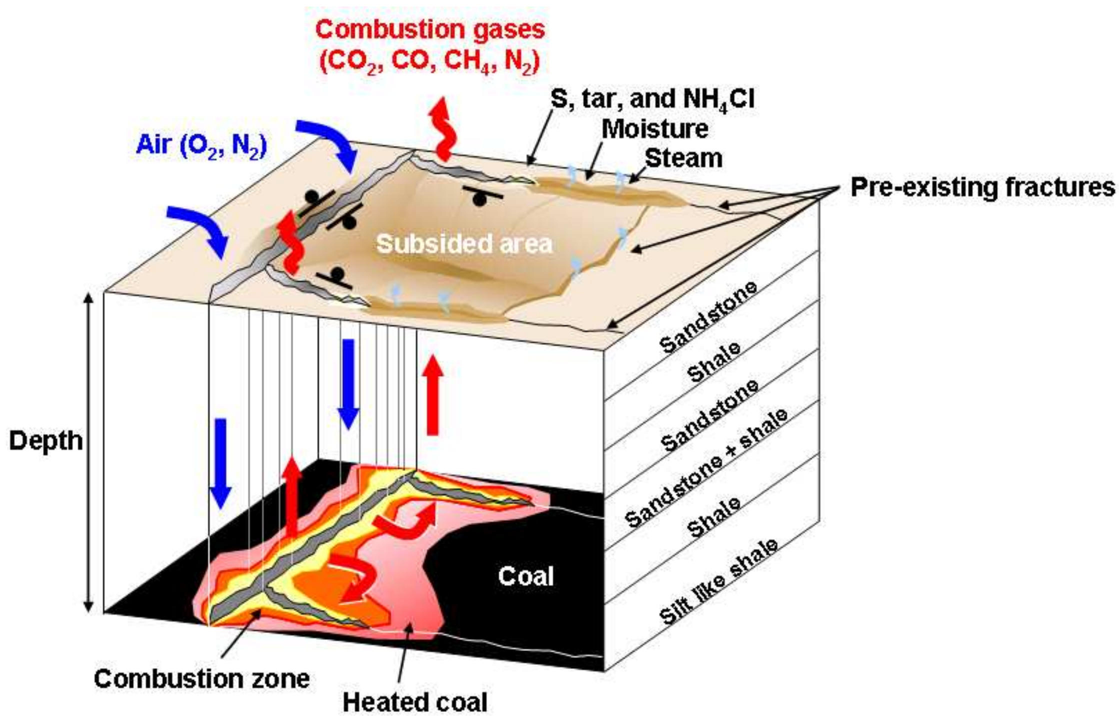

Figure 7: A conceptual diagram showing how air and combustion gases flow through the subsurface. Air is drawn in through fissures behind the combustion zone, while hot combustion gases are vented from newly formed fissures ahead of the combustion zone. Air and combustion gases are circulated by natural convection. When the combustion front migrates from one region to the next, fissures that are currently releasing combustion gases can later become inlet points for air.

When boreholes were drilled in 2012 near hot fissures at the Wise Hill coal fire near Craig, Colorado, a zone of fractured rocks, void areas, and mined out areas were encountered immediately above the burning coal seam. Similar fractures were observed at a coal fire in the San Juan Basin near Durango, Colorado, when boreholes were drilled in between cool, inlet fissures and hot fissures venting exhaust gases. At the latter site, fractures were observed using a down-hole camera. Hot air flowed through these fractures, suggesting that air being drawn into the subsurface is being heated as it flows towards the combustion zone. It is reasonable to assume that ambient fissures and the combustion fissures are connected by heavily fractured and / or subsidence induced void regions lying atop burning coal seams. This network of fractures and voids in the subsurface suggests that high volumes of air can feed the combustion zone.

1.3.3 Circulation through abandoned mine workings

Old mine workings and entryways can be a factor in keeping the fire active by allowing air and combustion gases to enter and leave the subsurface combustion zone. Many of the mines in Colorado along the Grand Hogback were mined using the stope mining technique. This mining technique is typically used for hard rock mining and not for coal mining in the west. However, for steeply dipping coal seams such as those found in the Grand Hogback region, this was a cost-effective method of coal extraction. A representative diagram depicting this coal extraction technique is shown in Figure 8. Exact dimensions and specific layouts will differ for each mining site, but the figure is meant to highlight the fact that the abandoned mines often have a chimney-like configuration.

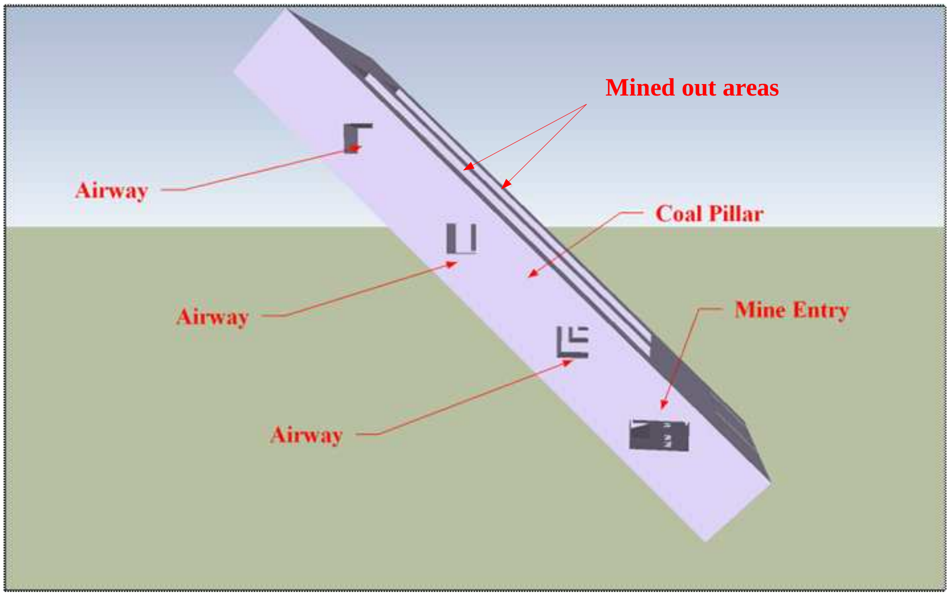

Figure 8: Idealized diagram depicting stope coal extraction. This mining technique promotes natural convection of air flow through the subsurface by leaving chimney like structures.

The mine entry as shown in Figure 8 was constructed parallel to the strike of the coal seam. The mine entries were typically constructed through the coal seam that was being extracted. An idealized expanded view of a stope mine main haulage corridor is shown in Figure 9.

Coal was extracted up dip on the coal seam on approximately forty feet intervals, starting from the mine entry working parallel to strike. Miners created overhead rooms, or stopes. When excavated from the stope, coal would cascade down the underlying void to the mine entryway. The coal was then removed using a transportation system that ran inside of the main entryway. To maintain safe oxygen levels, airways were constructed parallel to the main entry but at higher elevations as the seam extraction moved up dip. The extraction process continued up dip until a small amount of coal, commonly referred to as the crown coal, remained at the top.

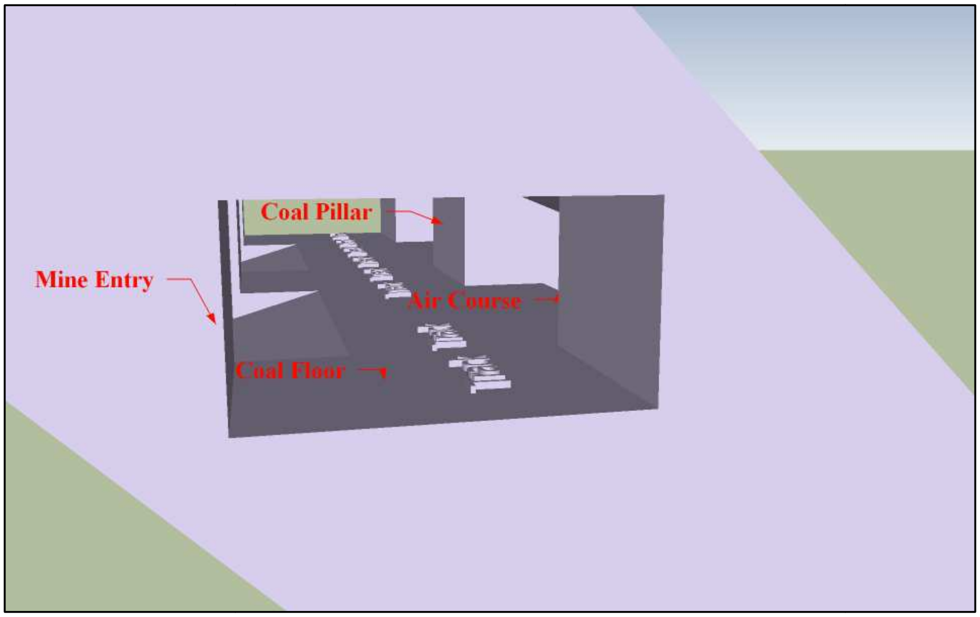

Figure 9: An expanded view of an idealized main haulage corridor of a stope mine.

When stope mines were abandoned prior to the 1970’s, operators were not required to maintain positive pressures or to backfill any of the mined areas. Figures 8 and 9 indicate that conduits within the mines permit air to flow freely into the subsurface and for mine atmosphere to escape to the ground surface. Airways and entryways were purposefully constructed to maximize air circulation. The stope mine construction is especially conducive to natural circulation due to its chimney-like geometry.

Underground mines that were mined using the room-and-pillar method may not be as conducive to air circulation as those mined using the stope method. However, open rooms and haulage ways still allow large volumes of air to flow freely in the subsurface.

Chapter 2

USEFUL FIELD MEASUREMENTS AND OBSERVATIONS

Below, measurements and observations that were collected to investigate coal fires burning in Colorado are presented. Various data were integrated to enhance evaluation of the sub-surface fire conditions at each site. Table 3 summarizes how each of the observations and measurements help enhance our understanding of the coal fire. A conceptual model of a fire was proposed based on data and observations, which is presented in the next chapter.

Not all methods of coal fire characterizations are applicable for every coal fire. For example, magnetometer surveys, which rely on changes in magnetic properties and alignments of the overburden above burning and previously burned coal seams, are useless at outcrop fires that lack sufficient overburden or at sites that are known to contain large volumes of abandoned mine materials. Experience and geostatistical probability analyses are drivers that help decide on which method of coal fire characterization is most useful at a given coal fire site.

2.1 COMMON COAL RANK AND THE DEVOLATILIZATION PROCESS

At the most of the coal mine fires documented in Colorado, the coal appears to be High volatile B and C (HvB and HvC) grade coal. Coal composition and rank information are especially well documented along the northern edges of the Piceance Basin, where over 60% of the known fires in Colorado occur (**Collins, 1985**). High volatile B and C coals are defined by their calorific value limits on a moist, mineral-matter-free basis. These coals contain high volatile matter, which are defined to be species that are produced when the coal is heat to 950^{o}C. Volatiles contain steam, carbon dioxide, carbon monoxide, hydrogen, and various gaseous aromatic and aliphatic species. Char and ash remain at the conclusion of heating. This transformation of coal into gas and solid ash and char takes place with or without oxygen; all that is needed is heat. When carbon-bearing gaseous species come into contact with oxygen, combustion reactions take place.

2.2 METHANE PRESENCE AT COAL FIRES

Methane is commonly detected at the ground surface above underground coal fires in Colorado. Methane may play a significant role in promoting combustion at some coal fires in Colorado.

There are two sources of sub-surface methane which can be differentiated by an isotopic distinction. The first source of methane is desorption of the gas from the coal surface. This is a physical process which frees adsorbed methane from coal surfaces when pressures in the coal seam are lowered. The second source of methane is derived from chemical transformation of the coal through pyrolysis and/or devolatilization as the coal is heated. This was described briefly in Section 3.1.

2.2.1 Migration of desorbed methane

In some areas, methane desorption from coal cleats may take place further down dip of the coal fire, away from the outcrop, as a result of commercial coal bed methane production. Figure 10 shows the migration path of methane molecules as a result of natural gas production. During gas production, the water table is lowered in order to lower the pressure that keeps methane molecules tightly bound to the coal matrix. If the desorbed methane molecules are not fully captured by surrounding wells, they may migrate up dip through fractures and coal cleats. While the leaky hydrodynamic water seal provides some resistance to the flow of methane, coal seams that crop out at the edge of geologic basins often do not have structural barriers to prevent methane from escaping to the atmosphere. These upward flowing methane molecules can participate in combustion reactions if they reach an active outcrop fire.

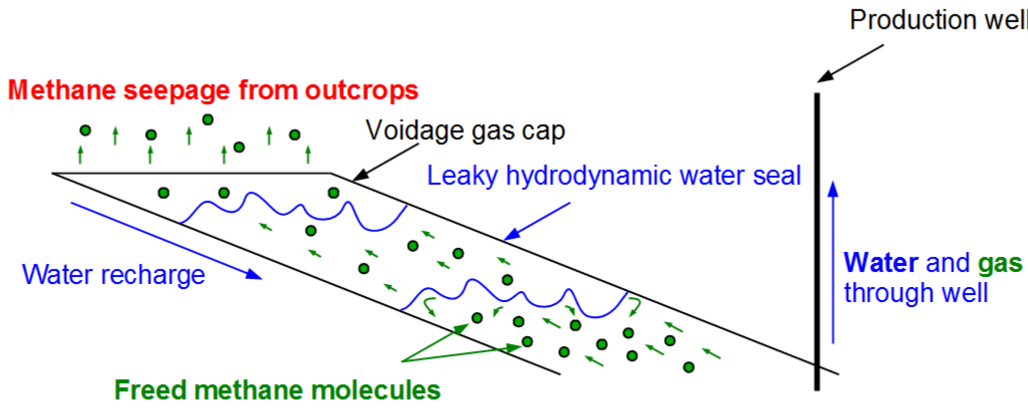

Figure 10: A conceptual diagram showing how methane can become freed, migrate from a deeper part of the basin, and escape from the outcrop. This phenomena occurs independent of a coal fire. Methane that encounters a coal fire burning near the outcrop can participate in combustion reactions.

Just down dip of the South Canyon fire, a number of boreholes were drilled by Vessels Coal and Gas Inc. Their results indicated that methane molecules were adsorbed to the coal fractures, which readily desorbed when pressure was lowered. This result could indicate that the methane molecules which were freed down dip, farther away from the South Canyon coal fire, could contribute to keeping coal fires burning. Isotope measurements of limited gas samples collected at the South Canyon coal fire did not support this hypothesis. However, additional sampling should be undertaken at this fire to determine whether methane that is flowing up dip is contributing to the fire.

The up dip migration of methane is not unique to coal fires evaluated as part of this investigation. At a coal fire located along the San Juan Basin outcrop on the Southern Ute Reservation, the migration of coal bed methane from the central part of the basin plays a critical role in keeping the fire burning. The migration and subsequent escape of fugitive methane from coal outcrops in the San Juan Basin and Raton Basin, is well documented by the Colorado Oil and Gas Conservation Commission. At an active coal fire in Jarkhand, India, which has similar geologic and geometric features as the outcrop fires in Colorado, up dip migration of methane to the fire from a lower elevation was recently confirmed.

2.2.2 Evolution and migration of methane originating from inside of the coal matrix

Methane can also evolve when the coal matrix undergoes intense heating. As previously discussed, the coal matrix breaks down into various combustible volatiles and solid char during the heating process. In this scenario, the origin of methane is close to the fire front.

2.3 Gas analysis

2.3.1 Gas composition

The state of a subsurface coal fire can be inferred from gas compositions of gases that are collected at fissures over coal fires or boreholes. For example, a gas sample that contains concentrations of hydrogen implies that a fresh coal surface was exposed to the combustion front in the subsurface in an oxygen lean environment. Hydrogen can evolve from the coal when it is exposed to heat. If sufficient oxygen were present, then the hydrogen would be immediately oxidized to form steam. The presence of hydrogen also implies that the coal fire is spreading and consuming new coal. The new frontier of the fire is presumably where gas sample containing hydrogen was collected.

Gas samples were measured at a number of coal fire sites using two methods. In the first method, a Landtec GEM5000 handheld gas composition monitor was used. In the second method, a hand pump was used to fill Cali-5 bond bags. These samples were shipped and subsequently analyzed by Isotech Laboratories Inc. Samples were measured from boreholes or from fissures actively emitting combustion gases. Samples collected from boreholes are more informative, since measured gas compositions can be associated to an exact depth or a specific seam. Gas compositions from fissures are harder to interpret since it is unclear how the surface feature is connected to the subsurface.

2.3.2 Isotopes

There are two major fuel sources that can produce carbon dioxide at coal fires; coal and methane. To a lesser extent, other minor combustible species such as propane, ethane, and heavier hydrocarbons can exist. Isotopes of gas samples help distinguish and determine the fuel sources that result in carbon dioxide and methane at the surface.

Isotopic signature of a carbon is represented using $\delta^{13}C$, which measures the ratio of stable isotopes, ^{13}C and ^{12}C. The ratio of a given sample is measured against an agreed upon international standard ratio of ^{13}C to ^{12}C. More negative isotopic signatures mean that the sample's ^{13}C to ^{12}C ratio is less than that of the standard. Carbon bearing species that originated from the coal matrix, chemically have a $\delta^{13}C$ value of -23.5 to -26.7 per mil, where as methane molecules that desorbed from coal cleats have are typically depleted in ^{13}C and have an isotopic value of approximately -40 per mil. Carbon that originated from the coal matrix will retain its -25 per mil isotopic characteristic even if it participates in combustion reaction. For example, the carbon in a carbon monoxide molecule that evolves from the coal upon heating will have a $\delta^{13}C$ value of around -25 per mil. Even if it is subsequently oxidized and converted to carbon dioxide, the carbon in the carbon dioxide will still have the same $\delta^{13}C$ signature. Thus, by measuring the isotopic value of the gases created at the surface, it is possible to better understand what carbon species are being consumed by the subsurface combustion.

Methane and other combustible molecules that are either chemically derived or desorbed likely burns along with the coal to keep a coal fire active. One way to determine the fractional contribution of each of the fuel sources fires (chemically derived hydrocarbons, desorbed hydrocarbons, and coal) at each fire is to measure the isotope values of carbon bearing gases that are collected at the surface directly above the fires. A number of gas samples were collected in a Cali 5-bond bag and sent to a laboratory for $\delta^{13}C$ analyses. Carbon dioxide samples were collected from six different fires: South Canyon fire, Coryell fire, New Castle #1 fire, New Castle #3 fire, Streeter fire, and Wise Hill fire. Methane samples were collected at the South Canyon fire and the Wise Hill fire. Table 1 shows the measured $\delta^{13}C$ isotope signatures of gases.

Isotope results represented in Table 1 show that the carbon dioxide from many of these fires are derived from chemical transformations of coal. Coal can undergo chemical transformations when it is burned or simply by being heated. When it is burned, the carbon contained in the coal produces carbon dioxide. When coal is heated, chemical bonds within the coal matrix is reorganized, which leads to the evolution of carbon monoxide, methane, and carbon dioxide. Carbon monoxide and methane are oxidized further to produce carbon dioxide. Table 1 shows that of the 11 carbon dioxide samples analyzed, eight have $\delta^{13}C$ values which suggest that the carbon dioxide resulted from chemical transformations of the coal. These eight samples were collected from locations where the fire once burned intensely, but now appear to have cooled as the fire migrated to another location. These gas samples were likely sampled from Zone 1 as depicted in Figure 10.

Three of the 11 samples, Streeter, Wise Hill #2, and South Canyon, however, show a $\delta^{13}C$ enrichment (more positive), -22.5, -19.2, -21.8 per mil, respectively, compared to $\delta^{13}C$ signature expected from coal-derived samples. These readings are inconsistent with carbon dioxide derived from chemical transformations of coal. These gas samples were all collected from the area just ahead of the existing combustion front, as indicated by the magnetometer surveys. One possible explanation for the observed enrichment is the combustion of heavier hydrocarbons which is enriched in ^{13}C (more positive $\delta^{13}C$ signature). Heavier hydrocarbons could have desorbed and migrated from down dip of the coal fire. Carbon bearing species that are freed via physical mechanisms do not necessarily share the same carbon isotopic signature with carbon bearing molecules that are derived from chemical transformations of coal.

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Sample Name	H_2S %	He %	H_2 %	Ar %	O_2 %	CO_2 %	N_2 %	CO %	C_1 %	C_2 %	C_2H_4 %	C_3 %	C_3H_6 %	iC_4 %	nC_4 %	iC_5 %	nC_5 %	C_6+ %	$\delta^{13}CO_2$ ‰	$\delta^{13}C_1$ ‰	δDC_1 ‰	Specific Gravity	BTU
Corryell Outcrop	na	nd	nd	0.960	10.99	7.80	80.25	nd	0.0010	nd	nd	nd	nd	nd	nd	nd	nd	0.0009	−25.91			1.029	0
NC #1 Outcrop	na	nd	0.0159	0.940	18.36	2.34	78.23	0.10	0.0129	0.0006	nd	0.0001	nd	nd	nd	nd	nd	0.0010	−25.21			1.009	1
NC #3 Outcrop	na	nd	nd	0.938	18.46	2.44	78.13	0.024	0.0042	nd	nd	nd	nd	nd	nd	nd	nd	0.0003	−25.63			1.010	0
NC #3 Upper Seam Outcrop	na	nd	nd	0.947	11.00	8.70	79.34	nd	0.0090	0.0003	nd	0.0001	nd	nd	nd	0.0001	0.0002	0.0062	−24.35			1.034	0
South Canyon (Top SC)	na	nd	nd	0.937	9.73	10.81	77.90	nd	0.597	0.0140	0.0013	0.0029	0.0002	0.0015	0.0004	0.0004	0.0002	0.0012	−21.82	−30.96	−207.2	1.042	7
Streeter Outcrop	na	nd	0.0163	0.938	6.46	13.21	79.12	0.078	0.148	0.0106	0.0004	0.0037	0.0005	0.0008	0.0010	0.0007	0.0008	0.0093	−22.53			1.052	3
Wise Hill #1	na	nd	0.0438	0.933	10.43	8.90	78.98	0.65	0.0489	0.0081	0.0011	0.0034	0.0008	0.0004	0.0007	0.0002	0.0003	0.0012	−24.99			1.034	3
Wise Hill #2	na	nd	4.49	0.744	0.39	22.06	63.10	0.046	7.71	0.922	0.0247	0.304	0.0435	0.0377	0.0655	0.0160	0.0223	0.0217	−19.23	−32.99	−315.5	1.025	124
Wise Hill #3	na	nd	0.0149	0.948	1.81	17.08	79.89	0.095	0.152	0.0062	0.0003	0.0008	0.0001	0.0002	0.0001	0.0001	nd	0.0008	−23.67			1.067	2
Wise Hill #6	na	nd	3.19	0.857	1.06	17.20	72.23	0.82	4.27	0.209	0.0623	0.0532	0.0170	0.0061	0.0107	0.0020	0.0032	0.0053	−24.39	−30.44		1.022	64
Wise Hill #7	na	nd	0.192	0.963	0.12	17.10	81.09	0.33	0.176	0.0186	0.0009	0.0057	0.0014	0.0009	0.0009	0.0005	0.0004	0.0033	−23.73			1.064	4

Table 1: Measured $\delta^{13}C$ isotope signatures of gases from 11 sample locations in Colorado. Isotope signatures of carbon in the carbon dioxide were analyzed for all of the samples, and isotope signatures of carbon in the methane were analyzed in three of the samples.

An isotope analysis of a heavier hydrocarbon sample that was collected near the South Canyon East fire was performed (not listed in Table 1). Results showed that propane derived from the coal-bearing Williams Fork Formation has a $\delta^{13}C$ signature of approximately -22. (If the propane had chemically originated from the coal matrix, the carbon dioxide that results from its combustion would have a $\delta^{13}C$ signature of approximately -25 per mil). It is possible that some of this propane and other heavier hydrocarbon that is enriched in ^{13}C are reaching the outcrop fire from farther down dip. Their contribution to the carbon dioxide could explain why the $\delta^{13}C$ values at a number of the samples collected at Streeter, Wise Hill, and South Canyon are not consistent with coal combustion.

One hypothesis had been that adsorbed methane that had been freed somewhere deeper in the basin is flowing up dip towards the fires burning at the outcrop, then subsequently burn to form carbon dioxide. This methane is different from the methane that originates from the chemical transformation of coal. Isotope measurement suggests that this may not be the case. Methane signatures that are produced from natural gas production wells near the South Canyon fire has $\delta^{13}C$ isotope measurements are -38 to -42 per mil. This is consistent with the -40 per mil isotope signature of desorbed methane. If all of the carbon dioxide had resulted from burning this methane, the resulting carbon dioxide would have been more depleted in ^{13}C (more negative) rather than more enriched (more positive) compared to carbon dioxide that results from chemical transformation of coal.

This is not to suggest that desorbed methane does not contribute to the carbon dioxide that is measured at the surface. For example, consider a gas with a mix that contains many molecules of ^{13}C enriched, desorbed, heavy hydrocarbons compared to the number of desorbed methane molecules. Carbon dioxide that results from burning such a gas mixture will be ^{13}C enriched.

3.3 Changes in magnetic properties of rocks above coal fires

3.3.1 Magnetic susceptibility

Magnetic susceptibility of a rock is determined by the concentration of magnetic materials contained in the rock. Higher concentrations of magnetic materials result in higher magnetic susceptibility. Changes in magnetic properties of a rock unit can change given the influence of outside factors, such as heating from an underlying fire. Such changes help to identify the degree of subsurface heating to which overlying rock units have been subjected. This in turn helps describe the intensity of a subsurface coal mine fire at some specific point in time.

Positive magnetic susceptibility of a rock can result from two sources: the presence of iron, nickel, or cobalt bearing minerals in the rocks, and the degree of alignment of the magnetic moments within these minerals (**Hooper, 1987**). To measure the magnetic susceptibility of rocks, samples collected from two fire sites, IHI No.3 and Harvey Gap, were crushed into fine particles and loaded into non-magnetic containers. When rocks are crushed, in-situ orientations of the magnetic minerals are destroyed; thus any preferential alignment of remnant magnetization was lost. Therefore, positive magnetic susceptibility, if any, that was measured using this method is due to the presence of magnetic minerals.

Natural sandstones and shales found over the IHI No. 3 and Harvey Gap coal fire sites initially possess positive magnetic susceptibilities on the order of 10^{-5} and 10^{-6} cgs, respectively. Magnetic susceptibility measurements conducted on heat-altered samples from these sites showed that there were positive changes, and new magnetic minerals were formed during the heating process. There was 10-10^{2} orders of magnitude increase in magnetic susceptibility of rocks compared to the same overburden layers from an unburned zone. Increases in magnetic susceptibility of a given rock sample indicate that the sampled rock unit was subjected to intense heat.

Heat that is produced from combustion reactions can leave the combustion zone either by convection of hot gases through fissures or by conduction through the overburden. Heat from the burning coal seam may lead to the formation of additional magnetite (Fe_3O_4) in the overburden by thermal decomposition of iron rich clay in shales and siltstones. Hematite (Fe_2O_3), which is anti-ferromagnetic, and thus does not enhance the preferential magnetic orientation of a region upon formation, can also result from heating shales and siltstones. The equilibrium between magnetite and hematite formation is a strong function of oxygen availability at temperatures typically observed at coal fires (200^{o}C - 1000^{o}C). For these temperature ranges, low oxygen concentrations lead to magnetite formation, while high oxygen concentrations lead to hematite formation (**Hooper, 1987**).

Rocks such as siltstones and shales above coal fires provide ideal environments for magnetite formation. The low permeability and the low porosity of these rocks limit the diffusion of oxygen into the matrix.

Sample / Location	Major Mineral Constituents	Minor Mineral Constituents	Magnetic Susceptibility (CGS)
IHI No. 3 Mine			
Altered Siltstone	Quartz (SiO_2)	*Hematite (Fe_2O_3) **Magnetite ($Fe^{+2}{}_3O_4$) Albite ($NaAlSi_3O_8$) Clinoenstatite ($MgSiO_3$)	1.14×10^{-4}
Unaltered Siltstone	Quartz (SiO_2)	Augite ($Ca(Fe,Mg)Si_2O_6$) Anorthite ($(Ca,Na)(Si,Al)_4O_8$)	3.80×10^{-5}
Altered Sandstone	Quartz (SiO_2) **Maghemite (Fe_2O_3)	Anorthite ($((Ca,Na)(Si,Al)_4O_8)$) *Hematite (Fe_2O_3)	1.29×10^{-5}
Unaltered Sandstone	Quartz (SiO_2)	Augite ($(Ca(Mg,Fe,Al)(Si,Al)_2O_6)$) *Hematite ($Fe_2O_3$)	1.35×10^{-5}
Harvey Gap Mine			
Altered Siltstone	Quartz (SiO_2)	*Hematite (Fe_2O_3) Microcline (K,AL,Si_3O_8)	7.75×10^{-5}
Unaltered Siltstone	Quartz (SiO_2)	Dolomite ($CaMg(CO_3)_2$)	1.90×10^{-6}
Altered Sandstone	Quartz (SiO_2)	Microcline (K,AL,Si_3O_8)	1.37×10^{-6}
Unaltered Sandstone	Quartz (SiO_2)	Dolomite ($CaMg(CO_3)_2$)	2.46×10^{-6}
Pyrometamorphic	Gehlenite ($Ca_2Al_2SiO_7$) Quartz (SiO_2) Anorthite ($((Ca,Na)(Si,Al)_4O_8)$) Diopside ($(Ca(Mg,Al)(Si,Al)_2O_6)$)	Anhydrite ($CaSO_4$) ***Iron (Fe)	3.37×10^{-5}

*Paramagnetic ** Ferrimagnetic ***Ferromagnetic

Table 2: X-Ray diffraction of major and minor mineral constituents and magnetic susceptibility values. Altered species, especially siltstones, show significant changes in magnetic susceptibility values. The increased concentration of these magnetic species demonstrates that rocks have been exposed to significant heat.

Magnetic susceptibility measurement is a useful tool to verify that a given rock sample was exposed to heat. In addition, these measurements show the different types of minerals formed during the heating process. Of these minerals, those that are ferrimagnetic and ferromagnetic play an important role in distinguishing whether a particular subsurface region is currently active, previously active and cooled, or was never affected by the coal fire. When these minerals are exposed to intense heat from the combustion zone, above their Curie temperature, the temperature at which their magnetic alignments become disorganized. When the combustion front moves to another location, and these rocks cool, the magnetic alignments of the minerals become aligned with the Earth’s magnetic field. The next section looks at how the differences in magnetic alignments can be detected using a pack-mounted magnetometer to gain a better understanding of the state of the subsurface.

3.3.2 Magnetic anomaly of rocks

Although many geophysical methods exist to image the subsurface, field measurement results showed that only magnetic anomaly surveys using a magnetometer were able to differentiate between unburned regions, burned and now-cool (i.e.: previously burned) regions, and currently active regions. Other geophysical methods such as shallow seismic, electrical resistivity, and ground penetrating radar, were also employed at a coal fire in Colorado, but they were met with limitations such as lack of depth penetration and low resolution which rendered them as less than optimal.

Magnetic anomaly measurements, which were collected using a cesium vapor magnetometer, can be used to distinguish differences between previously burned, currently burning, and unaltered regions by measuring the differences in both magnetic susceptibilities and magnetic orientation. Magnetic data were collected using a pack-mounted Geometrics G859 Cesium Vapor (CV) magnetometer with a built-in GPS unit. The GPS data, after post-processing yielded a positional accuracy of less than 0.5 meter. Data were recorded by traversing the area over each of the coal fire sites with a measurement frequency of 1 hertz.

Magnetic anomaly surveys differentiate between burned and cooled zones, currently active zones, and unburned zones by measuring the magnetic orientation of the mineral magnetite in the overburden. Before the overburden is exposed to a coal fire, there is a slightly preferential magnetic alignment. When the overburden is heated to temperatures approaching the Curie temperature of the magnetic minerals, 585^{o}C (1085^{o}F) for magnetite, the alignment of the magnetic moments-and thus magnetization-are randomized, and any preferential magnetic alignment that existed within the overburden prior to exceeding this critical temperature is lost.

Magnetic anomaly maps at each of the coal fires investigated are found in Chapter 5 of this report. Generally, blue regions are where the overburden was heated and subsequently cooled, the red/orange regions are where some portion of the overburden is above the Curie temperature of magnetite (1085 ^{o}F) at the time of measurement, and the light green regions are where the overburden remains unaltered by the coal fire.

When the combustion front advances to another area, the temperature of the overburden cools below the Curie temperature again. As the overburden cools, the magnetic moments in the overburden become aligned to the Earth's ambient magnetic field, enhancing the magnetization of the region. The enhancement is attributed to both the new preferential alignment of magnetic moments and the newly formed magnetite in the overburden.

Where available, supporting data such as locations and orientations of surface fissures, snowmelt boundaries, gas composition, well logs, and subsidence features, were collected to corroborate magnetometer results. Generally, additional data collected agreed well with the magnetometer results. Detailed commentary can be found pertaining to specific fires in Chapter 5 of this report.

Based on magnetometer results collected at a number of fire sites within the State, it can be concluded that the magnetometer results can be used to differentiate between four regions: coal outcrop, unaltered overburden, burned and cooled overburden, and overburden that is currently above the Curie temperature.

Magnetometer results can be extremely difficult to interpret and provide very little insight into the extent of the combustion zone in the subsurface when there is a large amount of metal and iron remaining underground in the mine workings. These objects tend to overwhelm subtle changes to the overburden induced by the heat of the coal fire.

3.4 Surface feature mapping using a GPS

Various surface features that are found over coal fire sites were mapped with a pack mount GPS. Surface features are important to map, since they often help approximate the extent of the fire. While surface expressions are not necessarily correlated to the subsurface activity, it does provide a good first order estimate of fire boundaries. When surface features are plotted along with mine maps, methane surveys, and geophysical data, a holistic understanding of a specific fire site emerges.

Features that were mapped at the surface at coal fire sites include fissures, subsidence, mine features (rocks, adits, entries), thermally altered rocks, coal outcrops, and snowmelt boundaries.

Mapping the snowmelt boundaries is particularly useful in delineating the thermal extent of a given coal fire site, as snowmelt is a direct result of conductive heat transfer to the surface from the subsurface fire. The snowmelt boundaries are approximations of the subsurface heating because there will be some spread through the overlying rock mass from lateral conduction of heat. Snowmelt outlines were surveyed at the majority of the coal fires that were characterized. Inside of the snowmelt outline, the ground temperature was above freezing, while snow remained on the regions outside of the outline. The snowmelt survey is unable to distinguish whether the snow is melting because the coal seam below is actively on fire or because there is residual heat in the rock immediately above a burned out coal seam. Magnetometer surveys can help distinguish between these two scenarios.

Figure 11: Example of a snowmelt pattern at the New Castle No. 3Coal Mine Fire on a snow day. Heat from the coal fire is conducted to the surface and leaves a snowmelt pattern at the surface.

3.5 TEMPERATURES

Ground surface temperatures were measured using a handheld Raytek infrared thermometer and thermocouples at a number of coal fire sites. A handheld device was used to measure temperatures of hot gases flowing out of surface fissures. Temperatures measured in this way should not be interpreted to mean that the subsurface is at the same temperatures. As the gas migrates through a tortuous path connecting the coal seam to the surface, heat is lost to the surrounding rock. In addition, heat loss at the atmosphere also lowers the temperature of the gases significantly. Temperature readings taken by a handheld device are most useful when trying to determine relative levels of activity at a given coal fire.

A more accurate measurement of the temperature within the coal seam is to lower a thermocouple wire to the coal seam. Temperature readings that are measured using thermocouples reflect the temperatures to which coal seams are exposed in the subsurface. A thermocouple is a bi-metallic wire surrounded by insulation. When this is lowered into the fire zone, the metals heat at different rates and a voltage is produced. This voltage is sent to a handheld device which converts the electronic impulse into a temperature measurement. Based on the temperature conditions, it is possible to estimate the transformation that the coal matrix or the overburden may be undergoing in the subsurface.

3.6 SURFACE METHANE SEEPS OVER COAL FIRES

Presence of methane seeps over a coal fire was first reported above a coal fire termed the North Coal Fire that is located along the Hogback monocline of the San Juan Basin (**Ide, 2011**). To determine whether methane seepages occur at other coal fire sites in Colorado, methane seep measurements were conducted using Picarro Incorporated's portable methane concentration detector at three different coal fire sites: Wise Hill, Skull Creek and South Canyon. At these fire locations, readings of ~2.00 parts per million (ppm) were common. In other locations, however, methane concentrations ranged between several hundred ppm to over 1,000 ppm. By comparison, ambient atmospheric methane concentrations are approximately 1.81 ppm.

The presence of elevated methane seepage over these three coal fires suggests that anomalies in surface methane concentrations may be used to forecast the next region to which the coal fire will likely migrate. Methane molecules that are in the immediate vicinity of the hottest combustion front will likely be consumed immediately. Ahead of the fire front, however, methane can rise to the surface without burning because the temperature is high enough for methane to evolve from the coal matrix, but not yet high enough for combustion reactions to take place. High concentrations of methane are also observed near regions that were once heated above the Curie temperature of magnetite but have since cooled.

Data measured or documented	Instrument used	Units of measurement	Method	Drilling required?	Attributes	Reasons for measurement	Attributes to look for	Limitations
Surface features								
Fissures	Geometrics G859 / Trimble	(m)	Packmount / Handheld	No	Length and orientation of surface fissures	Fissure attributes can help determine past, current, and future fire progression in the subsurface.	Moisture along the ground (first sign of coal dehydration), sulfur and ammonium chloride, hot gases.	It is impossible to find all of the fissures, as some may be buried.
Subsidence	Geometrics G859 / Trimble	(m)	Packmount / Handheld	No	Outline of subsidence expressions at the surface	Subsidence expressions can indicate coal consumption and/or void spaces.	Large sinkholes or cratered areas that do not follow the region's contour.	Subisidence that is not associated with fire activities may occur at old mine sites.
Mine features	Geometrics G859 / Trimble	(m)	Packmount / Handheld	No	Outline of mine features observable at the surface	Mapped mine features can be used to corroborate mine maps and identify possible air entry points.	Rock cuttings that do not look natural, iron pipes and railings.	Mine features may not always be identifiable, and even if they are, they may not be associated with the fire.
Outcrop	Geometrics G859 / Trimble	(m)	Packmount / Handheld	No	Orientation of exposed coal outcrop	Identifying outcrop locations help establish a reference point for field surveys.	Exposed coal, especially the contact point between coal and overlying/ underlying strata.	Coal outcrop is not always visible, especially if the coal seam has burned along the outcrop.
Snowmelt	Geometrics G859 / Trimble	(m)	Packmount / Handheld	No	Outline of the snowmelt boundary	Snowmelt is observed in locations where heat from the coal fires has reached the surace via conductive heat transfer.	Areas where the snow has melted over the coal fire.	Snow is not always present, and when there is snow, travelling to fire sites may be impossible.
Geophysics								
Magnetometer	Geometrics G859	(nT)	Packmount	No	Changes in magnetic orientation of rocks above underground fires	Magnetic orientation of the overburden above coal fires are only altered after being exposed to coal fires, and thus magnetometer measurements can be used to distinguish between burned and cooled, currently active, and unaffected regions.	Higher magnetic orientation (burned and cooled areas) compared to reference, lower magnetic orientation compared to reference (currently active areas), and areas that have magnetic orientations comparable to reference.	Strong magnetic signals from left over steel and/or iron mining equipment will sometimes make it hard, if not impossible to identify subtler signals from rock alterations caused by coal fires.
Gas Analysis								
Isotope analysis	Isotech	(‰)	Laboratory	Yes; No if sampled from fissures	Ratio of ^{13}C to ^{12}C in order to determine souce of carbon bearing gases	Gases that originate from coal all have a unique carbon isotopic signature. If carbon isotopic signatures that are measured at the surface deviates from this coal signature, it indicates the presence of another carbon source.	$\delta^{13}C$ of approx. -25‰ is observed when carbon-bearing species originate from coal. An enrichment or depletion from the -25‰ value suggests the presence of other contributing sources.	Sampling error and turnaround time can be an issue.
Gas composition	Isotech / Landtech	(mole %)	Lab / Portable	Yes; No if sampled from fissures	Mole fractions of various gas species (CH_4, CO, H_2S, H_2, CO_2, N_2, O_2, C_2+) contained in gases emitted at coal fire sites	Gas compositions can help with the understanding of air flow and other combustion conditions.	CO_2 indicates a well-established fire. Presence of H_2 is observed where the coal is exposed to high temperatures for the first time, but in an O_2 depleted environment.	Sometimes GC machines, especially portable ones, can give erroneous results due to overlapping peaks. Sampling error is an issue.
Temperature								
Surface	Raytek	(°F)	Handheld	No	Temperature anomalies detected at the surface	Surface temperature measurements can be useful in the absence of snow.	Values and changes of gas temperatures from fissures over active zones.	Gas can be much cooler than when it originated in the subsurface if the gas cools while following a tortuous path from the coal seam to the subsurface.
Subsurface	Thermocouple	(°F)	Handheld	Yes; No if sampled from fissures	Temperature anomalies detected in the subsurface	Subsurface temperature measurements help determine the temperatures to which coal is exposed in the subsurface.	Elevated temperatures and changes in temperatures over time at fixed locations.	Thermocouple shorting has led to many false readings of high temperatures.

Data measured or documented	Instrument used	Units of measurement	Method	Drilling required?	Attributes	Reasons for measurement	Attributes to look for	Limitations
Surface Gas Surveys								
Surface methane seepage	Picarro H0101	(ppm)	Packmount	No	Presence of methane above coal fires	High methane concentrations are correlated with high combustion activities.	Methane concentrations that are several orders of magnitude higher than the ambient methane concentration of approx. 2.00 ppm that signifies high combustion activity.	Wind can dilute the concentration of methane inches above the surface.
Surface carbon monoxide flux	Landtec GEM 5k NAV	(ppm)	Handheld with flux chamber	No	Presence of carbon monoxide above coal fires	Carbon monoxide flux is usually only observed above coal fires.	High, steady flux of carbon monoxide from the ground above suspected coal fire regions indicate combustion below.	Local geography may prevent dense data sampling. Instrument sensitivity could be a limiting factor.
Mine Schematics								
Mine maps	DRMS archive	(-)	(-)	No	Mine diagrams showing mine shafts, entries, and coal seams that were mined	Old mine workings provide insight into the locations of high permeability conduits through which air and combustion gases can flow.	Mine workings that inersect the outcrop, as those areas tend to be good entry points for air flow into the subsurface.	Mine maps are not available at all of the sites, and when they are they may not be correctly geo-rectified.
Images								
Digital images	Cannon	(-)	Handheld	No	Surface anomalies of areas above coal fires	Changes in surface expressions over fires can supplement other data to track fire development.	Signs of dead vegetation, snowmelt, large fissures, and combustion gases.	Only qualitative damages caused by the fire can be documented using a camera.
Infrared images	FLiR camera	(-)	Handheld	No	Images of temperature anomalies above coal fires	Surface temperature anomaly pictures can help identify fissures that are currently covered by topsoil.	Hot fissures that are covered by topsoil.	IR cameras are only helpful in discovering fissures that are buried in the subsurface by a thin layer of topsoil. It is a mistake to assume that the IR image represents the subsurface nature of the fire. The camera is best suited for dcumenting surface temperature anomalies.

Table 3: A list of observations and measurements made to study coal fires in Colorado. These observations and data are integrated in order to gain a holistic understanding of a given fire.

Chapter 3

A CONCEPTUAL DIAGRAM OF HOW WELL-DEVELOPED FIRES BURN

A conceptual diagram that describes the coal consumption process is shown in Figure 12 represents a fire that has burned sufficiently far away from the outcrop, such that fresh air and combustion gases are entering and exiting the coal fire via fissures or abandoned mine features. This diagram is consistent with data collected and observed in the previous chapter. This conceptual diagram is most applicable for well-developed fires in the state, which include South Canyon East, Wise Hill, Skull Creek, Harvey Gap, Streeter, IHI No. 3, Sunshine, Black Diamond, and States Fires. These fires are some of the most active fires in the state, and they tend to burn into the formation, perpendicular to the strike. Understanding how coal is consumed at these sites is valuable for fire mitigation design. Other active fires are likely contained near the outcrop, and they burn along the strike rather than into the formation. Figure 3 (Chapter 1) is more suitable for explaining how those fires work.

In Figure 12, oxygen is provided to the fire as it is drawn into the subsurface through a cool fissure or a mine entry in Zone 1. Cool fissures or cool mine entries are located in areas where the fire was once active but have subsequently cooled.

Once air reaches the subsurface, a small pressure gradient that is induced by temperature differences between the subsurface and the surface draws the air through either abandoned mine workings and/or low resistance fractures which have apertures of 1 to 5 centimeters. This region is subsequently referred to as the High Permeability Zone. In

Figure 12, the High Permeability Zone is depicted as the area over the coal seam, but this zone can also exist within the coal seam; mine tunnels and haulage ways from old mine workings would be examples of High Permeability Zones inside of the coal seam.

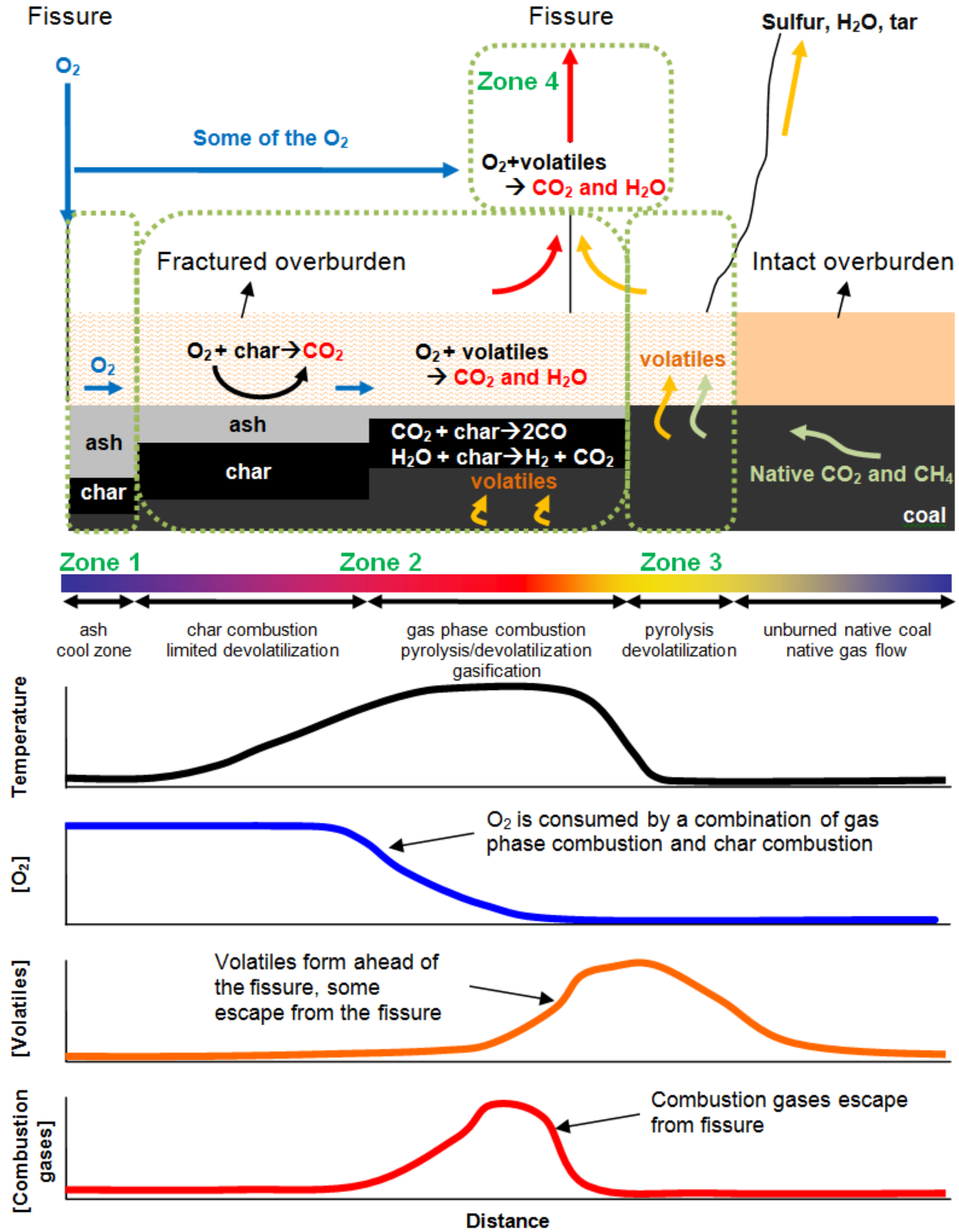


Figure 12: Conceptual diagram that shows subsurface coal consumption process.

A cross-section of the High Permeability Zone is shown in Figure 12 (gas flow is moving in and out of the page). It was photographed during an excavation project of the Soda Springs coal mine fire, near Durango, Colorado. It is evident that the hot combustion gases are moving through the High Permeability Zone.

Figure 13: A picture of the cross-section of a High Permeability Zone at the Soda Springs Mine Fire. The picture clearly shows that the smoke and the combustion is taking place in the High Permeability Zone. Only coal that is near the High Permeability Zone is affected. Most of the combustion reactions likely take place in the gas phase.

In Figure 12, the profiles below the conceptual picture are for temperatures and concentrations of gaseous species. The profiles approximate the conditions in the High Permeability Zone. In the colorbar, colder zones are represented by blue while hotter regions are represented by red. In Zone 1, the temperatures have begun to cool, due to less combustion taking place in the High Permeability Zone. Combustion reactions are not as active in this region for the following reasons:

1) The layer of ash on top of the coal prevents oxygen from easily accessing the char surface, and thus coal does not burn as easily; and
2) Gaseous species have been depleted from the coal seam in this region (because those species evolved first), and thus combustion reactions between oxygen and flammable gases do not occur here.

Although combustion reactions are not as active, there is heat trapped in the rocks in the area from combustion reactions that previously took place in the region. This residual heat warms the incoming air as it flows from Zone 1 to Zone 3.

In Figure 12, heated air from Zone 1 travels to Zone 2 through the High Permeability Zone. The heated air first comes into contact with char and ash, which are remnants of the coal after all of the gaseous species have left the coal. When sufficient concentrations of oxygen react with char, carbon dioxide and heat are produced. As the air propagates to the right, the air stream becomes depleted in oxygen. Under oxygen lean environments, incomplete combustion with the char will take place, and carbon monoxide is produced instead of carbon dioxide.

These complete and incomplete char-oxygen combustion reactions compete with a set of gas phase combustion reactions that are five orders of magnitudes faster. Gas phase combustion reactions include those between: oxygen-hydrogen, oxygen-carbon monoxide, oxygen-hydrocarbon species (methane, ethane, propane, butane, etc). Hydrogen, carbon monoxide, and methane evolve from the coal matrix when coal is heated. Hydrocarbons, which can include methane, likely migrate to the combustion zone from deeper parts of the basin. Many of the coal seams where coal fires occur in Colorado bears hydrocarbon gas. Such gases that are liberated downstream can break free and migrate towards the structurally higher outcrop where coal fires burn today,.

The heat that is produced in Zone 2 is likely transferred ahead of the combustion zone to the right as well as deeper into the coal seam. Areas affected by this heat transfer are defined as Zone 3 in Figure 12. When the coal seam temperature increases, volatiles will emerge from the coal. Unlike in Zone 2, where combustible gaseous volatiles react with oxygen, gases that are formed in Zone 3 may rise to the surface without reacting. This is because the oxygen is used up in the combustion reactions in Zone 2, leaving little or no oxygen molecules to react with the gases that evolve from the coal in Zone 3. Steam and water production dominate in regions that are ahead of the active combustion zone. Some elemental sulfur will also evolve in reducing environments (**Berkowitz, 1985**). Steam and gaseous tar that is produced in these areas can migrate upwards through pre-existing fractures and condense at the surface as it cools. This picture is consistent with the observed moisture, tar, and sulfur that occur over coal fires, which foreshadow the opening of a pre-existing fracture to form a fissure.

Zone 4 is defined in Figure 12 as the region inside of the hot fissures. As gases migrate upward through the chimney, combustible, gaseous species such as carbon monoxide, hydrogen, and methane, that did not react in the subsurface may react with additional air that is entrained through near surface fractures. This is evident in gas compositions collected from the Wise Hill boreholes #2 and #6.

When temperatures inside of the fissures are higher than the auto-ignition temperatures of the combustible volatiles, they can burn without an ignition source, assuming that the oxygen concentration limits are satisfied. Temperatures inside of the fissure, which can be as high as over 1000^{o}C, exceed the autoignition temperatures of carbon monoxide, hydrogen, and methane which are 609^{o}C, 500^{o}C, and 580^{o}C, respectively. Blue flames, which likely result from carbon monoxide combustion, were visible in the dark at the mouth of the fissure near the surface during early morning field visits. These additional combustion reactions keep the temperature of the gases in the fissure high, which makes the rocks glow such as in pictures presented on the South Canyon East fire in Chapter 5. Secondary combustion reactions in the fissures explain why carbon monoxide, hydrogen, and methane mole fractions are often non-existent or on parts per million levels at the top of the fissure where the gas samples are collected.

Moreover, these reactions enhance the temperature differential between the chimney temperature and the ambient air temperature. This in turn increases the buoyancy driven flow that circulates air and combustion gases through the subsurface. Zone 4 is not represented on the temperature and species concentration profiles.

Chapter 4

DISCUSSION OF FIRE FIGHTING TECHNIQUES

There are three necessary requirements to sustain combustion; fuel, oxygen, and heat. An effective fire fighting design requires removal of one or more of these key components. In addition, a detailed site characterization is important such that appropriate designs can be engineered and deployed in strategic locations such that one of these three combustion requirements can be effectively eliminated. In this section, several fire fighting techniques that are in literature are presented.

4.1 Removal of fuel sources

4.1.1 Coal removal

At any coal fire, removal of coal is the surest way to contain or extinguish an existing fire and to prevent future fires. There are a number of ways to remove the coal. The first way is to excavate the burning coal and surrounding overburden. This method of fire fighting is most applicable when the coal fire is contained along an outcrop. Data can show that a coal fire has not burned sufficiently into the formation. The excavated material is mixed and cooled, and sometimes mixed with additional incombustible fill before packing the material tightly in its original location. Tightly packing the return fill can reduce the ability for the fire to exchange air and combustion gases. Extra fill material may need to be added in order to make up for the volume lost due to compaction when returning the overburden.

Another way to remove coal without excavating the entire fire is to trench the coal seam ahead of the fire. In this method, a trench is dug ahead of the presumed coal fire front down to the coal seam. The trench is then backfilled with non-combustible material, such that when the fire arrives at the trench, it cannot continue to burn. Care should be exercised when choosing the incombustible material. In addition to being incombustible, the material should provide insulation such that heat is not easily transmitted from the hot side of the trench to the unburned coal seam. Even in the absence of oxygen, coal can undergo pyrolysis in the presence of heat. This leads to the release of volatile gases, some of which are combustible, and loss of coal volume. Loss in coal volume can lead to subsidence which may cause new fractures to form at the surface. These fractures in turn can deliver fresh air to the regions where volatile species are newly present. Under such a scenario, the fire could 'jump' the trenched area and commence burning on the previously un-combusted side of the trench.

A number of well-known examples have shown that trenching can be ineffective when the coal fire front is not accurately located. An example of a failed trenching project took place in Centralia, Pennsylvania, where several trenching efforts attempted to remove the coal that was believed to be in the pathway of the combustion front. In reality, the trench was mistakenly placed in the middle of a combustion zone, and it failed to prevent the propagation of the fire (**GAI Consultants, 1983**). In another example of trenching, a large scale trapezoidal trench–measuring over 300 meters long, 80 meters wide, and 40 meters deep was dug in the Jharia Coal Mines in Dhanbad, India. Due to poor characterization of the area prior to trenching, the trench was placed in the middle of the combustion zone.

Today, signs of fire exist on both sides of the trench. Trenching is a method that should be undertaken after a detailed characterization has been performed at any given fire site in order that the trench is appropriately located.

A controlled burn out of the coal seam can also be an efficient way to remove the coal from the subsurface, and it can be an effective fire fighting method, especially if this is coupled with well placed trenches. A controlled burnout is performed by forcing air through boreholes that are drilled near the combustion zone and drawing out the combustion gases using forced convection (**Kim and Chaiken, 1993**). This directs the flow of air entering the subsurface and limits the burning to a specific section of the field. The method of directing fresh air into an underground coal seam and removing combustion gases from the subsurface is similar to the Underground Coal Gasification (UCG) process, where steam and oxygen is injected through an injection well and carbon monoxide and hydrogen are removed at a nearby production well.

To deploy this method properly at a coal fire, the target coal seam should be isolated, and the locations of air inlets and exhaust outlets must be well documented. If not, hot gases may travel in unintended directions through the subsurface network. This type of fire fighting is most suitable for abandoned coal mine fires where the combustion zone can be isolated, and the shafts through which air and exhaust gases are flowing are well defined.

4.1.2 Methane removal

In a number of coal fire sites in Colorado, coal bed methane can migrate from deeper parts of the basin toward the outcrop under buoyancy flow. At a coal fire in the San Juan Basin, up dip flowing methane played an integral part in keeping the fire burning for over a decade.

To reduce the effect of transient methane on coal fires, wells can be drilled down dip of the coal fire in order to capture the rising methane before it reaches the atmosphere. Such methane capture wells exist in the San Juan Basin, and these wells have been shown to lessen the amount of methane emitted to the atmosphere through coal outcrops. Therefore, it is assumed that this methane capture also reduces the volume of methane available to the subsurface fire.

Wells with similar design as those in the San Juan Basin may be drilled in strategic locations to help combat fires in other Colorado Basins. Fires that are burning along the Grand Hogback of the Piceance Basin could benefit from this fire fighting technique. Firefighting by methane capture may be effectively employed at other coal fires such as Kaspar, Black Diamond, Skull Creek, and Wise Hill coal fires

4.2 Removal of heat

Removal of heat is another proposed method of fighting an underground fire. Kim and Chaiken, propose injecting cryogenic foam or liquid into the subsurface to remove heat from the system (**Kim and Chaiken, 1993**). Generation of such foam may be expensive, depending on how much is needed to remove the heat trapped in the subsurface. Sweep efficiency, or the ability for the injected foam to come into contact with the burning coal, in the subsurface would remain a problem. The injection design will have to be studied using a model to determine the path that it will take once it has been injected into the subsurface.

4.3 Removal of oxygen

A final method of firefighting is by excluding oxygen from the combustion zone. Traditional ways to exclude oxygen are by either covering the entire surface with a thick, low permeability surface cover (**Personal communications, 2010**), or by injecting grout into the subsurface to plug abandoned shafts and surface fissures (**McPhee, 1995; Williamson, 1999**). A low permeability cover usually consists of fine-grained earthen material compacted into place over the surface expression of a subsurface fire. Grout injection generally involves injecting low permeability cement grout into a subsurface fire via bore holes completed from the ground surface above a subsurface fire, thus isolating the burning materials from oxygen sources.

Theoretically, these methods work by preventing the escape of combustion gases and the entry of fresh air into the subsurface. However, successful implementation of these methods can be challenging. Low permeability surface covers can fail from natural erosion and/or subsidence. Grouting is difficult to successfully implement due to the inability to locate all of the fissures that are venting and providing air to the fire. In the case when grout is delivered to the subsurface through boreholes, difficulties in reaching all parts of the burning mine from the surface from the borehole remain.

Inert gas injection is another way in which the fire can be controlled by excluding oxygen from the combustion zone. There are three important design criteria to consider in an inert gas injection scheme. These are a) the amount of inert gas required to displace subsurface oxygen, b) the injection pattern in order effectively sweep the combustion zone, and c) the duration of injection required to remove the heat from the subsurface. A pilot inject test that was undertaken at the San Juan Basin in 2010 to demonstrate the feasibility of flooding a combustion zone with carbon dioxide. When the carbon dioxide was injected into the subsurface, it was drawn into the combustion zone by the same natural convection flow that was responsible for the circulation of air and combustion gases. The rise in carbon dioxide concentrations at multiple monitoring locations around the injection point showed that oxygen could be successfully displaced.

One potential problem with fighting fires by inert gas injection is the low heat capacities of gases, which limits the ability to quickly remove the heat trapped in the subsurface. Even if the inert gases can sweep the coal fire zones thus effectively and temporarily suspending exothermic reactions, the trapped subsurface heat must be removed in order to prevent the restart of natural circulation of air once injection ceases. If the injection is stopped before the subsurface temperature falls below the threshold devolatilization temperature, combustible volatiles will evolve from the coal. This would likely lead to exothermic combustion reactions between the volatiles and air in the fractured zone above the coal seam. One way to remove this subsurface heat would be to continue the inert gas injection until enough of the subsurface heat dissipates through the surface and the surroundings by conduction.

Chapter 5

STATUS OF COAL FIRES IN COLORADO

5.1 OVERVIEW OF THE FIRES EVALUATED

There are 35 fires listed in Table 4. Out of the fires included in Table 4, 19 fires remain active today. Of the 19 fires, a subset of 11 fires out of the 19 is considered highly active. The level of activity of the fires are noted under the ‘Status’ column in Table 4.

High activity includes features such as, but not limited to, combustion gases escaping from the fissures, high surface temperatures over a large area (> 30,000 ft^2), signs of new fissures forming, and new subsidence activities observed during semi-annual follow-up trips. Geologic conditions may vary across more complex sites. For example, the South Canyon West fire is burning at the outcrop under hundreds of feet of overburden. In contrast, the South Canyon East fire is burning along the outcrop but with minimum overburden covering the fire.

In another example, fires such as Skull Creek, and Kaspar are more or less located in one area and in one seam, whereas fires such as IHI No. 3, Wise Hill, Black Diamond, Harvey Gap, and Sunshine show pockets of combustion zones, and sometimes in two different seams.

Fire intensity at the surface also appears to differ from one site to the next. At Harvey Gap, the fire once burned at extremely high temperatures near the atmosphere, evidenced by the fused pyromorphic rocks along the outcrop. Such pyromorphic rocks were not discovered at the outcrops of 10 other highly active coal fire sites.

Fire Name	Latitude	Longitdue	Region	Coal Field	Formation	Seam	Mining method	Strike	Dip	Coal Rank	Coal thickness	Approximate area affected	Status
Wise Hill Number 3 / Hart	40.4317	-107.6460	Green River	Yampa	Williams Fork	H (Middle Coal)	Drift	N20W	8o	HvC/HvB	~5 to 10	836,000	Highly Active
Kaspar	40.3381	-107.1342	Gren River	Yampa	Williams Fork	Wadge (Middle Coal)	Stope	N30W	28o	HvC/HvB	<10	84,000	Highly Active
North Coal Fire	37.0358	-108.1077	San Juan River	Durango-Pagosa Springs	Fruitland	Lower	Unmined	N25E	12o	HvA	~25	650,000	Active
Soda Springs	37.0531	-108.1044	San Juan River	Durango-Pagosa Springs	Fruitland	Lower	Drift	N25E	12o	HvA	~25	215,000	Dormant
McElmo	37.3386	-108.5803	San Juan River	Nucla-Naturita	Dakota	Unnamed	Drift	*	4o	*	*	*	*
New Cast No. 3	39.5732	-107.5438	Uinta	Grand Hogback	Williams Fork	*	Stope	N65W	56o	HvB	<50	850,000	Highly Active
Haas / IHI No. 2	39.6195	-107.7318	Uinta	Grand Hogback	Williams Fork	Wheeler	Stope	N75W	57o	HvA	<50	78,000	Low activity
IHI No. 3 (D&H)	39.6206	-107.7350	Uinta	Grand Hogback	Williams Fork	Wheeler	Stope	N75W	57o	HvA	<50	941,000	Highly Active
Coryell	39.5681	-107.5355	Uinta	Grand Hogback	Williams Fork	Wheeler, D, U, E	Drift	N60W	53o	HvB	<50	280,000	Low activity
New Castle Number 1	39.5610	-107.5123	Uinta	Grand Hogback	Williams Fork	Allen	Drift	N67W	50o	HvB	*	280,000	Low activity
Vulcan	39.5609	-107.5067	Uinta	Grand Hogback	Williams Fork	Wheeler	Stope	N63W	47o	HvB	<50	280,000	Low activity
Elk Creek	39.5889	-107.5878	Uinta	Grand Hogback	*	*	Drift	N73W	54o	HvA	*	*	Active
Morgan	39.5940	-107.6034	Uinta	Grand Hogback	Williams Fork	Wheeler	Stope	N45W	53o	HvA	<50	*	Active
Harvey Gap	39.6011	-107.6651	Uinta	Grand Hogback	*	*	Drift	N55W	53o	HvB	*	123,000	Highly Active
South Canyon East	39.5309	-107.4078	Uinta	Grand Hogback	Williams Fork	Wheeler, D, U, E	Stope	N60W	53o	HvA	<50	762,000	Highly Active
South Canyon West	39.5364	-107.4210	Uinta	Grand Hogback	Williams Fork	Wheeler, D, U, E	Stope	N61W	54o	HvA	<50	762,000	Highly Active
South Canyon No. 1	39.5361	-107.4195	Uinta	Grand Hogback	Williams Fork	Wheeler, E	Stope	N53W	57o	HvA	<50	*	Dormant
Sunshine	39.4025	-107.3253	Uinta	Grand Hogback	*	*	Stope	N14W	40o	HvB	*	903,000	Highly Active
Pocahontas	39.4113	-107.3224	Uinta	Grand Hogback	*	*	Drift	N17W	42o	HvB	*	0	Dormant
Black Diamond	40.0569	-107.9267	Uinta	Danforth	Williams Fork	Fairfield, Goff, or Lion	Slope	N60E	18o	HvC/HvB	<10	30,000	Highly Active
Rienau Numer 2	40.1124	-107.8470	Uinta	Danforth	Williams Fork	Fairfield, Goff, or Lion	Drift	N30W	18o	HvC/HvB	<10	*	Active
Streeter / Collon	40.2625	-107.7903	Uinta	Danforth	Williams Fork	Fairfield, Goff, or Lion	Slope	*	2o	HvC/HvB	<10	*	Highly Active
Skull Creek	40.1847	-108.8028	Uinta	Lower White River	*	Seems B or D	*	N60E	4o	HvC	*	89,000	Highly Active
Minnesota Creek	38.8817	-107.5233	Uinta	Somerset	*	*	*	*	*	HvB/HvA	*	*	*
Oliver	38.9248	-107.4317	Uinta	Somerset	*	Oliver	*	N90W	3o	HvB/HvA	*	*	*
States	38.9281	-107.9492	Uinta	Grand Mesa	Mount Garfield	One of A through F	Drift	N54W	6o	SubC to HvA	*	68,000	Low activity
Go Boy	39.1259	-108.3110	Uinta	Book Cliffs	Mount Garfield	Cameo	Slope	N25W	2o	HvC	<23	0	Dormant
Garfiled	39.1272	-108.3813	Uinta	Book Cliffs	Mount Garfield	Palisade	Drift	N20W	11o	HvC	*	*	Active
Farmer's Mutual	39.2248	-108.5063	Uinta	Book Cliffs	Mount Garfield	Cameo	Slope	N35W	3o	HvC	<23	0	Dormant
Lewis No. 1 and 2	39.9564	-105.2223	Denver	Boulder-Weld	Laramie	*	Slope	N45E	4o	Lignite A to SubA	*	0	Dormant
Marshall No. 1 and 2	39.9547	-105.2294	Denver	Boulder-Weld	Laramie	*	Drift	N45E	4o	Lignite A to SubA	*	0	Dormant
Bright Diamond / Slagle	38.2706	-107.6622	San Juan River	Tongue Mesa	*	*	Drift	*	*	SubC/SubB	*	*	Active
Riach	40.5604	-106.4396	North Park	Coalmont	Coalmont	Riach	Slope	*	*	SubC/SubB	<80	*	Active
Double Dick Vicinitiy	38.2908	-105.1669	Canon City	*	Vermljo	Brookside	Drift	N5E	4	*	*	*	*
Morley Waste-Dump	37.0344	-104.5075	Raton Mesa	*	*	*	*	*	*	*	*	*	*

Table 4: Key facts such as the geological formation, estimated thickness of the coal seam(s) affected by the fire, and the method of mining are presented for each fire.

Dormant fires do not necessarily indicate that the fires are permanently dormant. However, dangers associated with fire activity or fast spreading of the fire were not present at the time of the survey. The most telling sign of a dormant fire was that snow accumulated over the presumed fire region after a snow storm.

It is important to remember that the assessments of these fires are based on a high order characterization. More detailed characterizations will need to be carried out in order to design optimal solutions to control and/or extinguish these fires.

5.2 Locations of the Fires Evaluated

Figure 14 is a map showing the known locations and names of fires in Colorado. Field data was collected at most of these fires, while at other fires. The most active fires are bounded by red boxes. These were also noted in Table 4. In the following section, summaries and data collected, where available, are presented.

Figure 14: Location and names of known coal fires in Colorado. The most active fires are enclosed by red boxes.

5.2 Executive summaries and data of fires evaluated

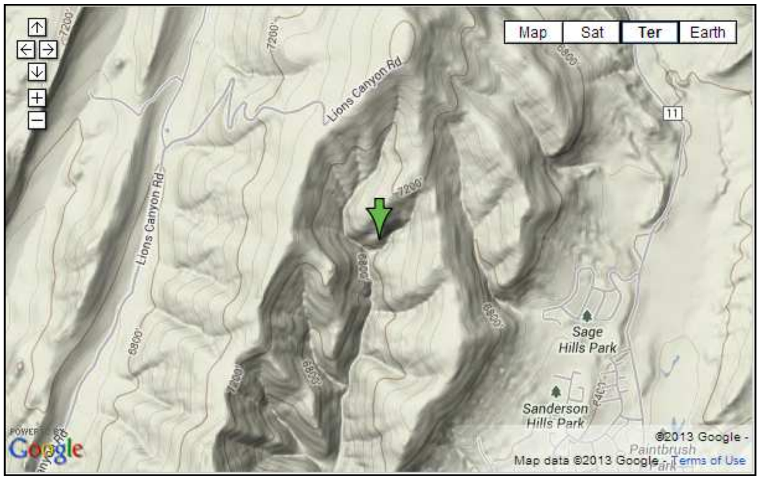
This section presents executive summaries and mapped data at many of the coal fires listed in Figure 14.

The presentation is organized as follows:

- Alphabetical presentation of all fires with data available
- Alphabetical presentation of fires where only minimal data is available

Minimal data is available for: Double Dick, Elk Creek, Garfield, McElmo, Minnesota Creek, Morley Waste Dump, Morgan, Oliver, Riach, Rienau, and Slagle. At all other fires, various data such as geological, geophysical, gas composition, gas isotope, and surface features were collected.

Black Diamond



Summary:

Location (lat/long): 40.0569 /-107.9267
Region / Coal field: Uinta / Danforth
Formation: Williams Fork
Seam: Fairfield, Goff, or Lion
Mining method: Slope
Strike / Dip: N60E / 18^o
Coal Rank: HvC/HvB
Coal Thickness Affected (ft): <10
Area Affected (ft^2): 30,000
Status: Active

Data Gathered:

- Gas composition
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Black Diamond fire is located in Meeker, CO (Rio Blanco County). To reach this fire from either Denver or Grand Junction, take Hwy. 13N to Meeker. Take a slight right at the fork to continue on 13N towards downtown Meeker. Take a left onto 12th St., then another left after 5 blocks, on Hill St. After parking on Hill St., go through the gate at the west end of the street. Follow the gravel road, which turns into Anderson Gulch. Follow the Anderson Gulch until it dead-ends. Facing north, the Black Diamond fire is located to the right.

Key Observations from Mapped Data:

The Black Diamond fire appears to be burning in two separate locations along a NE oriented coal outcrop. Of the two active regions, the fire burning at the northern end is more active. Pictures taken at the site show presence of sulfur and ammonium chloride, which indicates that the fire is beyond the earliest stages (early stage fires vent water rich gases) and in the process of heating up. Methane was detected in low single digit mole percentages when gas compositions were measured at this site.

Snowmelt regions that were mapped at the site were near the outcrop. Snow does melt around the less active fire location to the south, but to a lesser extent compared to the snowmelt around the north end of Black Diamond coal fire.

Magnetometer results differentiated between the burned region and currently active region. The snowmelt boundary locations and the magnetometer anomalies agree well. Snow melted immediately over areas where the magnetic anomaly signals were the strongest.

Risk Factors:

While this fire is sufficiently far from the town of Meeker, the fire is easily accessible by a trail called the Anderson Gulch. Surface vegetation may pose risk as a fire hazard in the summer time.

Recommendations:

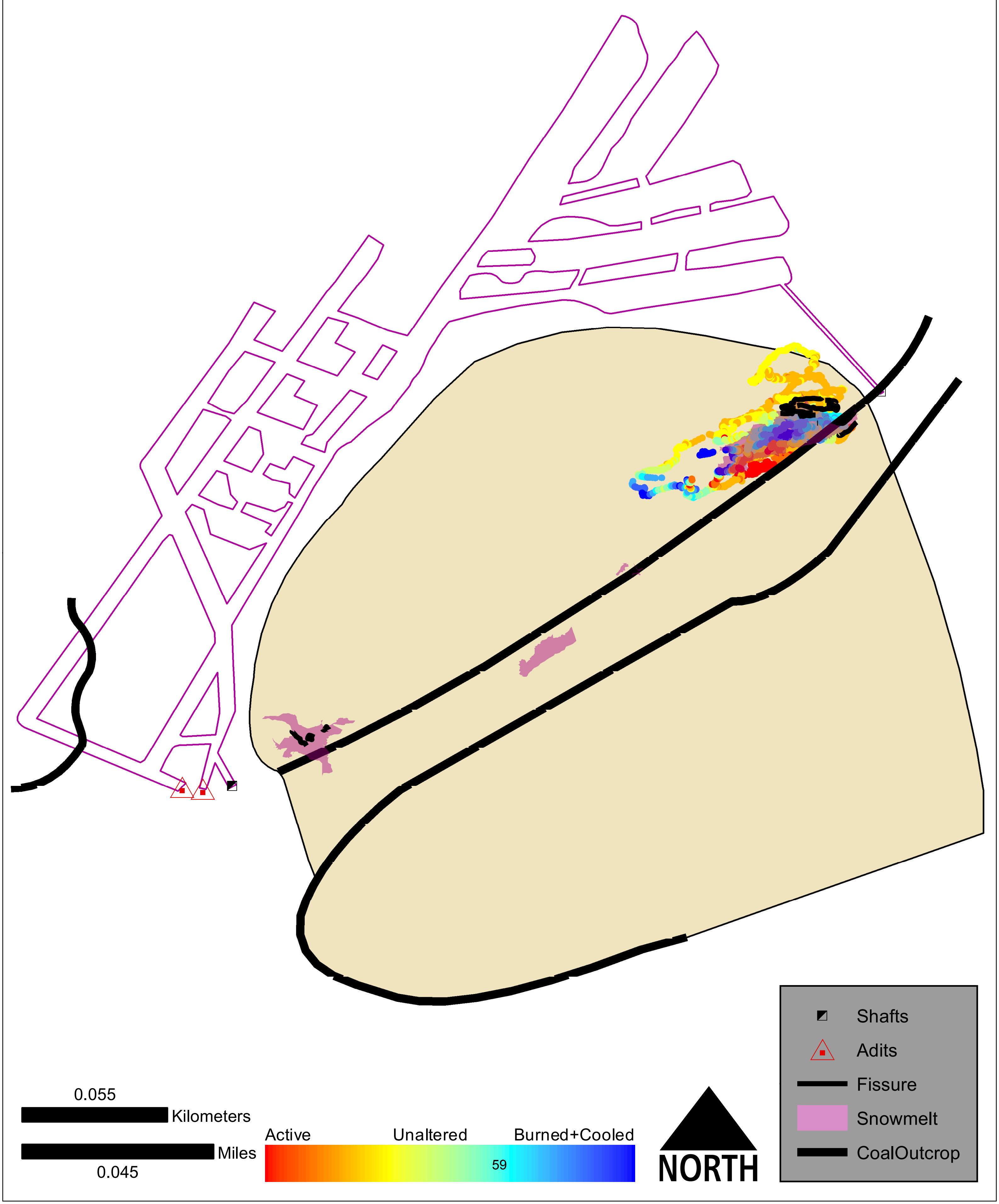
The Black Diamond fire seems to be contained near the outcrop. Therefore, excavating this fire may be a cost effective way to extinguish the fire. Although the Anderson Gulch provides an easy access to this fire, it is unlikely that it is wide enough for an excavator. Trees that are immediately above the active fire zones should be removed to alleviate the risk of a forest fire. High methane content in the gases also suggests that methane interception may be an effective way to fight the fire.

Hot combustion gases (left) and sulfur crystals (right) observed at the surface

Surface fissuring activity at Black Diamond

Looking to the north east at Black Diamond on a sunny day (left) and after a snowstorm (right)

Black Diamond



Coryell

Summary:

Location (lat/long): 39.5681 / -107.5354
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler, D, U, E
Mining method: Drift
Strike / Dip: N60W / 53^{o}
Coal Rank: HvB
Coal Thickness Affected (ft): <50
Area Affected (ft^2): 280,000
Status: Low activity

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Borehole drilling
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

There are four fires located near New Castle, CO (Garfield County) along the Grand Hogback. Three of these fires, Vulcan, Coryell, and New Castle No. 1 (from east to west) are located immediately south of and parallel to I-70 in New Castle. To reach these three fires, take Exit 105 off of I-70 and head South away from downtown New Castle. At the T-intersection, take a left onto CO Rd. 335 and head west. In order to reach either the New Castle No. 1 or the Coryell fire, park near the thrift shop and hike up the Hogback. To arrive at the Vulcan fire, take a right at the T-intersection onto CO Rd. 335 and head east, then park at the old coal loading dock and hike up the Hogback to reach the site.

Key Observations from Mapped Data:

The three fires that are burning south of I-70 are all slow burning. Methane was detected along the Grand Hogback where Vulcan, Coryell, and New Castle No. 1 are burning, so it is possible that methane is a contributing factor in keeping the fires burning. The methane signature collected near this site had the same signature as the methane that is being commercially produced from the same coal formation in the Piceance Basin.

However, a CO_2 sample that was collected at this site shows that the CO_2 originated from chemically transforming the coal. More CO_2 samples must be collected from this area to definitively understand whether the methane plays a significant role.

All three of these fires exhibit very low fire activities. This is corroborated by the fact that snow melts very slowly at these sites. The magnetometer survey shows that the fire has not migrated too far into the formation away from the outcrop. At these fires, the overburden is too thick to form fissures that are necessary to burn far into the formation. Crown coals that were left as a part of the mining operations are likely being consumed by the fire today.

Risk Factors:

Because coal consumption at these fires is extremely slow, there are no immediate risks associated with these fires. These fires are hard to access due to the steep incline and heavy brush to reach the fires.

Recommendations:

Methane removal from the site may help slow down or extinguish the fire. However, further methane seepage analysis must be undertaken before this option is seriously considered. The methane survey conducted under this contract showed that while there is a presence of methane at these fires, they do not always participate in the combustion process.

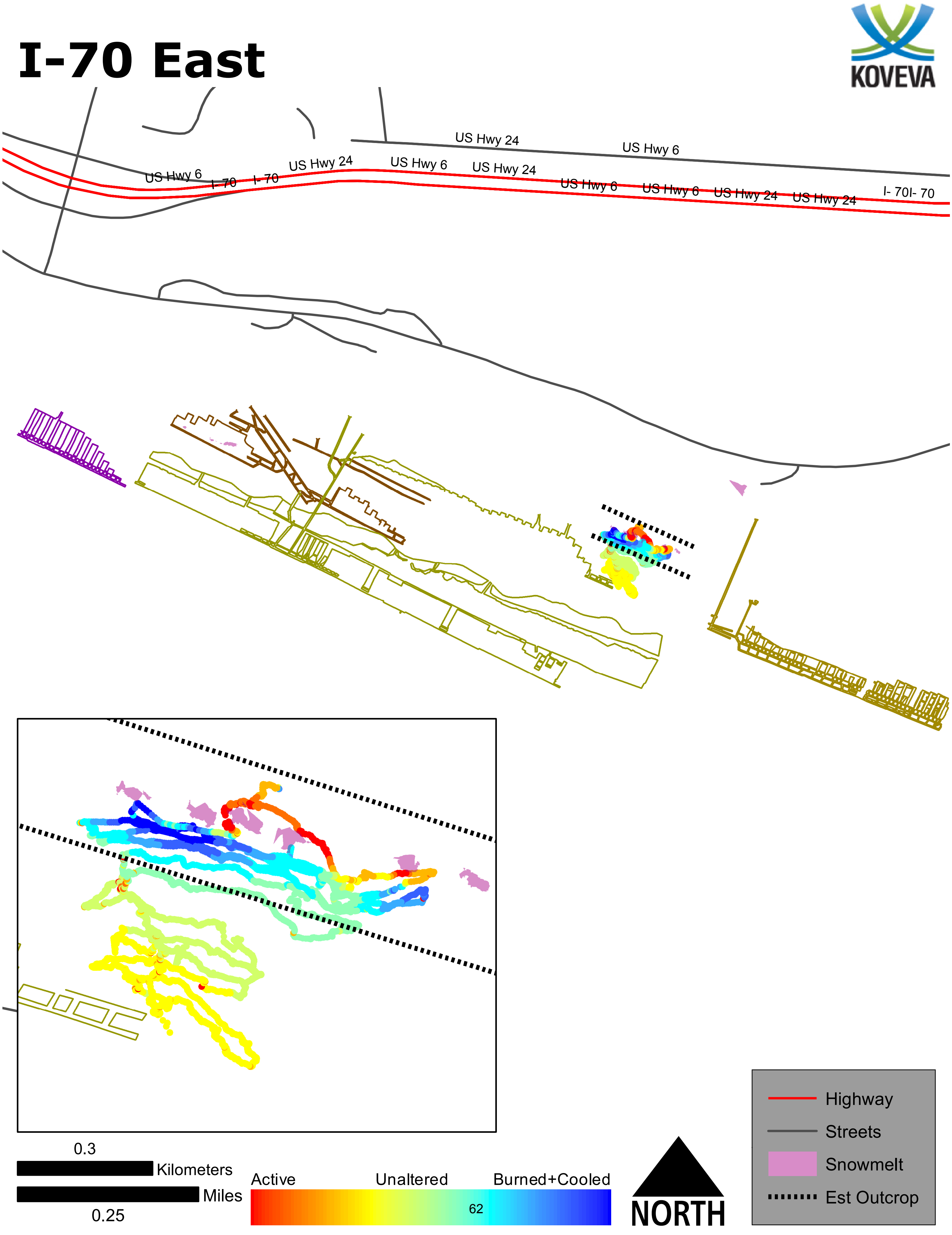
Other conventional methods of fire fighting may be hard to implement here due to the steep terrain in the area.

Coryell during a snowstorm

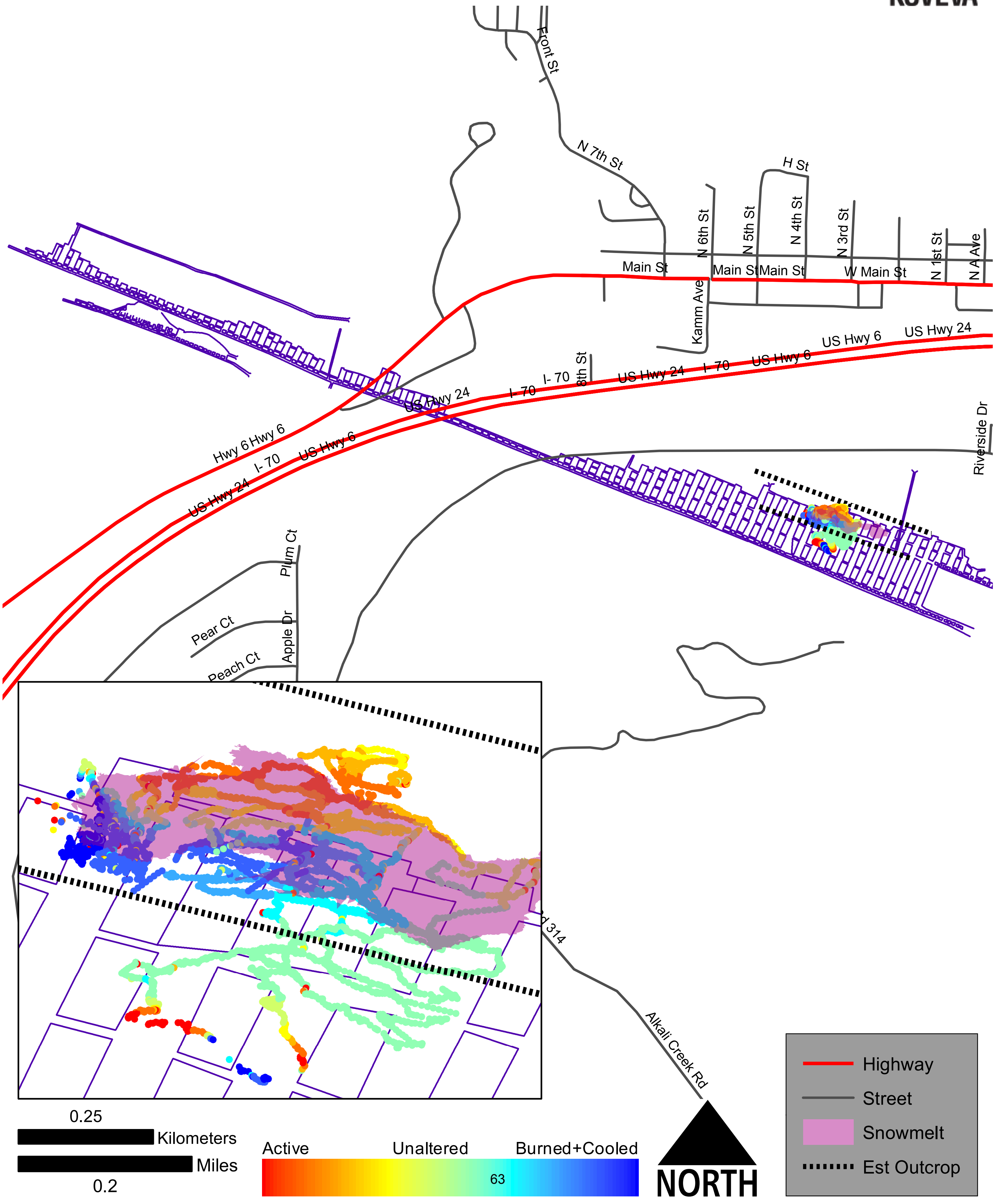
Outcrop containing Coryell, New Castle No. 1, and Vulcan

Outcrop containing Coryell, New Castle No. 1, and Vulcan after a snowstorm day
(Hogback on the right side of the picture)

I-70 East


KOVEVA
US Hwy 24
US Hwy 6
US Hwy 6
I- 70
I- 70
US Hwy 24
US Hwy 6
US Hwy 24
US Hwy 6
US Hwy 6
US Hwy 24
US Hwy 24
I- 70I- 70
0.3
Kilometers
Miles
0.25
Active
Unaltered
Burned+Cooled
62
NORTH
Highway
Streets
Snowmelt
Est Outcrop

I-70 West



KOVEVA
Front St
N 7th St
H St
N 6th St
N 5th St
N 4th St
N 3rd St
N 1st St
N A Ave
Main St
Main St
Main St
W Main St
Kamm Ave
US Hwy 6
US Hwy 24
I- 70
US Hwy 6
US Hwy 24
I- 70
8th St
I- 70
US Hwy 24
Hwy 6
Hwy 6
I- 70
US Hwy 6
US Hwy 24
Riverside Dr
Plum Ct
Pear Ct
Apple Dr
Peach Ct
314
Alkali Creek Rd
0.25
Kilometers
Miles
0.2
Active
Unaltered
Burned+Cooled
63
NORTH
Highway
Street
Snowmelt
Est Outcrop

Farmer’s Mutual

Summary:

Location (lat/long): 39.2248 / -108.5063
Region / Coal field: Uinta / Book Cliffs
Formation: Mount Garfield
Seam: Cameo
Mining method: Slope
Strike / Dip: N35W / 3^o
Coal Rank: HvC
Coal Thickness Affected (ft): <23
Area Affected (ft^2): 0
Status: Dormant

Data Gathered:

- Field observations
- Photos
- Mine maps

Directions:

The Farmer’s Mutual fire, which is now dormant and inactive, is located near Grand Junction, CO (Mesa County). To reach this fire from Grand Junction, travel north on N. 12th St. towards Grand Junction Regional Airport. Take a left on G Rd, then a right on 25 Rd. After approximately 3 miles, take a right onto the dirt road to stay on 25 Rd. Drive over a small water canal, and follow the dirt road for approximately 6.5 miles where the road becomes inaccessible to cars. Park the car, and follow the dirt path for about a quarter mile. The Farmer’s Mutual fire is on the right.

Key Observations from Mapped Data:

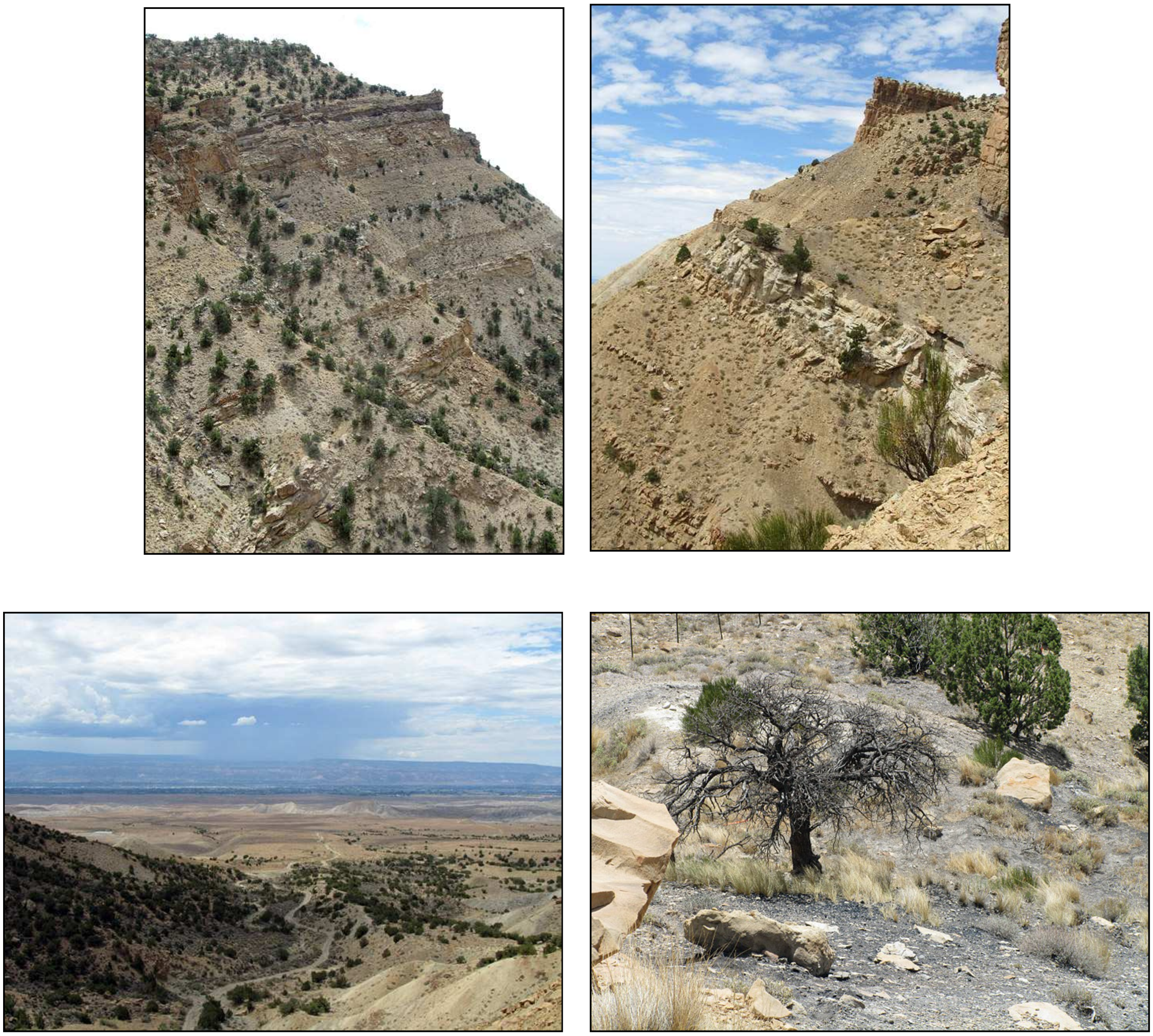
The Farmer’s Mutual fire was visited on two different occasions, once in the Fall of 2012 and again in the Spring of 2013. During both visits, there were no evidences of the fire. Snowmelt was not observed along the coal outcrop on 25 Rd. on the day of a snowstorm. The fire is currently dormant. The data map included with this file shows the 25 Rd. with respect to the old mine workings. The entryway to the mine workings is now covered, but it was presumably accessible from the 25 Rd. in the past.

Risk Factors:

Currently, there are no significant risks associated with this site because the fire is dormant. It is unlikely that the fire will suddenly grow out of control.

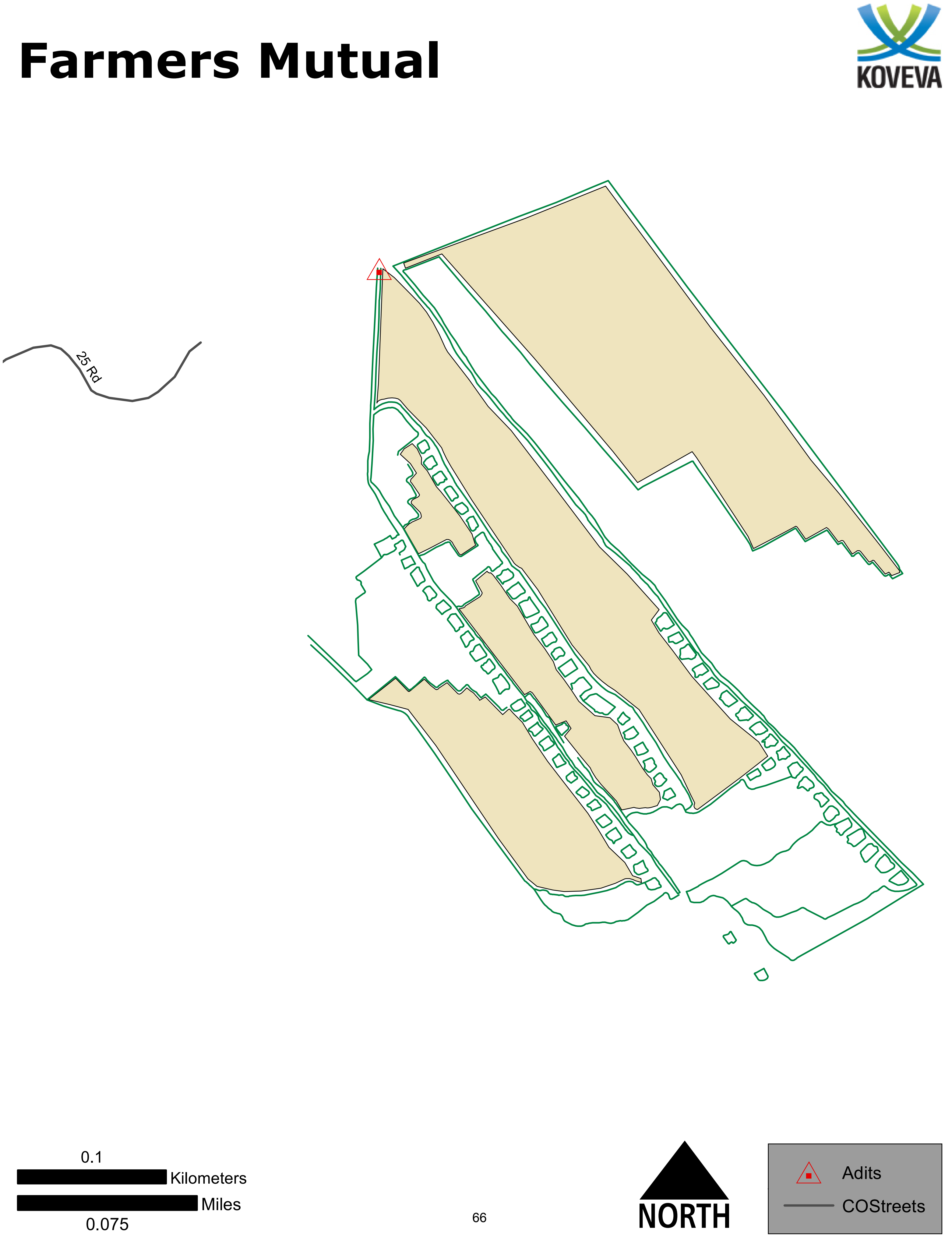
Recommendations:

Given the fire’s dormant state today, it may suffice to monitor the fire for fire activities only periodically, perhaps once every 6 months. Signs to watch for are, but not limited to, moisture on the ground, smells of creosote, and the formation of crystals such as sulfur and ammonium chloride.

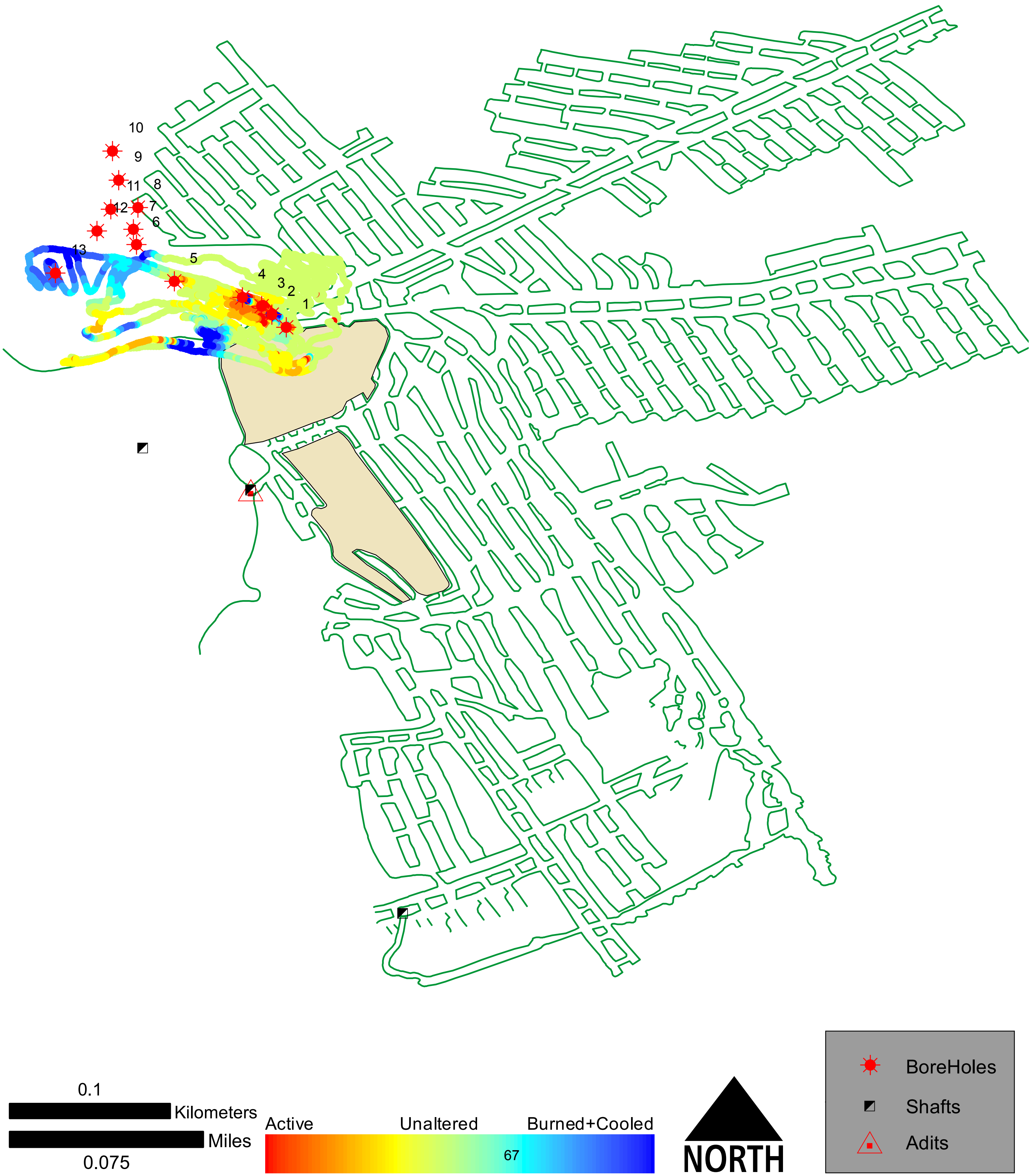


Coal outcrops and views near the Farmer's Mutual fire.
Currently, there are no signs of active fires at the site.

Farmers Mutual

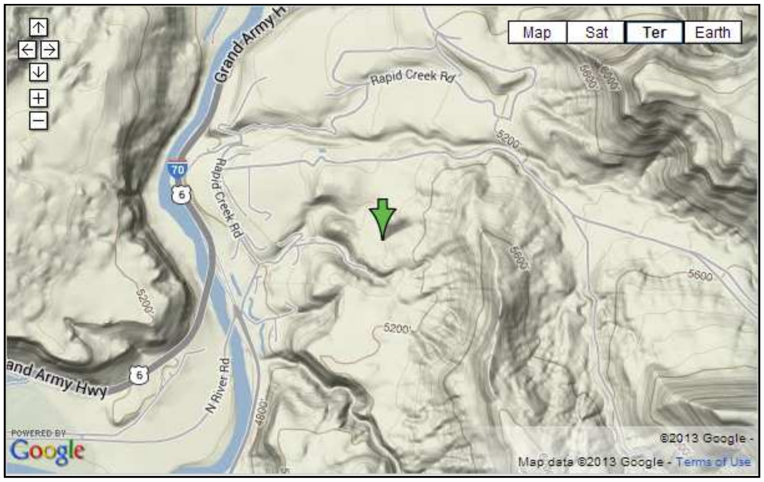


Go Boy



10
9
11
8
12
7
6
13
5
4
3
2
1
0.1
Kilometers
Miles
0.075
Active
Unaltered
Burned+Cooled
67
NORTH
BoreHoles
Shafts
Adits

Go Boy



Summary:

Location (lat/long): 39.1259 / -108.3110
Region / Coal field: Uinta / Book Cliffs
Formation: Mount Garfield
Seam: Cameo
Mining method: Slope
Strike / Dip: N25W / 2^{o}
Coal Rank: HvC
Coal Thickness Affected (ft): <23
Area Affected (ft^2): 0
Status: Dormant

Data Gathered:

- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Go Boy fire (now dormant) is located near Palisade, CO (Mesa County). To reach this fire from Palisade, take G Rd./U.S. Hwy. 6E towards Denver. Take a slight right onto Rapid Creek Rd., which is the last possible right before merging onto I-70E. Travel approximately 0.6 miles on Rapid Creek Rd. and take a right towards the water treatment facility. Park the car at the gate (unless a key is available). Follow the road for about half a mile and take a right (there will be another locked gate). After going through the gate, proceed for another half a mile to reach the fire. The dormant Go Boy fire is on the left.

Key Observations from Mapped Data:

Go Boy is currently dormant. There is an area of very slight activity near the outcrop, but it is not enough to melt the snow on a heavy snow day. The activity level at the surface is similar to the fire activity level that is observed at the lower bench at the States fire in Delta, CO. There are signs that fire previously burned at this location, such as thermally altered rocks and ash along the coal outcrop.

Steel casings that house thermocouple wires were all cold to the touch. These pipes were installed near the coal outcrop at the Go Boy fire several years ago by the DRMS. If there was a fire burning today, the pipe temperatures would be elevated due to conductive heat transfer.

The Go Boy data is mapped on the following page. Old mining plans are plotted along with magnetometer data (colored lines) and wellheads that hold thermocouple wires in place (red dots). The red areas shown by the magnetometer survey is not indicative of a fire. The high magnetic anomalies can be attributed to the metallic wellheads. The blue regions at Go Boy likely signify areas that were once very hot but have subsequently cooled. The magnetometer data is consistent with the lack of snowmelt on a snow day.

Risk Factors:

There are no known key risks at the Go Boy fire.

Recommendations:

A periodic monitoring of the fire to verify its dormancy is recommended.

Old mining road near Go Boy

Coal outcrop at Go Boy

Thermocouples installed at Go Boy

Harvey Gap

Summary:

Location (lat/long): 39.6011 / -107.6650
Region / Coal field: Uinta / Grand Hogback
Formation: no data
Seam: no data
Mining method: Drift
Strike / Dip: N55W / 53°
Coal Rank: HvB
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 123,000
Status: Active

Data Gathered:

- Magnetometer
- Magnetic susceptibility
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface feature

Directions:

The Harvey Gap fire is located north of Silt, CO (Garfield County). To reach this fire from either Grand Junction or Denver, exit I-70 at the Silt exit and head North on 9th St. take a left on Main St. Go west on Main St. for eight blocks, then take a right on N. 1st St./CO Rd. 231. Follow this road until a T-intersection, and take a left on Silt Mesa Rd./CO Rd. 233. Take a right onto Harvey Gap Rd./CO Rd. 237, and take the right-most fork after half a mile, then continue on Harvey Gap Rd. for 2.5 miles, then take a left onto a dirt road. This dirt road is located before the small parking lot along the left side of the road or the Grass Valley Reservoir.

Key Observations from Mapped Data:

Two different coal seams appear to be on fire at the Harvey Gap coal fire. Outcrop locations of both of these seams were identified during the site visit. The fire is currently migrating to the west along both outcrops.

The lower coal seam has a thick overburden, making the mechanics of this fire similar to the South Canyon West coal fire, while the upper coal seam only has a thin overburden, much like the South Canyon East and Kaspar coal fires. The top seam has more potential to migrate further along the dip (down the coal seam, away from the outcrop) since the overburden can crack and form fissures that are needed for the circulation of air and combustion gases.

The fire most likely burned at extremely high temperatures in the past. In addition to red, thermally altered sandstones and shale, there are rocks that have fused together. Rock samples collected from this site demonstrated that the concentration of magnetites will increase in the overburden when subjected to heat in an oxygen lean environment. The alignment/misalignment of these magnetites to the Earth's magnetic field helps distinguish between burned and cooled, active, and unburned sites.

Risk Factors:

The Harvey Gap fire is easily accessible from the road and the fire is actively expanding to the west. It is possible that surface vegetation may ignite due to the subsurface fire.

Recommendations:

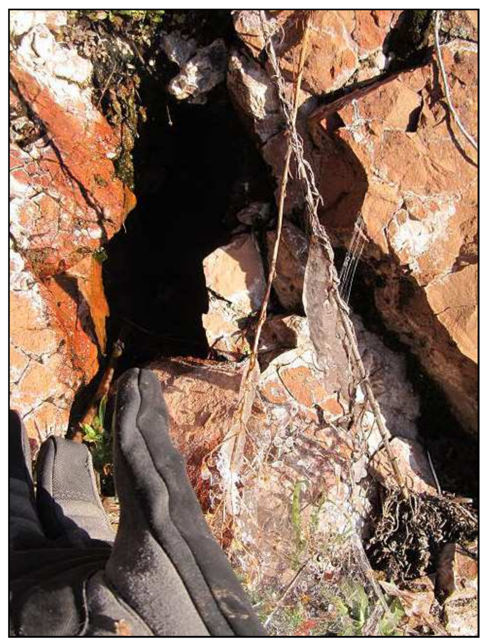
Excavation of Harvey Gap fire must be undertaken with care, since it appears that there are two active fires at this site. Excavating one fire may lead to exacerbating the other fire.

If water rights can be obtained from the Grass Valley Reservoir, this may be a fire that can be fought by injection of fire retardant cement/foam in strategic locations.

Because methane seepage in this area is likely based on coal quality and the upturned strata geometry, methane interception down dip of the fire may help to slow the fire down.

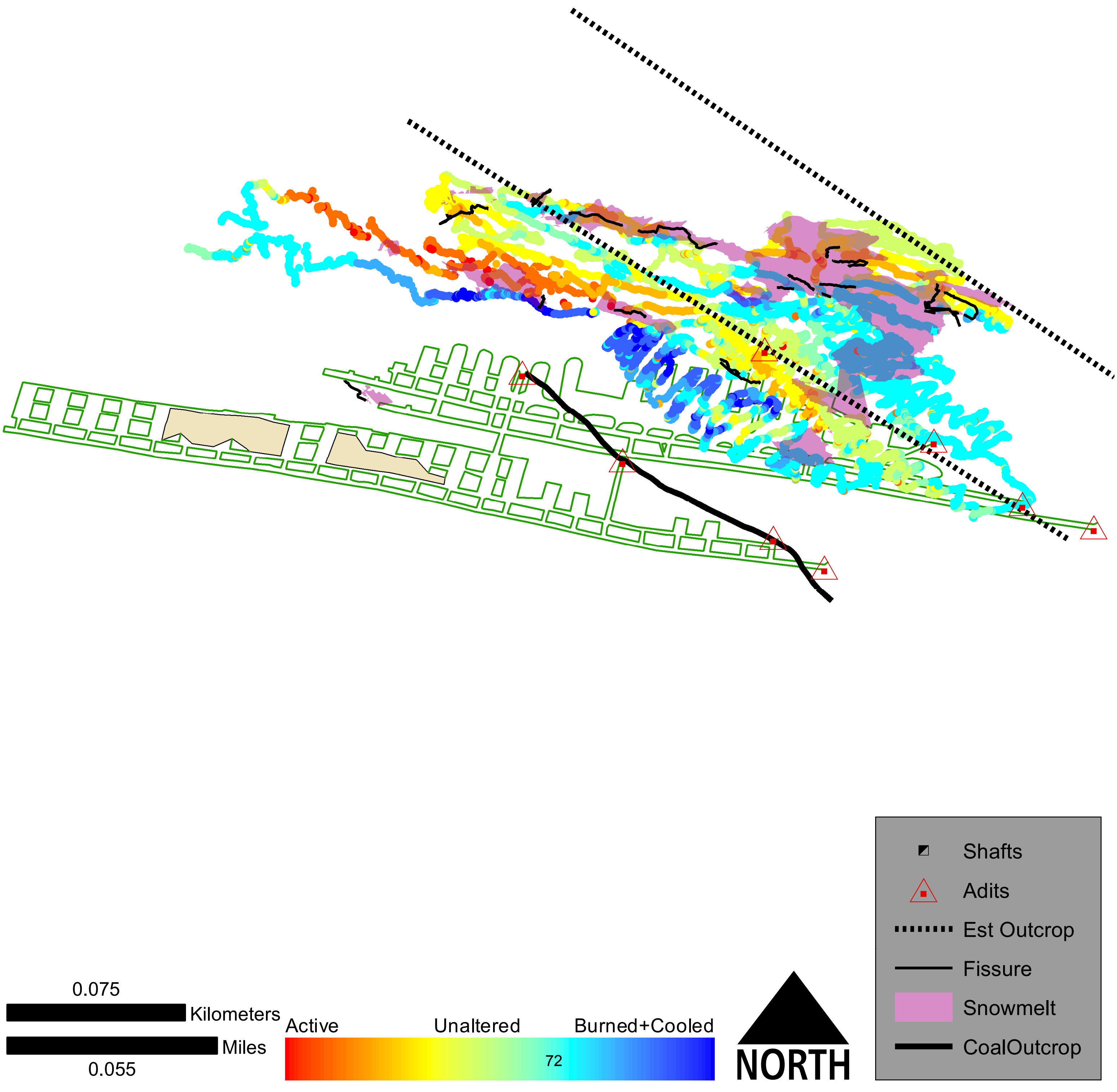
Grout injection is also an option. In order for grout to be injected, the coal mine map location will have to be rechecked to accurately estimate the volume of grout required. It appears that the old coal mine map is not properly geo-rectified.


A picture of the snowmelt boundaries show that two different seams are on fire (left).
The two seams are separated by a region where snow is not melted. The picture is taken looking in the SW direction. A coal seam outcrop is shown in the picture on the right.

A pyromorphic rock (left) indicating a very active coal fire in the past. This area is now cool.
An icicle has formed at the edges of a newly formed fissure (right), suggesting coal dehydration. Coal dehydration is associated with early stages of a coal fire.

Harvey Gap


Shafts
Adits
Est Outcrop
Fissure
Snowmelt
CoalOutcrop
0.075
Kilometers
Miles
0.055
Active
Unaltered
Burned+Cooled
72
NORTH

IHI No. 2 / Haas

Summary:

Location (lat/long): 39.6195 / -107.7317
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler
Mining method: Stope
Strike / Dip: N75W / 57^{o}
Coal Rank: HvA
Coal Thickness Affected (ft): <50
Area Affected (ft^2): 78,000
Status: Low activity

Data Gathered:

- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Haas (IHI No. 2) fire is located north of Rifle, CO (Garfield County). To reach the Haas (IHI No. 2) fire, take Exit 90 off of I-70 and head north on Hwy. 13N. Continue on Hwy. 13N then take a right onto Hwy. 325N and follow it for approximately 1.4 miles. Take a right onto N. Hasse Ln./CO Rd. 251, and continue to follow this road until it reaches a Y-intersection. This road is not traversable in the winter time. During the winter, it is advisable to park the car about 2.3 miles after taking the right onto N. Hasse Ln. then walking. Follow the Y-intersection to the right to reach the Haas fire. It is located about 3.5 to 4.0 miles after turning onto the N. Hasse Ln.

Key Observations from Mapped Data:

At the Haas coal fire site, there are many areas where the snow is melted, but the cumulative snowmelt area is not significant. It appears that the snowmelt follows underground mining shafts. Since the mine map in the area appears to be mis-plotted (the orientation appears to not follow the strike of the coal seam). it is currently not possible to align the snowmelt with mining features.

Fire activity at this site is very low. There are no active vents that are observed, and combustion gases appear to be diffusing slowly through the surface. It is believed that the leftover crown coal is on fire.

The Haas coal fire seems to have reduced in size and slowed between 2011 and 2013.

Risk Factors:

The Haas coal fire is hard to access, and there are no vegetations immediately at risk of ignition from the fire. This fire does not seem to be expanding; rather it appears to be extinguishing naturally.

Recommendations:

Because the fire has continued to shrink in size over the past two years, a periodic survey to monitor this trend is sufficient.

IHI No. 3

Summary:

Location (lat/long): 39.6205 / -107.7349
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler
Mining method: Stope
Strike / Dip: N75W / 57°
Coal Rank: HvA
Coal Thickness Affected (ft): <50
Area Affected (ft^2): 941,000
Status: Active

Data Gathered:

- Magnetometer
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The IHI No. 3 fire is located north of Rifle, CO (Garfield County). To reach the IHI No. 3 fire, take Exit 90 off of I-70 and head north on Hwy. 13N. Continue on Hwy. 13N then take a right onto Hwy. 325N and follow it for approximately 1.4 miles. Take a right onto N. Hasse Ln./CO Rd. 251, and continue to follow this road until it reaches a Y-intersection. This road is not traversable in the winter time. During the winter, it is advisable to park the car about 2.3 miles after taking the right onto N. Hasse Ln. then walking. Follow the Y-intersection to the left to reach the IHI No. 3 fire. It is located about 3.5 to 4.0 miles after turning onto the N. Hasse Ln.

Key Observations from Mapped Data:

The IHI No.3 mine is still active, but it seems to be less active than when it was reported in Renner's 2005 report. Magnetometer surveys conducted at this site in 2012 show that the fire front has not advanced significantly for years, since the results agree well with a previous magnetic anomaly survey that was conducted by another third party group in 2009/2010.

While snowmelt is extensive in this area, the magnetometer survey from 2012 suggests that much of the once-active areas in IHI No. 3 area are cooling. The heat at the surface of IHI No. 3 is likely due to the residual heat from previous fire activities.

Based on the location of the fire, it appears to be contained near the outcrop. Assuming that the coal was mined using the stope-mining method, the crown coal is on fire.

Risk Factors:

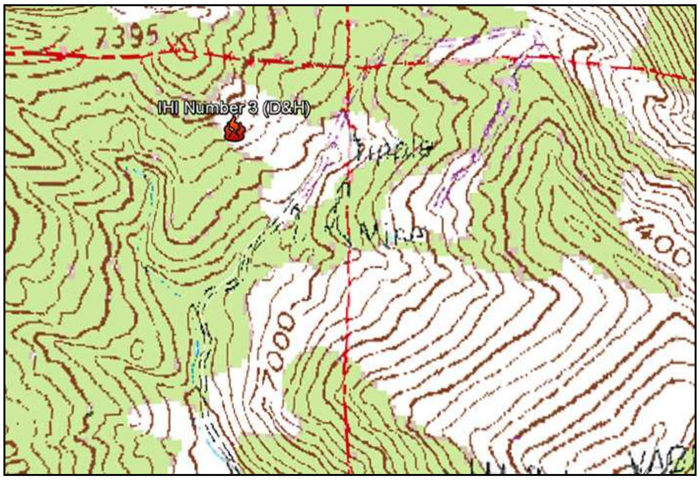
The IHI No. 3 fire is hard to access, especially in the winter time. Thus immediate risks to humans are low. The fire is still venting hot, combustion gases which could be harmful to the environment.

Recommendations:

Firefighting at this site will prove to be challenging.

Grouting at this particular fire may be futile. Much of the circulations of air and combustion gases are taking place near the top of the coal seam, where it is exposed to the atmosphere. This top portion is where the grout should be targeted in order to arrest the circulation required to keep the fire burning. In reality, however, targeting a grouting effort solely to the top of the stope will be challenging because of the dip of the coal seam. Any grout injected into the subsurface will likely flow along and down the dip of the coal seam before hardening. In order for the grout to be effective, the state will have to be prepared to pump grout into multiple stopes, each of which could measure as long as 50 to 100 ft and 30 ft wide.

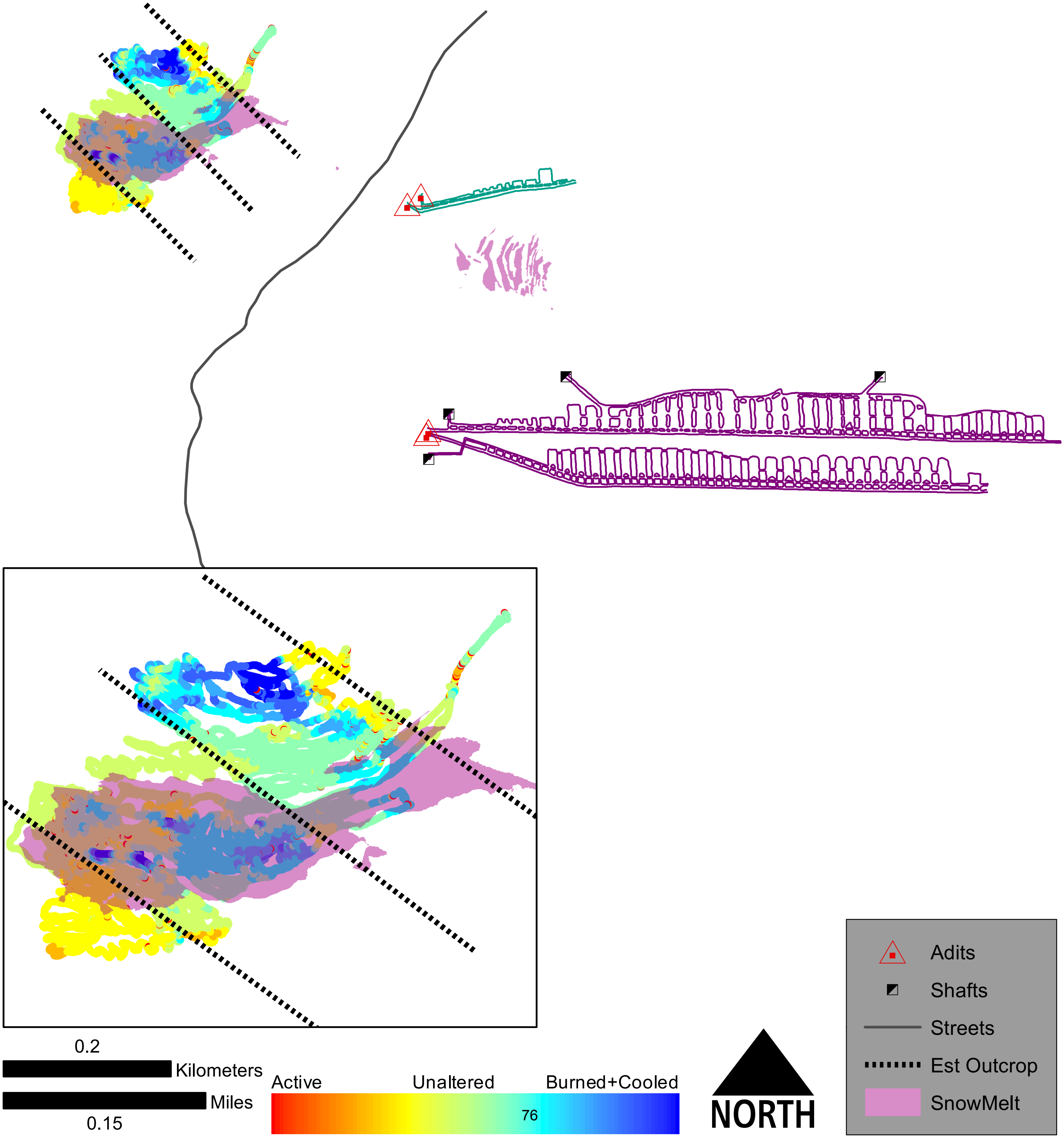
Blanketing the area with a cement carpet to deprive the area of oxygen could work. However, subsidence appears to be frequent, and erosion is also a problem in the area. To install a low permeability carpet, frequent monitoring may be required.



A topography map of the area affected by IHI No. 3.

A satellite image of the area affected by IHI No. 3. Not all of the cleared area is on fire.

Ingle Haas Ingle



Kaspar

Summary:

Location (lat/long): 40.3380 / -107.1341
Region / Coal field: Green River / Yampa
Formation: Williams Fork
Seam: Wadge (Middle Coal)
Mining method: Stope
Strike / Dip: N30W / 28^o
Coal Rank: HvC/HvB
Coal Thickness Affected (ft): <10
Area Affected (ft^2): 84,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Surface features

Directions:

The Kaspar fire is located southwest of Steamboat Springs, CO, and west of Peabody Energy's twenty-mile mine. To reach the Kaspar fire from I-70, take Exit 157 to get onto Hwy. 131N and follow it to Oak Creek. Go through Oak Creek, and then take a left onto CO Rd. 27 immediately after leaving town. Go straight on CO Rd. and take a left at the fork to stay on CO Rd. 27 (right at the fork is CO Rd. 33). From the fork, travel approximately 3.9 miles on CO Rd. 27 and take a left onto a dirt road, CO Rd. 37. Travel approximately 2.5 miles on CO Rd. 37 and the Kaspar fire is located on the right. Park the car near the driveway (it is the first driveway on the road) and climb the ridge in a north-easterly direction for about 0.25 miles.

Key Observations from Mapped Data:

The Kaspar coal fire has more creosote presence than any other coal fire in the state. This fire was likely much more active previously, suggested by the dark blue regions shown in the magnetometer survey map. This fire could become more active, since much of the remaining coal at this site seems to have already dehydrated.

Elevated temperatures above 500^{o}F were observed at many locations, which suggest that the subsurface is still warm. The south east region of this fire could be a new hot area that is above the Curie temperature (indicated by the red magnetometer anomaly region). However, there was no snowmelt immediately over this area. This is one of the few examples of a site where the snowmelt area did not correspond to a 'hot' zone indicated by the magnetometer. It is possible that the area recently became hot, and conductive heat transfer has not yet warmed the surface. Snow may begin melting there in the future. The coal seam dip in this area is severe (28^o), so there is much overburden to heat up before the warmth manifests itself at the surface.

Risk Factors:

While much of the area at the Kaspar coal fire site falls under the 'burned and cooled' status, residual temperatures are much more elevated relative to other burned and cooled coal fires around the state. The possible new fire development in the SE corner of this fire must also be monitored closely.

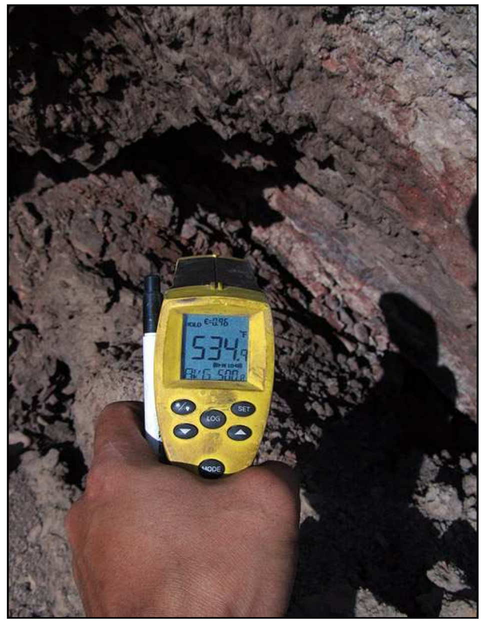
The rate at which creosote is being produced is high, indicating that new coal is being subjected to heat. If the subsurface temperatures remain elevated, rekindling of a fire at this site is a strong possibility.

If the fire becomes more active, surface vegetation is at risk.

Recommendations:

While the fire is currently showing little activity, this fire exhibits many features (creosote build-up, elevated temperatures, not much moisture in the combustion gases) that suggest that the fire can easily rekindle. Periodic monitoring of this site is strongly recommended.

Fighting the fire here could be achieved with methane removal down dip of the fire. It will be challenging to get equipment up to the site in order to pump grout or to excavate the fire

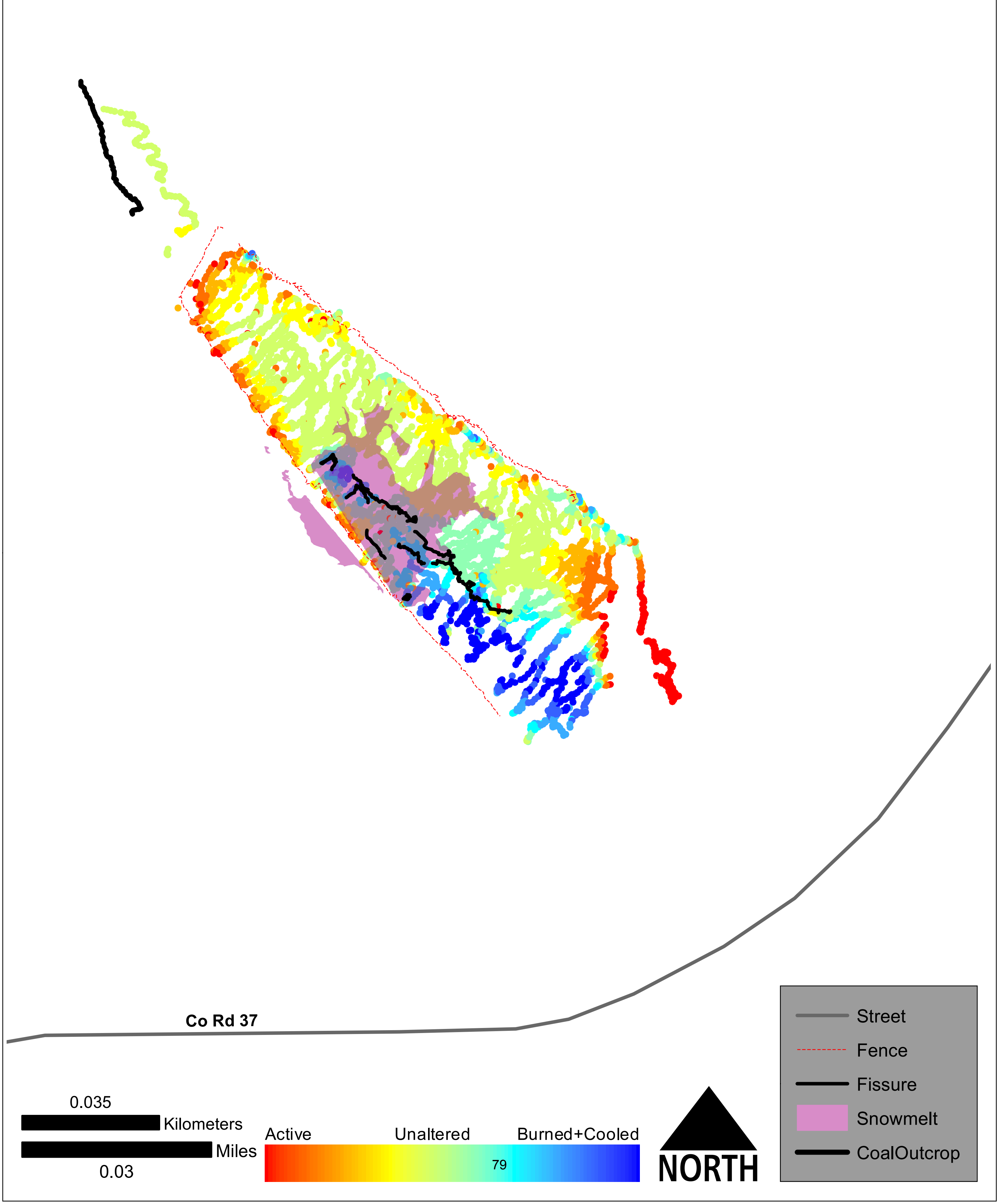



Hot combustion gas temperatures are measured at fissures above the Kaspar fire.


Coal outcrop (left) and burned coal outcrop, ash (right) at the Kaspar fire, photo looking to the NW.

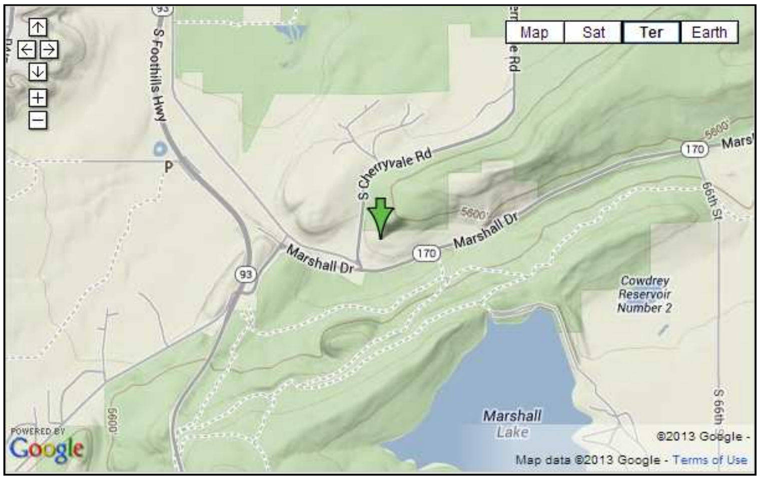
A plastic-like coal tar near the coal outcrop at Kaspar, similar to that found at South Canyon West.

Kaspar



KOVEVA
Co Rd 37
0.035
Kilometers
Miles
0.03
Active
Unaltered
Burned+Cooled
79
NORTH
Street
Fence
Fissure
Snowmelt
CoalOutcrop

Lewis



Summary:

Location (lat/long): 39.9564 / -105.2222
Region / Coal field: Denver / Boulder-Weld
Formation: Laramie
Seam: no data
Mining method: Slope
Strike / Dip: N45E / 4^{o}
Coal Rank: Lignite A to SubA
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 0
Status: Dormant

Data Gathered:

- Magnetometer
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Lewis fire is located north of Golden and south of Boulder, CO (Boulder County). To reach this fire from Golden, travel north towards Boulder on Hwy. 93N. Take a right on Marshall Dr. There is a house at the intersection of Marshall Dr. and S. Cherryvale Rd., and the fire is located on his property. Permission must be obtained prior to visit in order to access this fire.

Key Observations from Mapped Data:

The Lewis fire appears to be dormant. There is one small region (10ft x 5ft) that is warm enough to melt snow on a heavy snow day, but all other regions remain covered in snow. The suspected active fire area reported in Steve Renner's 2005 report no longer seems active based on its ability to hold snow at the surface. Surface cracks that once used to vent hot gases are no longer active.

The mine map of the area shows that this area was extensively mined. When the fire was active, it is likely that the fire took advantage of the fissures that formed due to subsidence in order to advance away from the outcrop.

Magnetometer measurements agree well with the snowmelt data. The included data map shows that the area is predominantly blue, indicating that Lewis coal fire area was once active but no longer active at this site. The blue areas appear to be concentrated near the coal outcrop, which is shown in the data map using thick black lines. Old mine maps show that the area was extensively mined using the room-and-pillar method.

Risk Factors:

None – the fire appears to be dormant.

Recommendations:

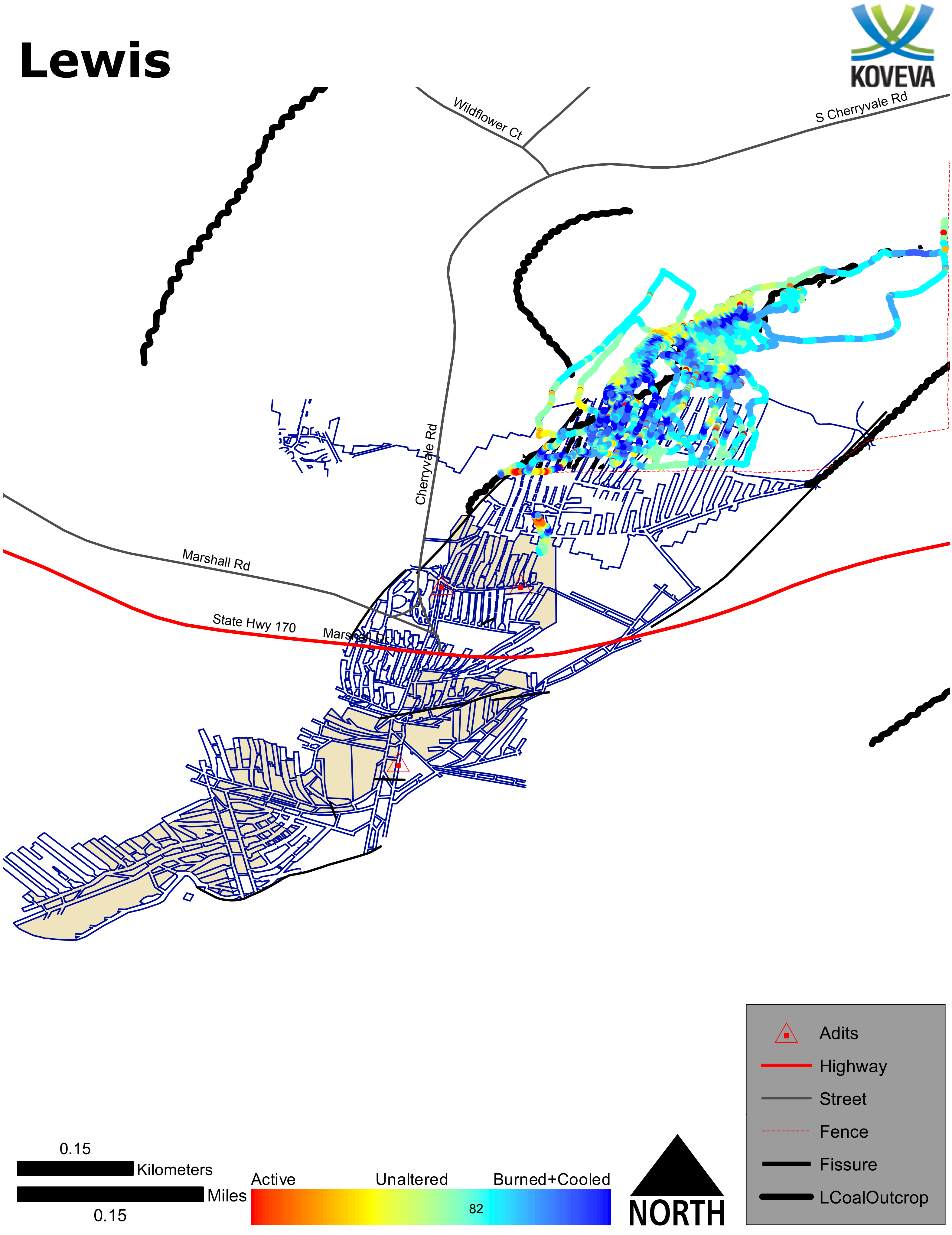
A periodic monitoring of the fire should be sufficient.

It may be worthwhile to dig out the small warm coal / ash location where the snowmelt is observed today. This region is along the outcrop and the excavation will be inexpensive.

Pictures of the Lewis fire from various perspectives on a snowy day shows that the surface above the suspected fire region is not warm enough to melt snow.

Snowmelt is only evident in very small regions over the Lewis fire near the coal outcrop. The affected region is <50 ft^2

Lewis


Wildflower Ct
S Cherryvale Rd
Cherryvale Rd
Marshall Rd
State Hwy 170
Marshall Dr
Adits
Highway
Street
Fence
Fissure
LCoalOutcrop
0.15
Kilometers
Miles
0.15
Active
Unaltered
Burned+Cooled
82
NORTH

Marshall

Summary:

Location (lat/long): 39.9547 / -105.2294
Region / Coal field: Denver / Boulder-Weld
Formation: Laramie
Seam: no data
Mining method: Drift
Strike / Dip: N45E / 4^{o}
Coal Rank: Lignite A to SubA
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 0
Status: Dormant

Data Gathered:

- Magnetometer
- Gas composition
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Surface features
- Methane seeps

Directions:

The Marshall fire is located north of Golden and south of Boulder, CO (Boulder County). This fire is across the street (Marshall Dr.) and to the south of the Lewis fire. To reach this fire from Golden, travel north towards Boulder on Hwy. 93N. Take a right on Marshall Dr. There is a gate to the right before reaching the intersection between Marshall Dr. and S. Cherryvale Rd. Park the car outside of this gate and walk in a south-westerly direction to reach the Marshall fire. This fire is located on BLM property, and thus can be accessed without permission.

Key Observations from Mapped Data:

The Marshall coal fire was visited on a number of different occasions. The last visit during a spring snowstorm in 2013 showed that there is only one small region which cannot hold snow, measuring less than 3ft by 5ft. Magnetometer results are consistent with the snowmelt. While there is a large area along the outcrop that shows previous fire activity (blue regions in the magnetometer profile), there appears to be no active fire regions today.

Combustion gases were not observed at the site. The small snow region is likely due to residual heat from past fire activities.

The family that lives directly across from the Marshall coal fire has a paper mine map of the Marshall No. 1 and 2 mines. This paper copy does not exist in the state archives. The mine map showed that the coal was accessed through the outcrop where the fire was once very active. The overburden is not thick over this area, and the dip of the coal in this area is shallow.

Risk Factors:

Currently, there appears to be very limited fire activity where the Marshall fire once very active. The previously active area was just south of the intersection between Marshall Dr. and Eldorado Springs Dr. There is a very small area where the coal appears to be going through a dehydration process, but it does not seem to warrant immediate action.

A report of new fire activity was reported on Dec. 10, 2012. The new fire location is southwest of the previously active fire zone. It is located just east of South Foothills Highway (Hwy. 93) and west of the coal seam trail. Pictures of fissures from December 2012 show that the fire is in early stages.

Recommendations:

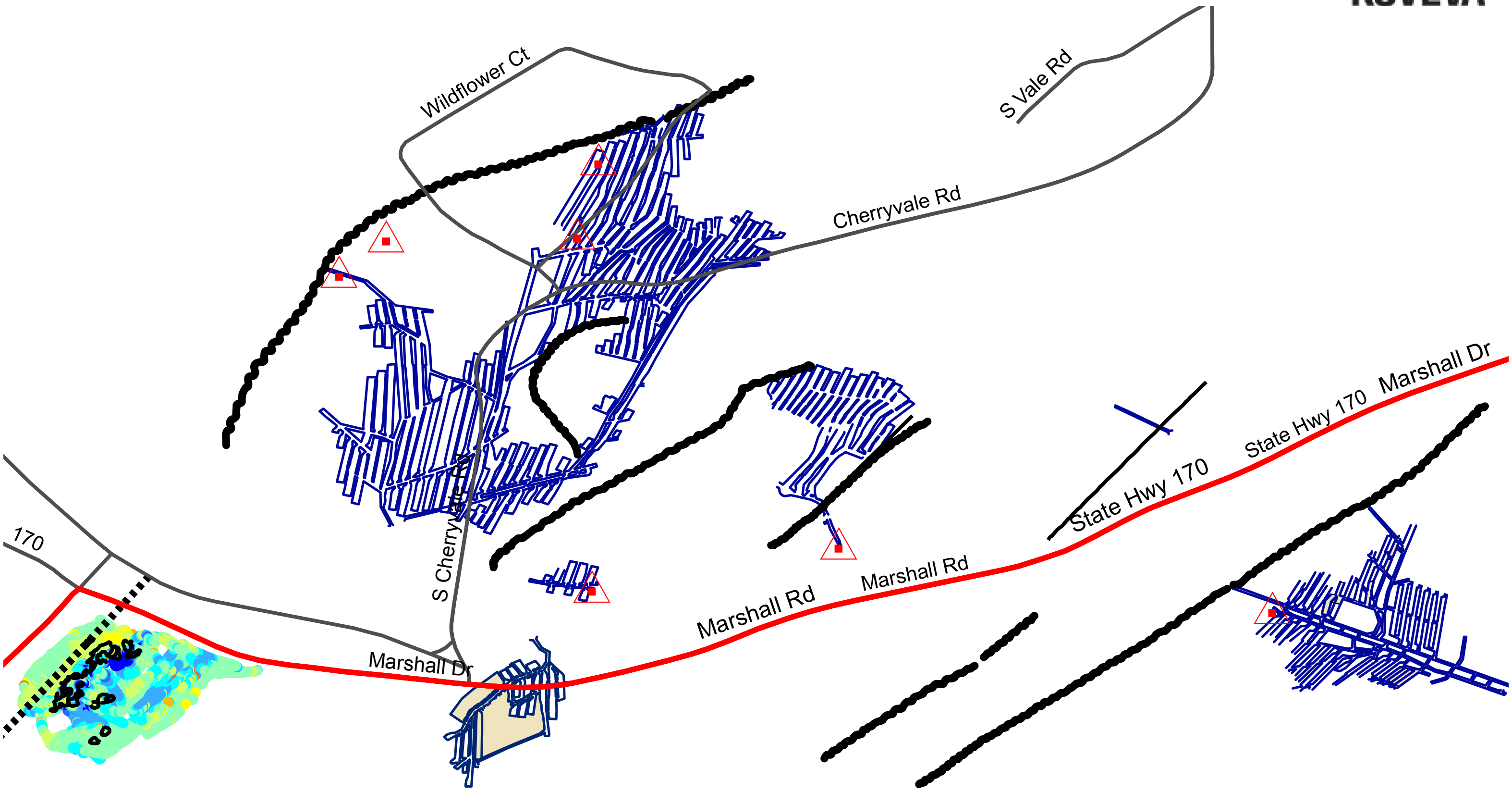
There is always a chance that the fire will reignite. The fire was known to be very active in 2003 during a survey conducted by Steve Renner. It may be worthwhile to dig out the outcrop while the fire is dormant to proactively prevent future fires. In the absence of any preemptive excavation, periodic monitoring for increased fire activities should be conducted over the next several years.



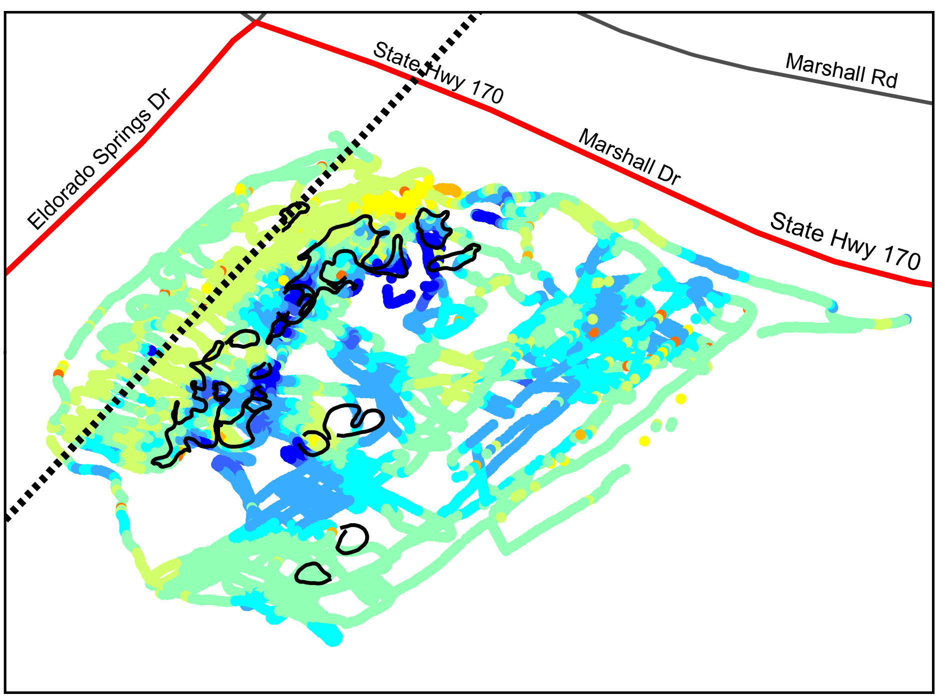

Four photos of the Marshall fire on the day of a snowstorm from various angles..
Snowmelt is not readily apparent.


The only area where snow was melted was at the southern region of the Marshall fire along the coal outcrop.
The snowmelt is very slow and limited to about 12 square feet.

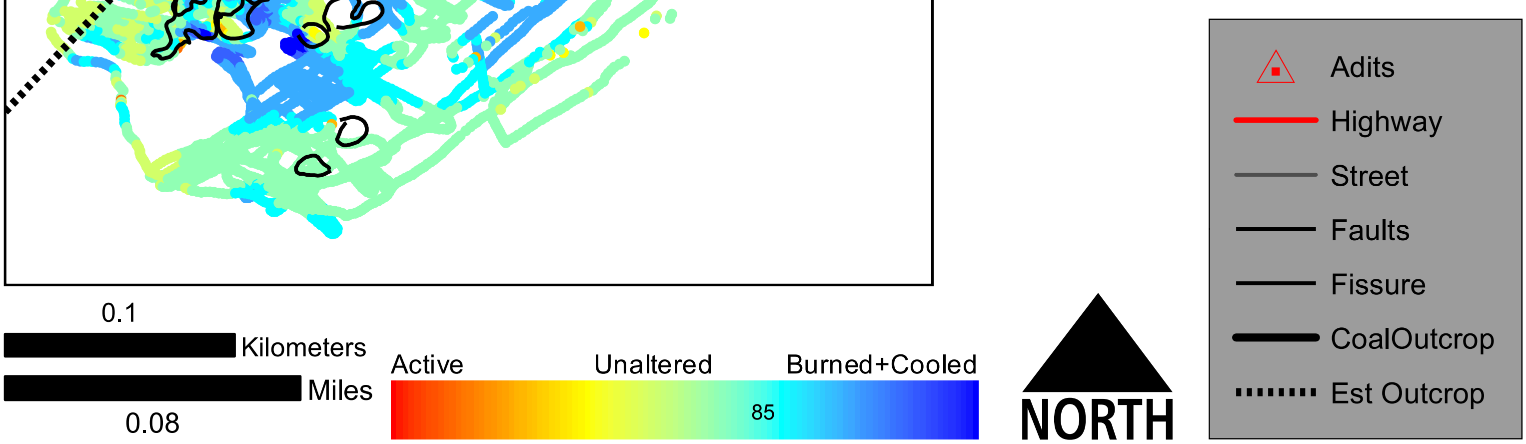
Marshall



Wildflower Ct
S Vale Rd
Cherryvale Rd
Marshall Dr
State Hwy 170
State Hwy 170
Marshall Rd
Marshall Rd
S Cherryvale Rd
170
Marshall Dr



State Hwy 170
Marshall Rd
Eldorado Springs Dr
Marshall Dr
State Hwy 170



0.1
Kilometers
Miles
0.08
Active
Unaltered
Burned+Cooled
85
NORTH
Adits
Highway
Street
Faults
Fissure
CoalOutcrop
Est Outcrop

New Castle No. 1

Summary:

Location (lat/long): 39.5609 / -107.5123
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Allen
Mining method: Drift
Strike / Dip: N67W / 50^{o}
Coal Rank: HvB
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 280,000
Status: Low activity

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Borehole drilling
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

There are four fires located near New Castle, CO (Garfield County) along the Grand Hogback. Three of these fires, Vulcan, Coryell, and New Castle No. 1 (from east to west) are located immediately south of and parallel to I-70 in New Castle. To reach these three fires, take Exit 105 off of I-70 and head South away from downtown New Castle. At the T-intersection, take a left onto CO Rd. 335 and head west. In order to reach either the New Castle No. 1 or the Coryell fire, park near the thrift shop and hike up the Hogback. To arrive at the Vulcan fire, take a right at the T-intersection onto CO Rd. 335 and head east, then park at the old coal loading dock and hike up the Hogback to reach the site.

Key Observations from Mapped Data:

The three fires that are burning south of I-70 are all slow burning. Methane was detected along the Grand Hogback where Vulcan, Coryell, and New Castle No. 1, so it is possible that methane is a contributing factor to keeping the fires burning. The methane signature collected near this site had the same signature as the methane that is being produced from the same formation in the Piceance Basin.

However, a CO_2 sample that was collected at this site shows that the CO_2 is solely due to coal combustion. More CO_2 samples must be collected from this area to definitively understand whether the methane plays a significant role at the I-70 fires.

All three of these fires exhibit very low fire activities. This is corroborated by the fact that snow melts very slowly at these sites. The magnetometer survey shows that the fire has not migrated too far into the formation away from the outcrop. At these fires, the overburden is too thick to form fissures that are necessary to burn far into the formation. Crown coals that were left as a part of the mining operations are likely being consumed by the fire today.

Risk Factors:

Because coal consumption at these fires is extremely slow, there are no immediate risks associated with these fires. These fires are hard to access due to the steep incline and heavy brush to reach the fires.

Recommendations:

Methane removal from the site may help slow down or extinguish the fire. However, further methane seepage analysis must be undertaken before this option is seriously considered. The methane survey conducted under this contract showed that while there is a presence of methane at these fires, they do not always participate in the combustion process.

Other conventional methods of fire fighting may be hard to implement here due to the steep terrain in the area.

New Castle No. 1 fire during a heavy snow fall.
Snowmelt is very slow and not immediately evident during the snow storm.

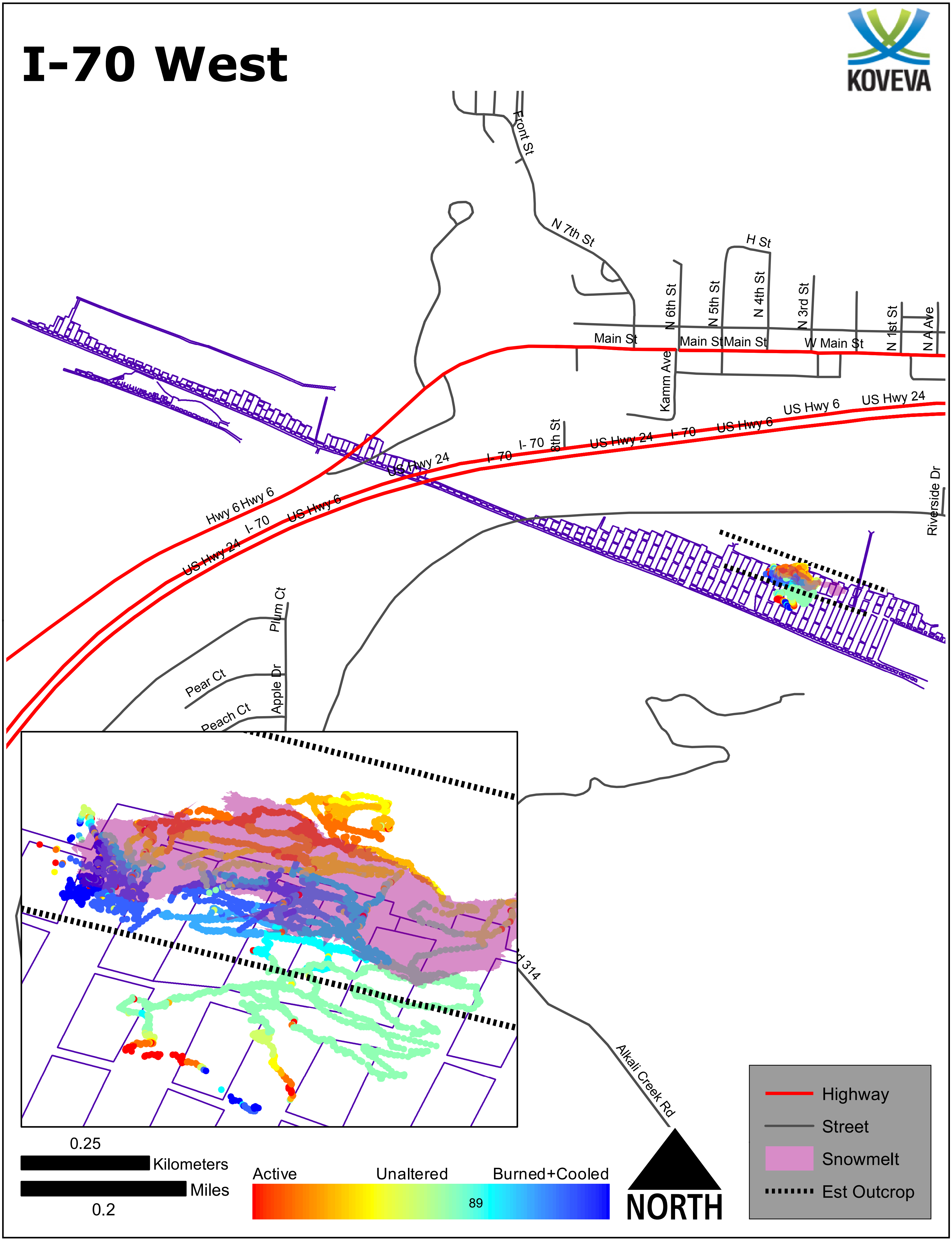
Outcrop containing Coryell, New Castle No. 1, and Vulcan.

Outcrop containing Coryell, New Castle No. 1, and Vulcan after a snowstorm day.
(Hogback on the right side of the picture)

I-70 East

US Hwy 24
US Hwy 6
I- 70
US Hwy 24
US Hwy 6
US Hwy 24
US Hwy 6
US Hwy 6
US Hwy 24
US Hwy 24
I- 70I- 70
0.3
Kilometers
Miles
0.25
Active
Unaltered
Burned+Cooled
88
NORTH
Highway
Streets
Snowmelt
Est Outcrop

I-70 West



KOVEVA
Front St
N 7th St
H St
N 6th St
N 5th St
N 4th St
N 3rd St
N 1st St
N A Ave
Main St
Main St
Main St
W Main St
Kamm Ave
US Hwy 6
US Hwy 24
I- 70
US Hwy 6
I- 70
US Hwy 24
8th St
I- 70
I- 70
US Hwy 24
Hwy 6
Hwy 6
I- 70
US Hwy 6
US Hwy 24
Riverside Dr
Plum Ct
Pear Ct
Apple Dr
Peach Ct
Rd 314
Alkali Creek Rd
0.25
Kilometers
Miles
0.2
Active
Unaltered
Burned+Cooled
89
NORTH
Highway
Street
Snowmelt
Est Outcrop

New Castle No. 3

Summary:

Location (lat/long): 39.5731 / -107.5438
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: no data
Mining method: Stope
Strike / Dip: N65W / 56^o
Coal Rank: HvB
Coal Thickness Affected (ft): <50
Area Affected (ft^2): 850,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

The New Castle No. 3 fire is located near New Castle, CO (Garfield County). The fire is located along the Grand Hogback monocline on the north side of I-70. To reach this fire, take Exit 105 and head north toward downtown New Castle. Take a left on Main St./Hwy. 6W, then take a right to park at Elk Creek Elementary School. The fire can be accessed by following the utility road in the south-westerly direction.

Key Observations from Mapped Data:

At the New Castle #3 site, two coal seams were previously on fire. Both of these fires are currently warm, but not as hot as it once was. The magnetometer survey shows two regions where they once burned above the Curie temperature of magnetites (1,085^{o}F), but is now below this threshold temperature. These regions appear as dark blue regions in the magnetometer survey. The outline of the region that cannot hold snow matches well with where the fire was burning most intensely. The heat at the surface is likely the residual heat propagating to the surface.

The dark blue region to the NW corner of the surveyed area also cannot hold snow; a snowmelt outline survey could not be conducted there due to steepness in terrain and difficulty collecting data there.

Gas compositions indicate that high concentrations of moisture are not observed in the gas samples collected near the snowmelt area.

Since the dip of the coal seam at this site is severe (56^o), the overburden becomes very thick over a very short distance. Thus fissures do not typically form at the surface of this fire. Instead, it is easier for the fire to spread laterally along strike.

Finally, surface methane concentrations showed that methane concentrations were highest where the fire used to burn the hottest. It is possible that methane is flowing to the surface from deeper parts of the Piceance Basin by buoyancy-driven flow.

Risk Factors:

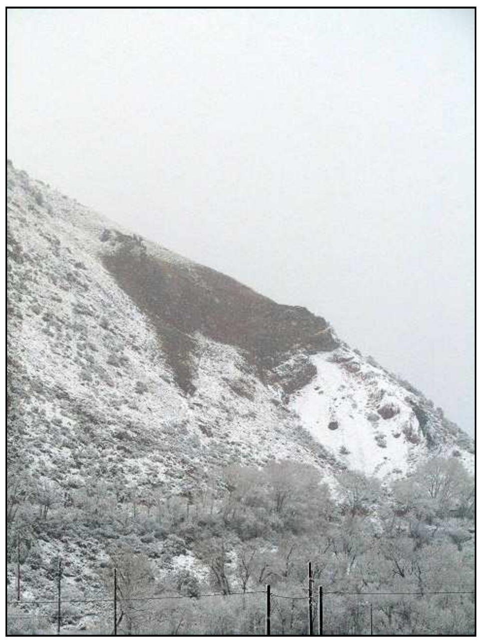
It appears that the fire is continuing to migrate to the NW along strike. Gases being vented from the NW region of the New Castle #3 coal fire contain high concentrations of moisture. This is indicative that virgin coal is being subjected to heat. The possibility of a continued migration of the fire to the NW remains high.

Recommendations:

This fire is currently burning near the outcrop. If grouting were implemented here, the injected grout will likely travel far down dip before solidifying. Blanketing the area with a low permeability cement carpet seems infeasible due to the terrain and the amount of erosion.

This site may be an ideal candidate for methane capture down dip of the coal fires. Presence of methane was measured at this fire. A thorough investigation of methane contributions at the New Castle #3 coal fires site warranted.

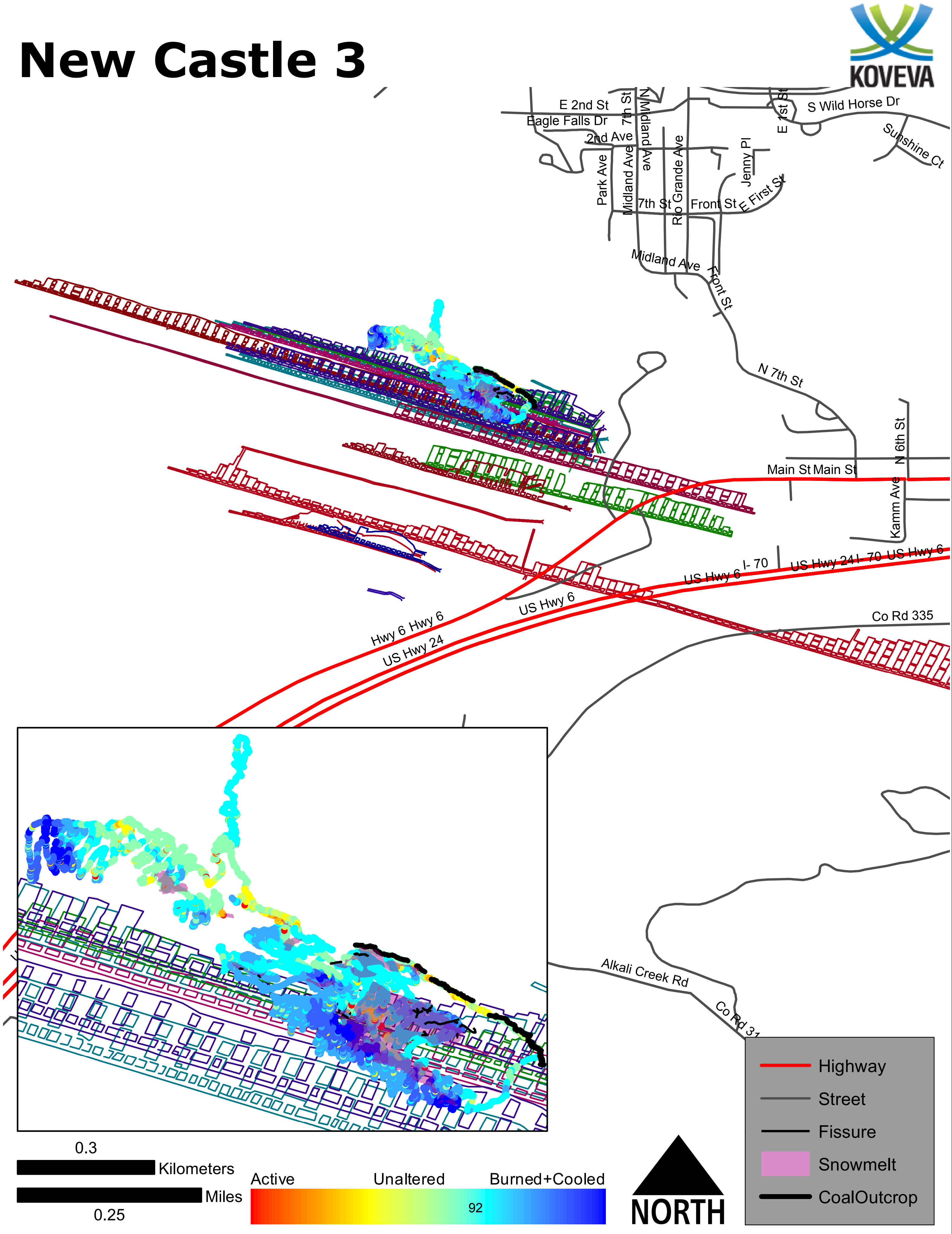
Coal seam outcrop at New Castle No. 3 (left), and
new fires extending towards the nortwest along the coal seam outcrop (right).



Snowmelt at New Castle No. 3 on the day of a snowstorm, photo taken looking to the NE.

Photos of the coal outcrop and the fire taken looking towards SW. Photo on the right on a sunny day, photo on the left after a snowstorm. Photo on the left shows melted areas (brown) along the outcrop.

New Castle 3


KOVEVA
E 2nd St
Eagle Falls Dr
2nd Ave
7th St
N Midland Ave
Park Ave
Midland Ave
7th St
Rio Grande Ave
Front St
Jenny Pl
E First St
E 1st St
S Wild Horse Dr
Sunshine Ct
Midland Ave
Front St
N 7th St
N 6th St
Main St
Main St
Kamm Ave
I- 70
US Hwy 24
I- 70
US Hwy 6
US Hwy 6
US Hwy 6
Hwy 6
Hwy 6
US Hwy 24
Co Rd 335
Alkali Creek Rd
Co Rd 31
0.3
Kilometers
Miles
0.25
Active
Unaltered
Burned+Cooled
92
NORTH
Highway
Street
Fissure
Snowmelt
CoalOutcrop

Pocahontas

Summary:

Location (lat/long): 39.4113 / -107.3224
Region / Coal field: Uinta / Grand Hogback
Formation: no data
Seam: no data
Mining method: Drift
Strike / Dip: N17W / 42^o
Coal Rank: HvB
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 0
Status: Dormant

Data Gathered:

- Magnetometer
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Pocahontas fire is located south of Glenwood Springs, CO (Garfield County). To reach this fire, take exit 115 (traveling on I-70E) or 116 (traveling on I-70W) and travel south on Hwy. 82/Grand Ave through Glenwood Springs. Take a right on 27th St., following signs toward Sunlight Mountain Resort. Take a left on Midland by going around the roundabout. Follow Midland for about 1.3 miles, then take a right onto CO Rd. 117/4mile Rd. Follow the 4 mile Rd. for exactly 8.1 miles, and park alongside the road. Follow the ATV trail in the northeasterly direction. When the trail splits in about 0.5 miles, take a right, and continue to follow the major trail. Within another half a mile, there will be coal piles on the road side. From the coal piles, head directly west up the slope through the trees. The Pocahontas fire is approximately a quarter mile from the coal pile.

Key Observations from Mapped Data:

The Pocahontas fire is dormant. Trips were made to the Pocahontas coal fire site on a number of snow days, and snow over the previously active Pocahontas fire area showed no signs of melting (see picture).

The magnetometer survey shows that the fire was most active near a mine entry way that connected the mine and the surface. This is evident when the mine map and the magnetometer results are plotted together. There are evidences of past fire activities in the area such as fissures and subsided areas. These correspond well to areas where the fire was most active in the past, based on the magnetometer data. These features do not emit hot combustion gases today, but based on the thermally altered rocks at the surface, they may have been actively venting in the past.

Risk Factors:

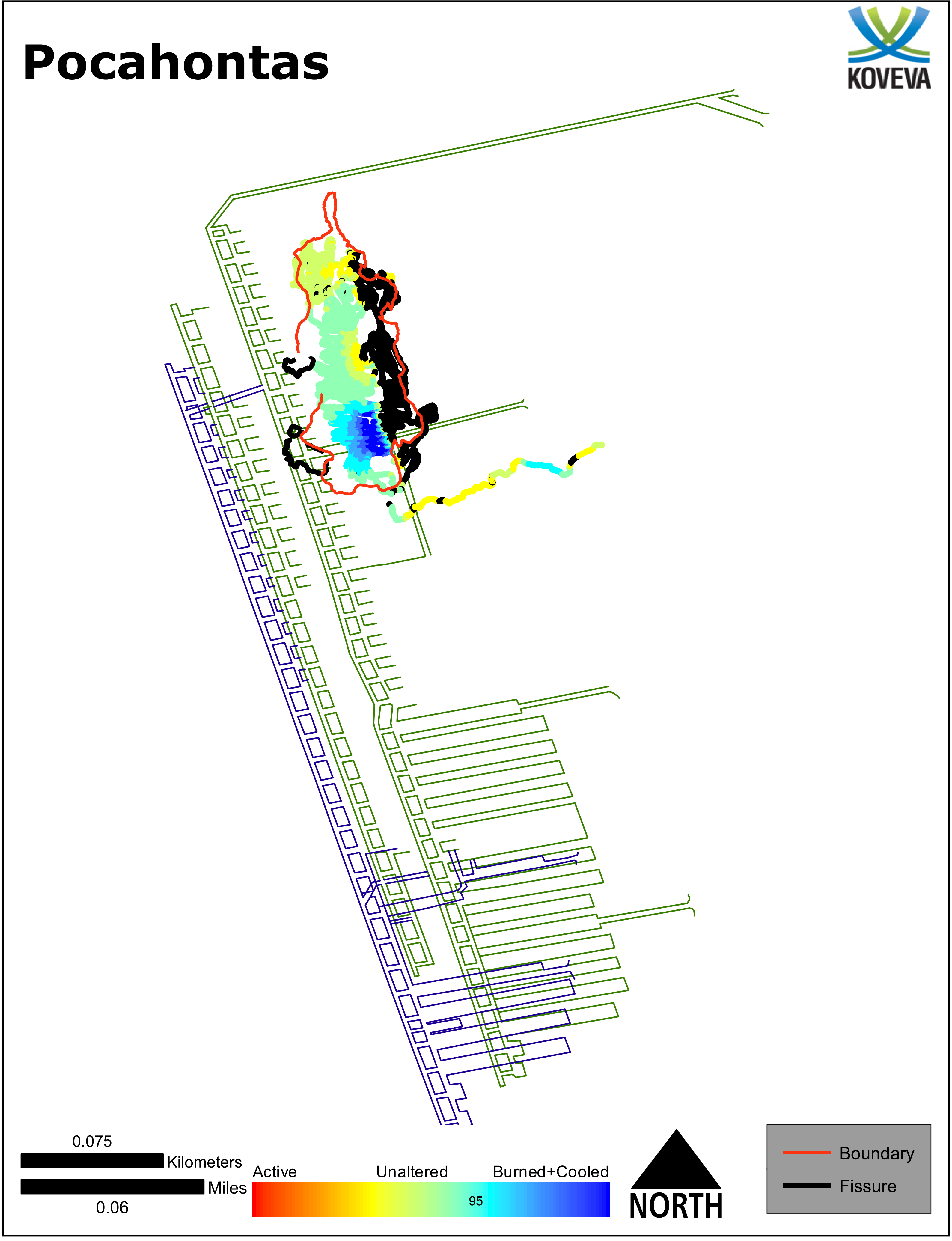
The fire appears to be dormant. No signs of activity were recorded during any of the visits between 2011 through 2013. Gas compositions, temperatures, surface methane concentrations were all ambient, and snowmelt was not observed on a number of visits made to the fire after snowstorms.

Recommendations:

There is always a chance that the fire will reignite. The fire was known to be very active in 2003 during a survey conducted by Steve Renner. It may be worthwhile to dig out the outcrop while the fire is dormant to proactively prevent future fires. In the absence of any preemptive excavation, periodic monitoring for increased fire activities should be conducted over the next several years.

The Pocahontas fire area two days after a snowstorm in 2012.
The fire was very active below the region where the trees have been cleared.
Snowmelt due to the fire was still not evident a week after this photo was taken.

Pocahontas


KOVEVA
0.075
Kilometers
Miles
0.06
Active
Unaltered
Burned+Cooled
95
NORTH
Boundary
Fissure

Skull Creek

Summary:

Location (lat/long): 40.1847 / -108.8027
Region / Coal field: Uinta / Lower White River
Formation: no data
Seam: Seams B or D
Mining method: no data
Strike / Dip: N60E / 4^o
Coal Rank: HvC
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 89,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Coal outcrop mapping
- Surface features
- Methane seeps

Directions:

The Skull Creek fire is located near Rangely, Colorado (Rio Blanco County). To reach this fire from Meeker, CO, take CO-64W towards Rangely for 46 miles. Coming from Grand Junction, take CO-139N towards Loma/Rangely. Take a right onto CO-64E at the dead end for 7.5 miles. Head north to get on CO Rd. 65 for approximately 5 miles, then take a left to head west on CO Rd. 96 for 3 miles to reach a T-intersection. The intersection is a good location to park. The Skull Creek fire can be reached by hiking 0.2 miles to the west from the T-intersection.

Key Observations from Mapped Data:

The Skull Creek coal fire was surveyed for both magnetic anomalies and existence of surface methane seepage. The magnetic anomaly results showed that the eastern region of the fire, which was once hot and burned above the Curie temperature of magnetites, is currently less active. This is indicated by the deep blue color in the eastern region. The small red dots in the eastern region are likely signal noises, and these have little relevance to the state of the subsurface fire.

The western portion of the fire is somewhat active. The zones that are active today show up as orange/red areas in the magnetic anomaly survey. Both in the western and eastern regions, the effects of the coal fire do not migrate too far away from the outcrop yet.

The measured surface methane concentrations were consistent with the magnetometer results. Where the magnetometer results showed current or previous activity of a fire, methane concentrations were high. Methane concentrations were close to the ambient atmospheric methane concentrations in other areas. These methane concentration surveys were conducted on a day with very little wind at the surface.

Further studies are required to determine whether the methane is a cause or an effect of coal fires. The field measurements at Skull Creek do establish that there is a relationship between methane seepage and coal fires.

Fissure mapping at Skull Creek demonstrates how subsidence affects the overburden near the outcrop when coal is consumed. Fissures form parallel to the strike as the outcrop coal is consumed and collapses under the weight of the overburden. Due to the heavy fracturing that has occurred at Skull Creek, it is possible for this fire to migrate into the formation.

The surface has subsided by over 3 ft in some areas over approximately five years.

Risk Factors:

The Skull Creek fire is active and remains hot. Fissures that connect the surface to the coal seam allow air to reach the subsurface fire. There is a high risk of the fire burning into the formation away from the outcrop.

Recommendations:

While the fire is currently contained near the outcrop, there is a high risk that the fire may burn into the formation away from the outcrop. There may be an opportunity to excavate the fire before it moves far into the formation.

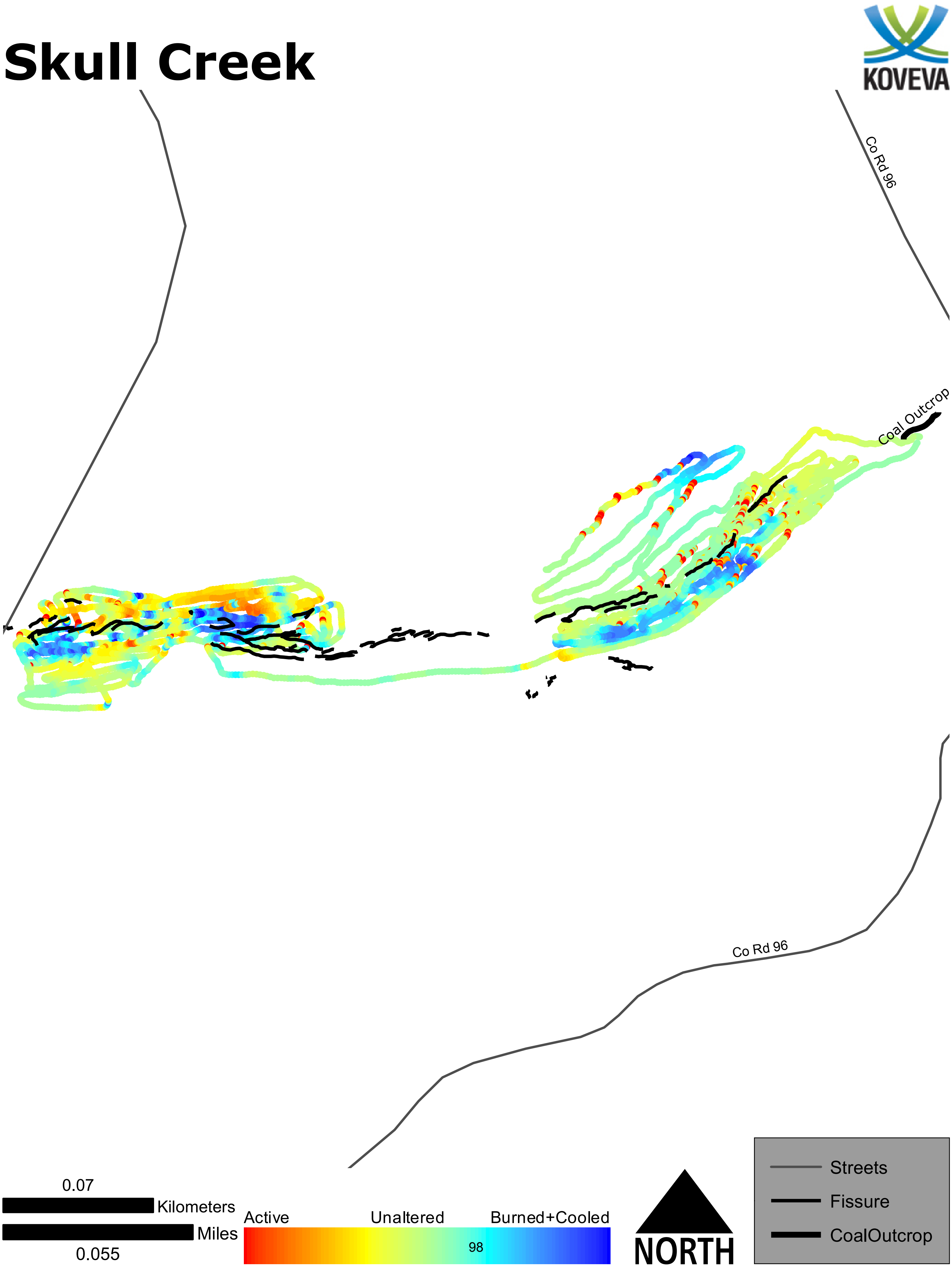
Since surface methane concentrations are high, it is also possible that removing methane from an area down dip of this fire will prove to be effective in slowing down the development of this fire.

Photos looking towards the SW of the coal outcrop (left) and a burned outcrop (right).

Evidence of subsidence at Skull Creek around thermocouple boreholes.

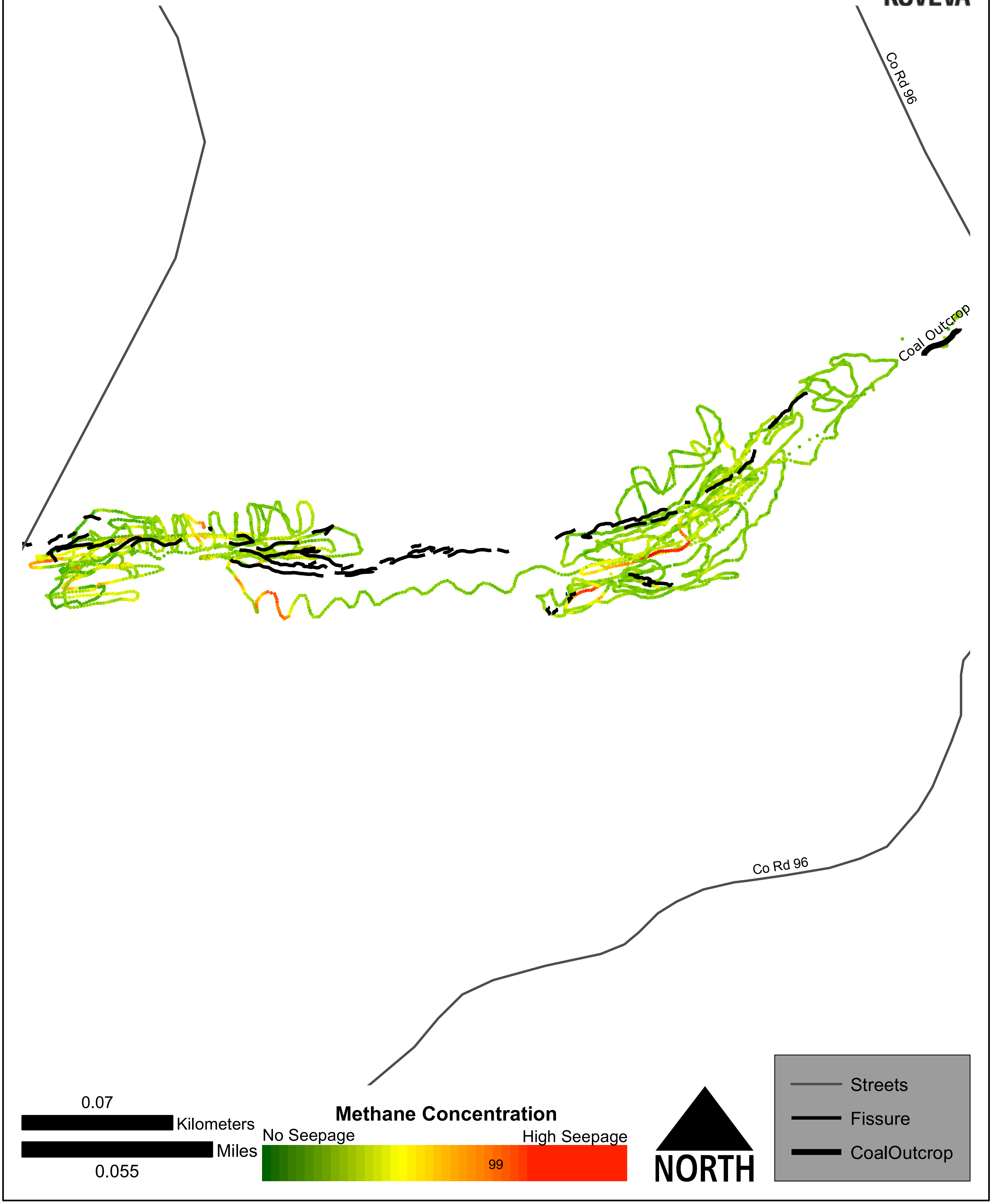
Picture of thermocouples and fissures looking towards the NE.

Skull Creek

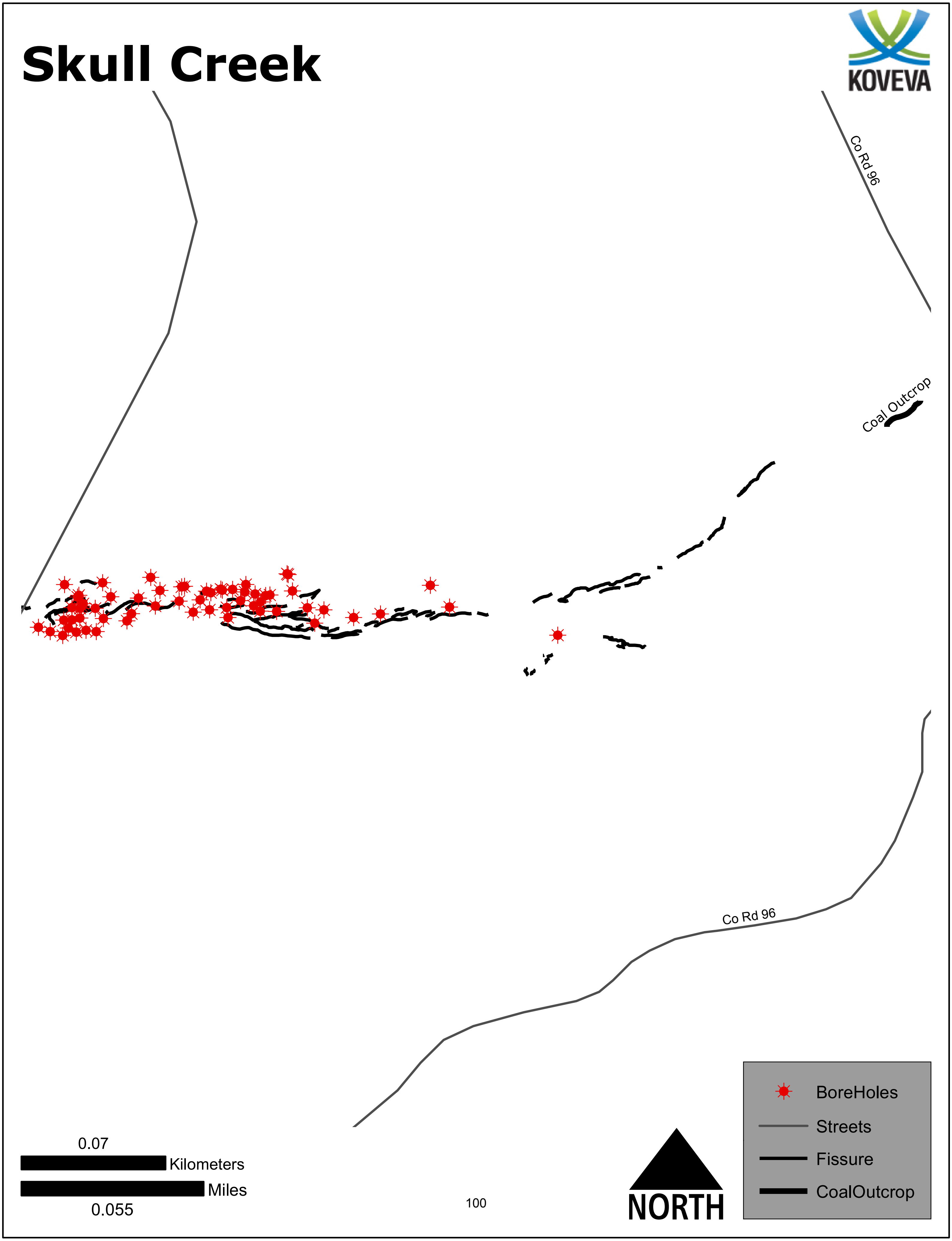


KOVEVA
Co Rd 96
Coal Outcrop
Co Rd 96
0.07
Kilometers
Miles
0.055
Active
Unaltered
Burned+Cooled
98
NORTH
Streets
Fissure
CoalOutcrop

Skull Creek


Co Rd 96
Coal Outcrop
Co Rd 96
0.07
Kilometers
Miles
0.055
Methane Concentration
No Seepage
High Seepage
99
NORTH
Streets
Fissure
CoalOutcrop

Skull Creek



KOVEVA
Co Rd 96
Coal Outcrop
Co Rd 96
0.07
Kilometers
Miles
0.055
NORTH
BoreHoles
Streets
Fissure
CoalOutcrop

South Canyon East

Summary:

Location (lat/long): 39.5309 / -107.4077
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler, D, U, E
Mining method: Stope
Strike / Dip: N60W / 53^{o}
Coal Rank: HvA
Coal Thickness Affected (ft): <50
Area Affected (ft^{2}): 762,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

The South Canyon East fire is located west of Glenwood Springs, CO (Garfield County). To reach the South Canyon fire, take exit 111 off of I-70. Take CO Hwy 134 toward South, then travel straight for 2.5 miles. The South Canyon East fire is on the left. The top of the South Canyon East fire may be reached by crossing the creek then hiking up half of a mile to the east.

Key Observations from Mapped Data:

The South Canyon fire is one of the most active fires in Colorado. The South Canyon fire is split into South Canyon East and South Canyon West by CO Hwy 134. The South Canyon East is the more active of the two fires.

Data collected at South Canyon East indicate that the fire is most active roughly half of a mile east of CO Hwy 134. Both surface and subsurface data indicate that in the past, fire was more active in the lower regions, closer to the road. Since then, the fire has migrated farther to the east. Topographically, the fire is now located on higher ground. The magnetometer data's blue region indicates that the fire that was once active in this area is now cooled. The snowmelt data suggests that there is still some residual heat that is trapped in the rocks, which is sufficient to warm the ground temperatures to melt the surface snow.

Methane seeps were detected over this coal fire, and gas samples were collected. Desorption tests conducted on the Wheeler coal (the coal seam that is believed to be on fire) that was recovered from a borehole just down-dip of this fire suggests that desorbed methane could be flowing toward the outcrop.

Risk Factors:

The main risk factor at this location is the continued propagation of the fire to the east toward higher grounds. Because the fire is burning close to the surface, subsidence can occur without warning. Some of the surface features that are found over the South Canyon East fire today indicate that fissures can sometimes open up suddenly. Forest fire risks are low, since trees in the area have either been removed or burned. Extreme heat from the fissures, coupled with subsidence risk could pose danger to the public since the fire is easily accessible.

Recommendations:

Heat from the currently active region is likely drying the coal in the easterly direction. Thus, arresting the spread of the fire to the east is most important. In order to do so, it will be important to understand the role played by methane. Two tests have been submitted to Isotech Laboratories to confirm whether the methane is originating from coal or else from desorption. Continued fieldwork, such as methane seepage mapping may be warranted.

South Canyon East fire on the day of a snowstorm, looking towards East.

Sulfur (left) and ammonium chloride (right) that formed at the surface at the edges of fissures.

Hot combustion gases from a fissure at the South Canyon Fire (left), and
a picture of the combustion area looking towards West (right),

South Canyon West

Summary:

Location (lat/long): 39.5364 / -107.4209
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler, D, U, E
Mining method: Stope
Strike / Dip: N61W / 54^{o}
Coal Rank: HvA
Coal Thickness Affected (ft): <50
Area Affected (ft^{2}): 762,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

The South Canyon East fire is located west of Glenwood Springs, CO (Garfield County). To reach the South Canyon fire, take exit 111 off of I-70. Take CO Hwy 134 toward South, then travel straight for 2.5 miles. The South Canyon East fire is on the left. The top of the South Canyon East fire may be reached by crossing the creek then hiking up half of a mile to the east.

Key Observations from Mapped Data:

South Canyon West fire is the western portion of a large fire that is commonly referred to as the South Canyon fire. South Canyon Creek bisects the South Canyon West and the South Canyon East fire.

As the pictures from this site indicate, the South Canyon West fire is propagating to the west along strike. The fire is migrating along the outcrop, and to a structurally high area. It is hard for the fire to migrate deeper into the formation away from the outcrop since the thick overburden prevents fissures from forming at the surface.

Unlike the South Canyon East fire, there are no obvious adits, airways, or entry ways that can provide air to the coal fire. It is likely that the fire is exchanging the air and exhaust gases at the outcrop.

The eastern-most portion of the South Canyon West fire, where it is the lowest in elevation, shows characteristics of a fire that has been burning for a long time. It is dry, low in water saturation, and the thermally altered overburden is hardened from years of heating. It is likely that the heat in this area is the residual heat from the combustion front that has now migrated to the west.

Slightly to the west of this region, ammonium chloride and sulfur can be observed near a number of fissures. These crystals form after much of the water has been driven off of the coal. Magnetometer surveys conducted at a number of coal fire demonstrate that the presence of these crystals at the surface usually imply active coal fire regions below. Creosote build-up is also evident in this area, indicating that the subsurface is hot enough for some of the heavier, tar-like material to evolve from the coal. The vaporized tar material then condenses at the surface as it comes into contact with cooler temperatures. This results in the plastic-like film of creosote. This feature is very similar to the Kaspar coal fire.

The highest, most westerly region of the South Canyon West fire is very damp, which is likely from the water that evolved from of coal dehydration. Coal dehydration is the first step of coal combustion. Heat from the coal fire is likely propagating east to west, and dehydrating the virgin coal seam.

Surface methane seepage surveys conducted at the site demonstrated that the surface concentration of methane at this site can be several orders of magnitude higher than ambient methane concentration of 1.80 ppm. Coal seams in this area have been documented to desorb methane. It was demonstrated by an isotope analysis that methane observed at the surface is the same methane that is being produced in the Piceance Basin, which is located down dip of the coal fire.

Risk Factors:

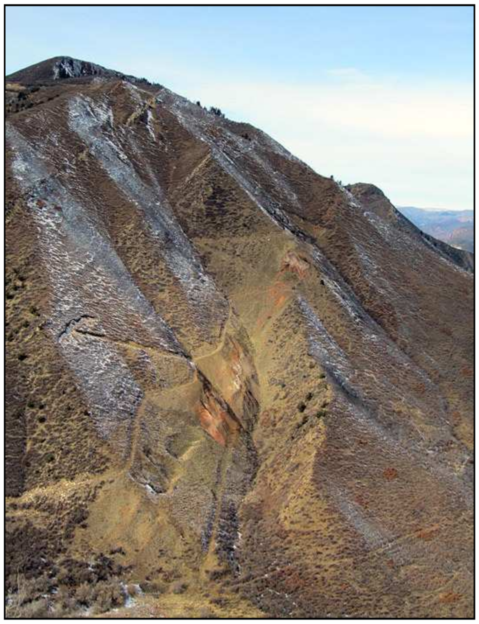
The fire is hard to access, especially the uppermost fire areas primarily due to the elevation gain and difficult terrain. Thus access risk is low. The fire is actively spreading to the west, however, and it is possible for surface vegetation to ignite as the fire spreads further to the west.

Recommendations:

Methane removal by drilling wells down dip of the fire may help slow the fire down, although the contribution of methane to the exhaust gases could not be concretely verified. However, the fact that methane is getting to the surface from deeper parts of the Piceance Basin does suggest that it can play a role in keeping the combustion active.

Excavation is likely not a cost-effective fire mitigation option due to the terrain.

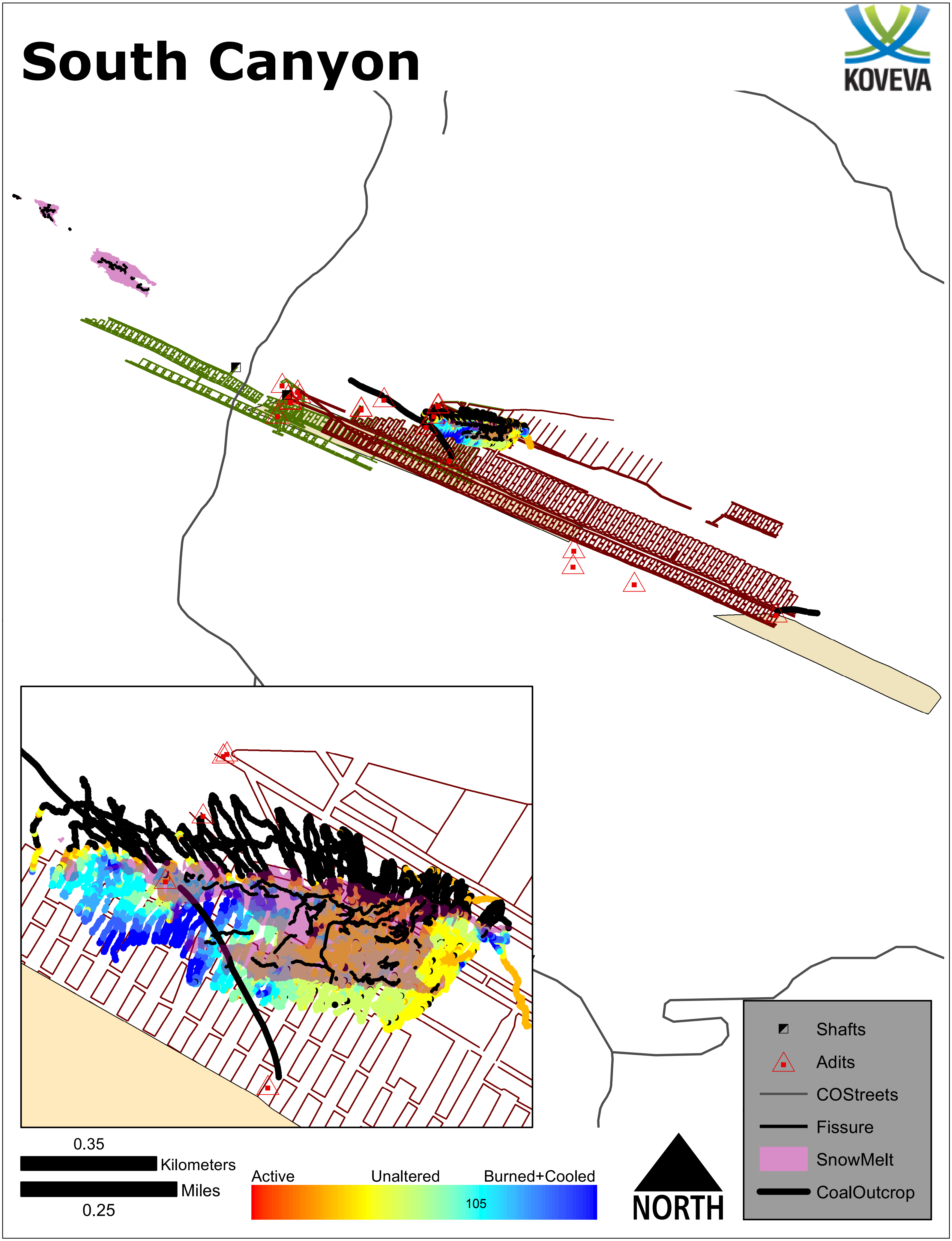
An on-going site investigation is warranted to assess various fire extinguishing options.



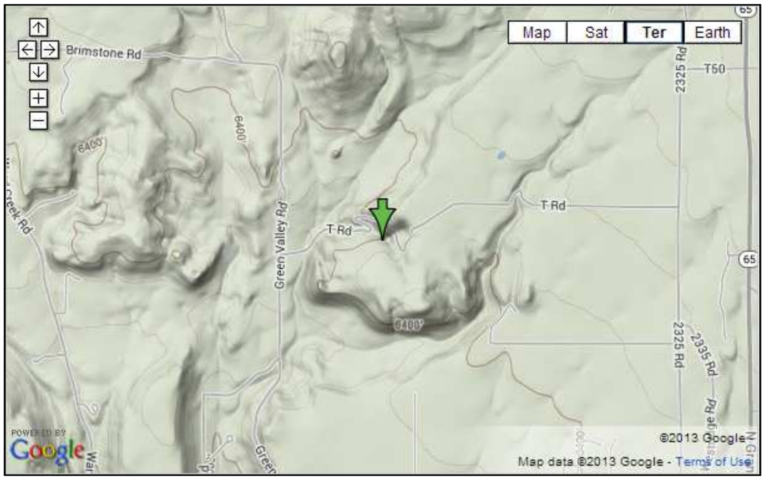
A picture of the coal seam outcrop that is on fire at the South Canyon West fire (left), looking to the NW. The areas that are on fire are indicated by reddish bands.
On a snowstorm day (right), snowmelt areas are visible over wide areas along the coal seam outcrop.

Tar (left) and ash (right) along the outcrop at the South Canyon West fire.

South Canyon



States



Summary:

Location (lat/long): 38.9280 / -107.9491
Region / Coal field: Uinta / Grand Mesa
Formation: Mount Garfield
Seam: One of A through F
Mining method: Drift
Strike / Dip: N54W / 6^o
Coal Rank: SubC to HvA
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 68,000
Status: Low activity

Data Gathered:

- Magnetometer
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The States fire is located northeast of Delta, CO (Delta County). To reach this fire, head East on US-50 E from I-70 toward Delta. Upon reaching Delta, take a left on CO-92 E, and travel approximately 4.0 miles. Turn left onto CO-65 N. After traveling approximately 12 miles, arrive at Cedaredge. Go through Cedaredge, then take a left onto S Rd./NW Sage Ave, followed by a right onto 2325 Rd. (second right). Go straight for 1.0 miles on 2325 Rd., and then take the 3rd left onto T Rd. Follow T Rd. for 1.5 miles to reach the States fire. T Rd. is poorly maintained in the wintertime, and it becomes impassible after a mile into the road.

Key Observations from Mapped Data:

There are two fire zones at the States coal fire, one to the north (lower bench) and another to the south (upper bench). The lower bench fire region is very shallow and shows subtle but definite fire activity. The upper bench fire region is deeper (~60 ft), and the fire activity there is even less pronounced than the lower bench fire region.

There are evidences to suggest that the fire may have once upon a time burned more intensely at the upper bench. There are large gaping fissures that likely formed from fire induced subsidence. Thermally altered rocks next to these fissures imply that there were hot gases exhausting from these fissures. At the upper bench, most of the magnetic anomalies show blue regions, which indicates that the fire that was active in the past is no longer burning.

On a heavy snow day, snowmelt in the upper bench area is non-existent. Snowmelt areas on the lower bench area were mapped, but they were very small. Each snowmelt area spanned no more than a rectangular region of 20 ft x 5 ft. A geo-rectified mine map shows that the lower bench area was extensively mined, and it is appears that the mine was shallow.

Risk Factors:

Risk factors at this site are limited, primarily because the fires here appear to be close to being dormant. The limited fire expressions suggest that the road above the lower bench fire is not at risk.

Recommendations:

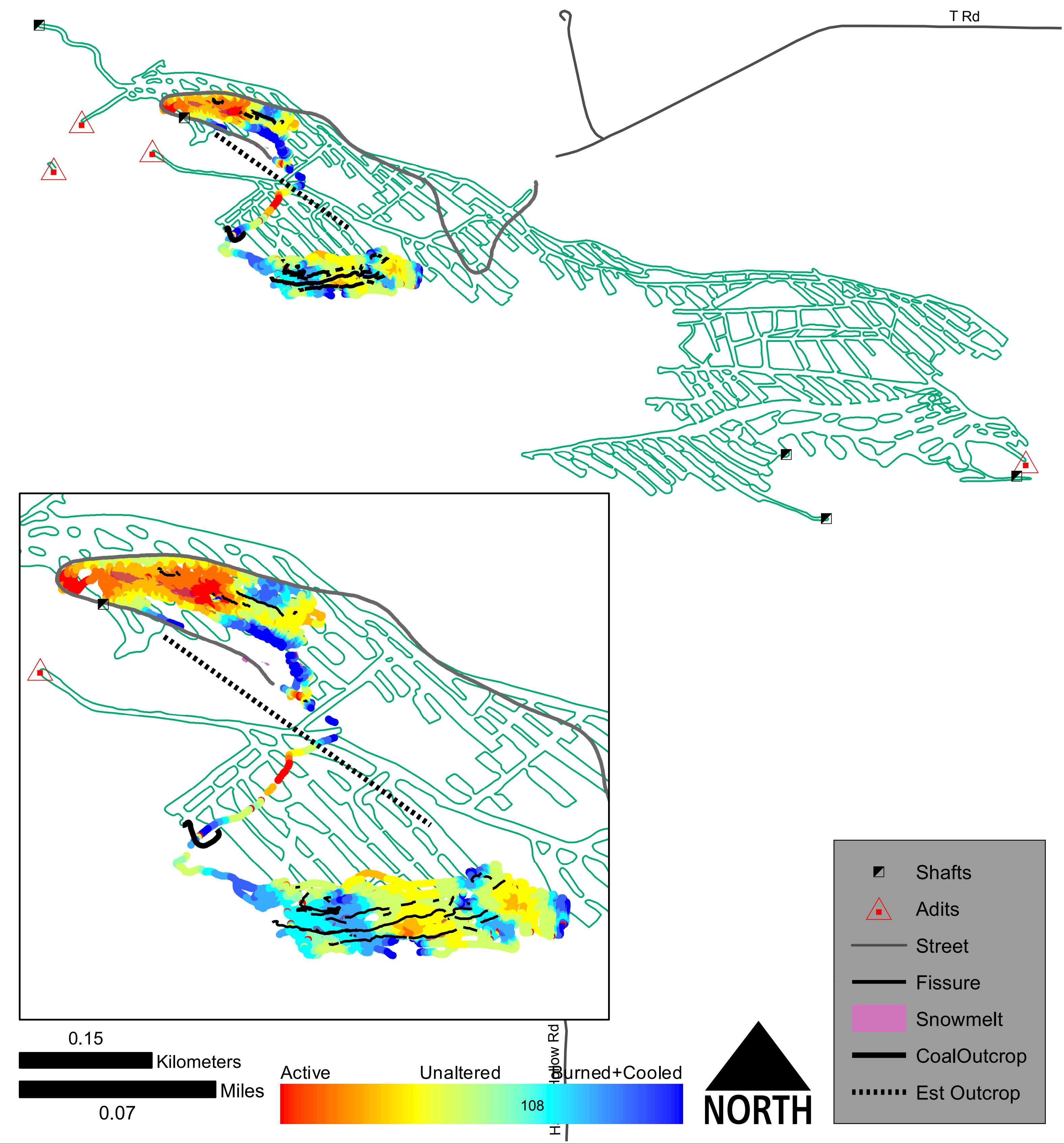
Periodic monitoring of this fire is recommended. Excavating the lower bench fire is also likely a very cheap option. Mixing the overburden soil material with some hardened incombustible grout, and then compacting the area to starve the shallow fire of oxygen may be effective.


Fissures along the upper bench of States fire

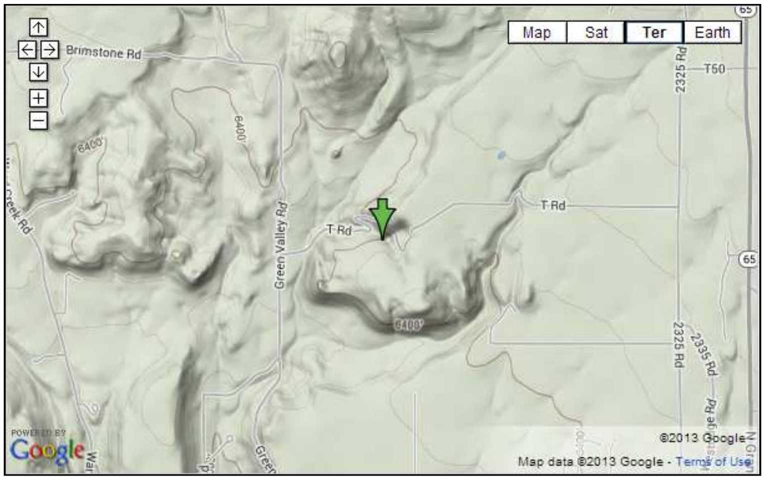

Limited snowmelt along lower bench (left) and upper bench (right) at States fire


Most of the area is covered in snow lower bench (left) and upper bench (right) at States fire

States


T Rd
0.15
Kilometers
Miles
0.07
Active
Unaltered
Burned+Cooled
108
NORTH
Shafts
Adits
Street
Fissure
Snowmelt
CoalOutcrop
Est Outcrop

Streeter



Summary:

Location (lat/long): 40.2625 / -107.7902
Region / Coal field: Uinta / Danforth
Formation: Williams Fork
Seam: Fairfield, Goff, or Lion
Mining method: Slope
Strike / Dip: no data / 2^o
Coal Rank: HvC/HvB
Coal Thickness Affected (ft): <10
Area Affected (ft^2): no data
Status: Active

Data Gathered:

- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Streeter fire is located south of Craig and north of Meeker, CO (Rio Blanco County). To reach this fire, take Hwy. 13N through Meeker towards Craig. The fire is located approximately 20 miles north of Meeker, CO. There is an access road leading up to the Streeter fire to the left. However, permission must be obtained by Colowyo Coal Company to access this fire.

Key Observations from Mapped Data:

The Streeter fire is active at two locations, along an eastern facing outcrop and a southern facing outcrop. The terrain map of the Streeter site shows how the same coal crops out in two different directions. The eastern facing outcrop is the older of the two fire locations. The fire at the southern facing outcrop appears to be relatively new, as it is currently releasing gases that are highly saturated in water. This is indicative of coal going through dehydration. The fire that is consuming the eastern facing outcrop is referred to as the Old Fire, while the fire that is consuming the southern facing outcrop is termed the New Fire.

Snowmelt at the Streeter fire shows that most of the fire activities for both the Old and New Fires are contained along their respective coal outcrops. There are five documented adits near the Old Fire. These adits likely allow fresh air to reach the Old Fire. Above this fire region, fissures at the surface are large and well developed in the overburden, which likely serve as primarily escape channels for the combustion gases.

At the New Fire, well developed surface fissures are less evident. It is likely that coal fire is so close to the surface here that the fire can exchange air and combustion gases at the outcrop. Along the southern facing outcrop but to the west of the New Fire region, there appears to be remnants of old fire activity.

Risk Factors:

If Colowyo is interested in reopening a mine close by, there is a possibility that such activity can exacerbate the current situation.

There also seems to be water that is actively discharging close to where one of the older adits that is mapped on the mine map (This is not related to the pond that is located near the coal fire site). There is a marsh/swamp that has formed due to this discharge. It may be worth testing the water for dissolved chemicals.

Recommendations:

Since the fire is easily accessible and shallow, this fire is a prime candidate for an excavation and refill. The dip of the coal seam here is gentle, unlike fires burning along the Hogback Monocline. The cost to cool the excavated coal/overburden can be minimized if the on-site pond water can be used.

Combustion gases from fissures at Streeter. Ammonium chloride shown in the left picture. Sulfur and tar shown in the right picture.

A large, hot fissure at east-side outcrop at Streeter

Eastern outcrop at the Streeter fire, picture taken looking north

Streeter

KOVEVA
State Hwy 789 Hwy 13 State Hwy 13
0.15
Kilometers
Miles
0.1
Active
Unaltered
Burned+Cooled
111
NORTH
Adits
Highway
Street
Snowmelt

Sunshine

Summary:

Location (lat/long): 39.4025 / -107.3252
Region / Coal field: Uinta / Grand Hogback
Formation: no data
Seam: no data
Mining method: Stope
Strike / Dip: N14W / 40^o
Coal Rank: HvB
Coal Thickness Affected (ft): no data
Area Affected (ft^2): 903,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features

Directions:

The Sunshine mine is located south of Glenwood Springs, CO (Garfield County). Follow the 4 mile Rd. for 8.4 miles, and park alongside the road. The Sunshine fire can be reached by hiking up a quarter mile due north. The Pocahontas fire is located south of Glenwood Springs, CO (Garfield County). To reach this fire, take exit 115 (traveling on I-70E) or 116 (traveling on I-70W) and travel south on Hwy. 82/Grand Ave through Glenwood Springs. Take a right on 27th St., following signs toward Sunlight Mountain Resort. Take a left on Midland by going around the roundabout. Follow Midland for about 1.3 miles, then take a right onto CO Rd. 117/4mile Rd.

Key Observations from Mapped Data:

At the sunshine coal mine fire, two coal seams are likely on fire. Both of the coal seams crop out at this fire, and they were identified. Of the two seams, the fire consuming the bottom seam is more active. The top coal seam appears to have recently ignited, primarily due to the high moisture content contained in the gases being exhausted. Coal seams at this mine were mined using the stope mining method.

The penetration of the fire far into the formation along the dip of the coal seam is unlikely, based on magnetometer results. These results show that only overburden that is close to the outcrop (<50ft) is affected by the fire (red regions). It is likely that the crown coals of both upper and lower coal seams (leftover from mining) are on fire.

The hottest surface expression of the fire is located along the outcrop of the lower coal seam. A fissure emits gases at over 600^{o}F there. All other fire expressions are not as active, and display a temperature anomaly of less than 300^{o}F.

A possible air inlet point seems to be an old mine entry point. The location of the approximate entry point is shown on the Sunshine Fire Data Integrated diagram using a brown outline. This is near the mine entry way shown on the mine map overlay.

The dotted lines in the Data Map show the presumed coal outcrop. Coal outcrops were traced in small sections at the Sunshine mine, which were extrapolated for this map.

Risk Factors:

There is not much surface vegetation at risk of ignition directly over the site. However, some vegetation is at risk of ignition within 100 ft of the outer boundaries of the fire. The site is easily accessible on foot both from the Four Mile Rd. as well as the 4-wheel road to the north. The fire’s proximity to the Sunlight Mountain Ski Resort is a cause for some concern.

Recommendations:

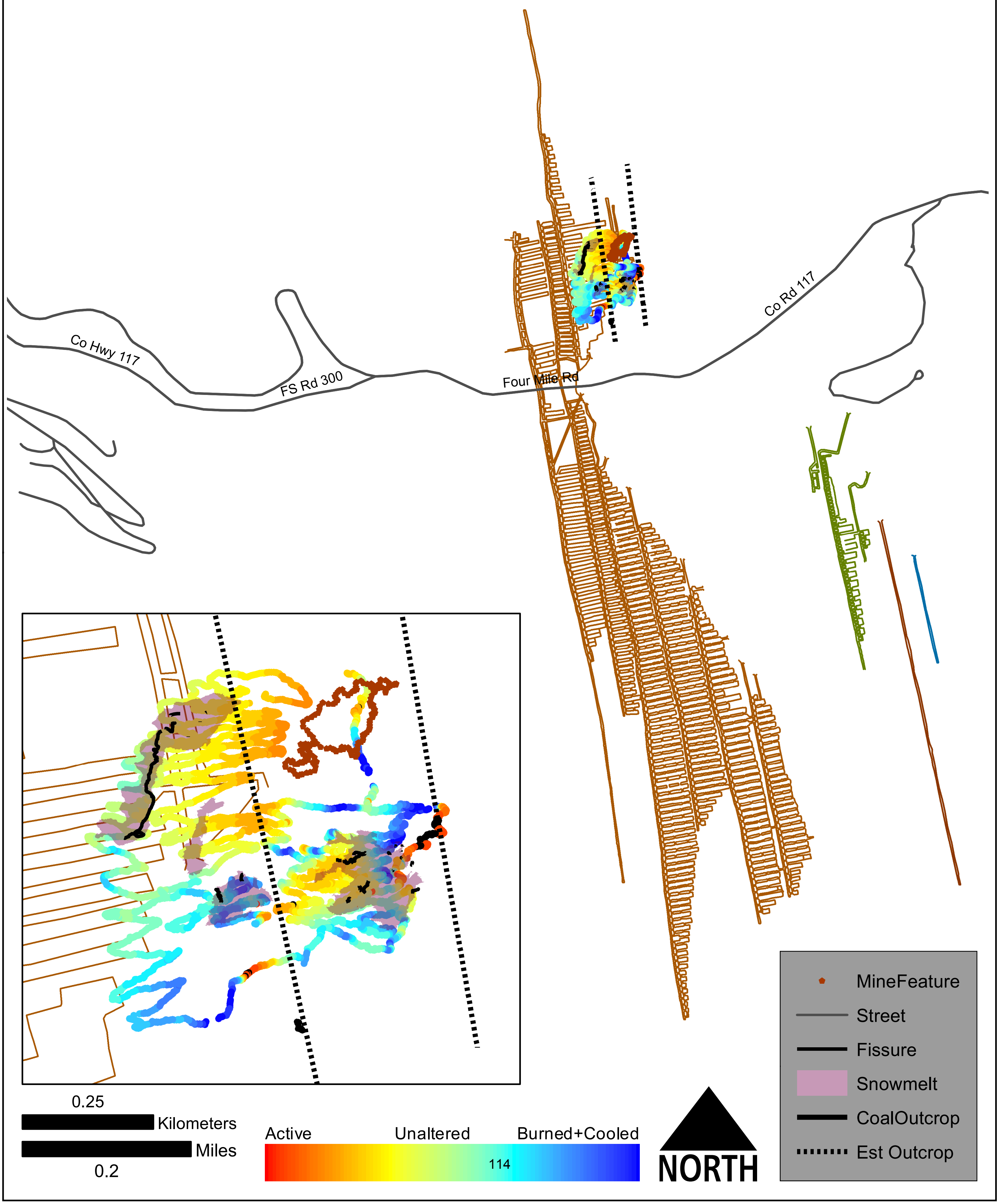
Given the shallow nature of this fire, excavation of this fire is warranted. A small backhoe can likely access the fire from the north side, where there is a well travelled 4-wheel road.

Coal in this region has proven to be gassy based on previous drilling along the Grand Hogback of the Piceance Basin. Thus further methane seepage work is warranted at this site. It is possible that methane may be migrating along the steep dip toward the atmosphere. If such methane can be recovered, it may slow down the fire and as well as provide heat/electricity to the Sunlight Mountain Ski Resort.

Sunshine fire on a sunny day (left) and during a snowstorm (right), looking to the north. The snowmelt region that is highlighted in the data map is not evident from this persepective.

Surface features at the surface of the Sunshine mine fire. Top left: a hot fissure above the lower coal seam. Top right: A plastic-like tar that has formed along the edges of the coal outcrop. Bottom: A temperature reading at a warm fissure above lower coal seam fire.

Sunshine



KOVEVA
Co Hwy 117
FS Rd 300
Four Mile Rd
Co Rd 117
0.25
Kilometers
Miles
0.2
Active
Unaltered
Burned+Cooled
114
NORTH
MineFeature
Street
Fissure
Snowmelt
CoalOutcrop
Est Outcrop

Vulcan

Summary:

Location (lat/long): 39.5609 / -107.5066
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler
Mining method: Stope
Strike / Dip: N63W / 47^o
Coal Rank: HvB
Coal Thickness Affected (ft): <50
Area Affected (ft^2): 280,000
Status: Low activity

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Borehole drilling
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

There are four fires located near New Castle, CO (Garfield County) along the Grand Hogback. Three of these fires, Vulcan, Coryell, and New Castle No. 1 (from east to west) are located immediately south of and parallel to I-70 in New Castle. To reach these three fires, take Exit 105 off of I-70 and head South away from downtown New Castle. At the T-intersection, take a left onto CO Rd. 335 and head west. In order to reach either the New Castle No. 1 or the Coryell fire, park near the thrift shop and hike up the Hogback. To arrive at the Vulcan fire, take a right at the T-intersection onto CO Rd. 335 and head east, then park at the old coal loading dock and hike up the Hogback to reach the site.

Key Observations from Mapped Data:

The three fires that are burning south of I-70 are all slow burning. Methane was detected along the Grand Hogback where Vulcan, Coryell, and New Castle No. 1, so it is possible that methane is a contributing factor to keeping the fires burning. The methane signature collected near this site had the same signature as the methane that is being produced from the same formation in the Piceance Basin.

However, a CO_2 sample that was collected at this site shows that the CO_2 is solely due to coal combustion. More CO_2 samples must be collected from this area to definitively understand whether the methane plays a significant role at the I-70 fires.
All three of these fires exhibit very low fire activities. This is corroborated by the fact that snow melts very slowly at these sites. The magnetometer survey shows that the fire has not migrated too far into the formation away from the outcrop. At these fires, the overburden is too thick to form fissures that are necessary to burn far into the formation. Crown coals that were left as a part of the mining operations are likely being consumed by the fire today.

Risk Factors:

Because coal consumption at these fires is extremely slow, there are no immediate risks associated with these fires. These fires are hard to access due to the steep incline and heavy brush to reach the fires.

Recommendations:

Methane removal from the site may help slow down or extinguish the fire. However, further methane seepage analysis must be undertaken before this option is seriously considered. The methane survey conducted under this contract showed that while there is a presence of methane at these fires, they do not always participate in the combustion process.

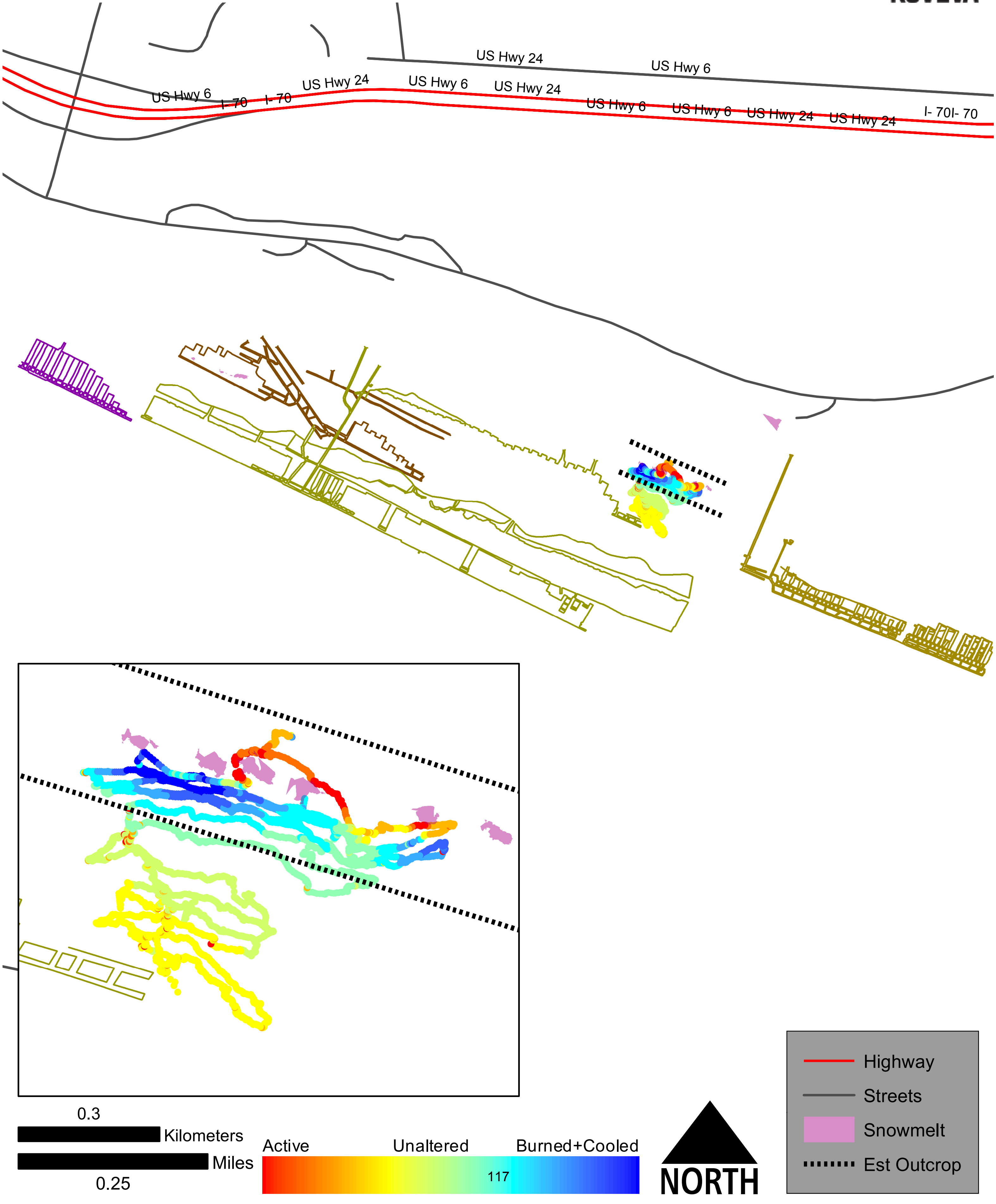
Other conventional methods of fire fighting may be hard to implement here due to the steep terrain in the area.

An old coal loading point near the Vulcan fire.

Outcrop containing Coryell, New Castle No. 1, and Vulcan

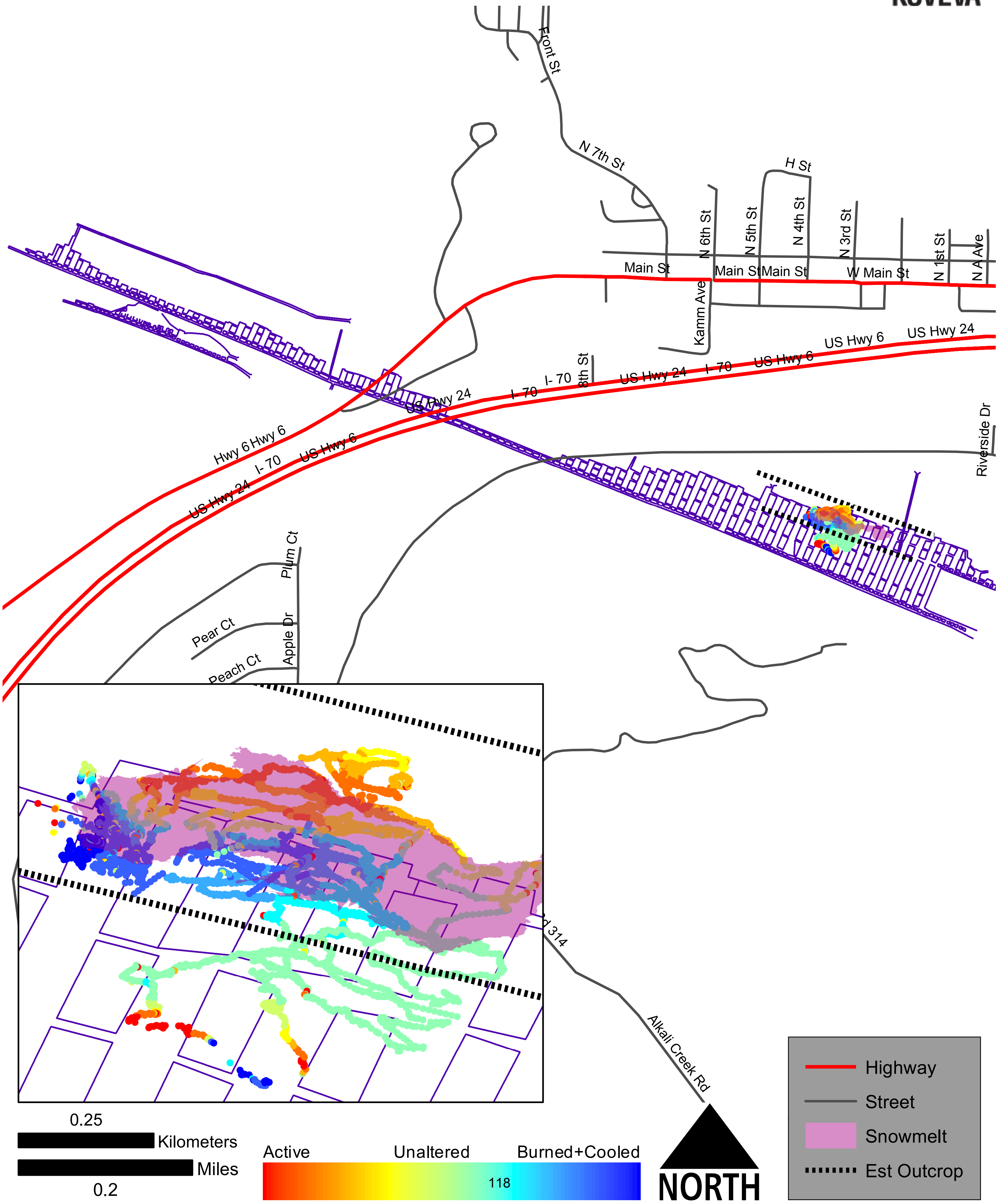
Outcrop containing Coryell, New Castle No. 1, and Vulcan after a snowstorm day
(Hogback on the right side of the picture)

I-70 East



US Hwy 24
US Hwy 6
US Hwy 6
I- 70
I- 70
US Hwy 24
US Hwy 6
US Hwy 24
US Hwy 6
US Hwy 6
US Hwy 24
US Hwy 24
I- 70I- 70
0.3
Kilometers
Miles
0.25
Active
Unaltered
Burned+Cooled
117
NORTH
Highway
Streets
Snowmelt
Est Outcrop

I-70 West



Front St
N 7th St
H St
N 6th St
N 5th St
N 4th St
N 3rd St
N 1st St
N A Ave
Main St
Main St
Main St
W Main St
Kamm Ave
US Hwy 6
US Hwy 24
I- 70
8th St
US Hwy 24
I- 70
US Hwy 6
US Hwy 24
I- 70
Hwy 6
Hwy 6
I- 70
US Hwy 6
US Hwy 24
Riverside Dr
Plum Ct
Pear Ct
Apple Dr
Peach Ct
Alkali Creek Rd
0.25
Kilometers
Miles
0.2
Active
Unaltered
Burned+Cooled
118
NORTH
Highway
Street
Snowmelt
Est Outcrop

Wise Hill

Summary:

Location (lat/long): 40.4317 / -107.6460
Region / Coal field: Green River / Yampa
Formation: Williams Fork
Seam: H (Middle Coal)
Mining method: Drift
Strike / Dip: N20W / 8^{o}
Coal Rank: HvC/HvB
Coal Thickness Affected (ft): ~ 5 to 10
Area Affected (ft^2): 836,000
Status: Active

Data Gathered:

- Magnetometer
- Gas composition
- Gas isotope
- Fissure mapping
- Snowmelt mapping
- Coal outcrop mapping
- Mine maps
- Surface features
- Methane seeps

Directions:

The Wise Hill fire is located just south of Craig, CO (Moffat County). To reach this fire, take Hwy. 13N through Meeker towards Craig. The fire is located approximately 39 miles north of Meeker, CO. There is an access road leading to the fire. However, permission must be obtained from Peabody Energy to access the Wise Hill fire

Key Observations from Mapped Data:

The Wise Hill coal fire is located on Peabody Energy's lease. When data collected at the site are superimposed on top of mine maps, it is evident that the coal fire has burned along the outcrop. Most of the activity is confined to within 0.3 miles from the outcrop. There are currently two active regions, one to the north and the other to the south. The northern portion of this fire is burning along old mine shafts, while the southern fire is burning along the outcrop. The magnetometer survey results agreed well with the rock cuttings returned from the boreholes that were drilled during 4Q of 2012.

Methane seeps were detected over the coal fire. Gas compositions returned from the boreholes showed that methane concentrations could be as high as ~10% in areas. Methane is believed to play a role in keeping the fire burning. The flow of methane out of these boreholes is not trivial, and it is estimated to be anywhere in between 20 to 50 MCFD.

Gas composition measurements were collected most extensively at the Wise Hill coal fire. These measurements show a clear distinction between gases coming from unburned coal regions and currently active combustion regions, which are defined by the magnetometer survey. These samples were measured at boreholes that were drilled by the state during October through December of 2012. Boreholes could not be drilled into formerly burned and now cooled regions due to subsidence concerns.

Gases from native, unburned coal seams have gas compositions are mostly oxygen and nitrogen. The presence of air in coal seams suggests that the air is entering the subsurface through shafts, adits, and/or the outcrop. In combustion regions, the exhaust gases contain carbon dioxide, carbon monoxide, methane, hydrogen, and nitrogen.

At one of the boreholes near the combustion front, Wise Hill #2, the nitrogen percentage is significantly lower than the expected nitrogen mole percentage contained in air. This suggests that there is some other source of gas besides air that is feeding the combustion zone. In addition, excesses of methane and hydrogen indicate that the environment is oxygen starved near Wise Hill #2.

Both the upper seam and the middle seam appear to be on fire, however, the middle seam is likely more active.

Risk Factors:

While the Wise Hill fire is burning near the outcrop today, it is possible that the fire can spread further into the formation. Available mine maps indicate that there are numerous adits and shafts through which air and combustion gases may migrate. The presence of methane in between the lower and upper explosive limits of methane (~5% and ~16%, respectively) could result in dangerous explosions in the subsurface.

Recommendations:

A comparison between observations in Steve Renner's report and the site visit on June, 11, 2012 shows that additional subsidence has occurred in the area. As a direct consequence to subsidence, new vents have opened up above the fire. However, a comparison of satellite images provided by Google Earth dating back to 1993 shows that areal span of the fire has remained largely unchanged for the past 20 years.

These observations suggest that the rate of consumption of the coal into the formation and away from the outcrop is likely slow. Large subsidence features near the outcrop suggests that the fire is consuming most, if not the entire thickness of the coal seam at the outcrop before working its way into the formation.

This slow migration pattern suggests that it may be possible to cut off further propagation of the fire into the formation by digging a trench ahead of the coal consumption zone. Such a trench would be located at least 400ft away from the outcrop, parallel to the strike.

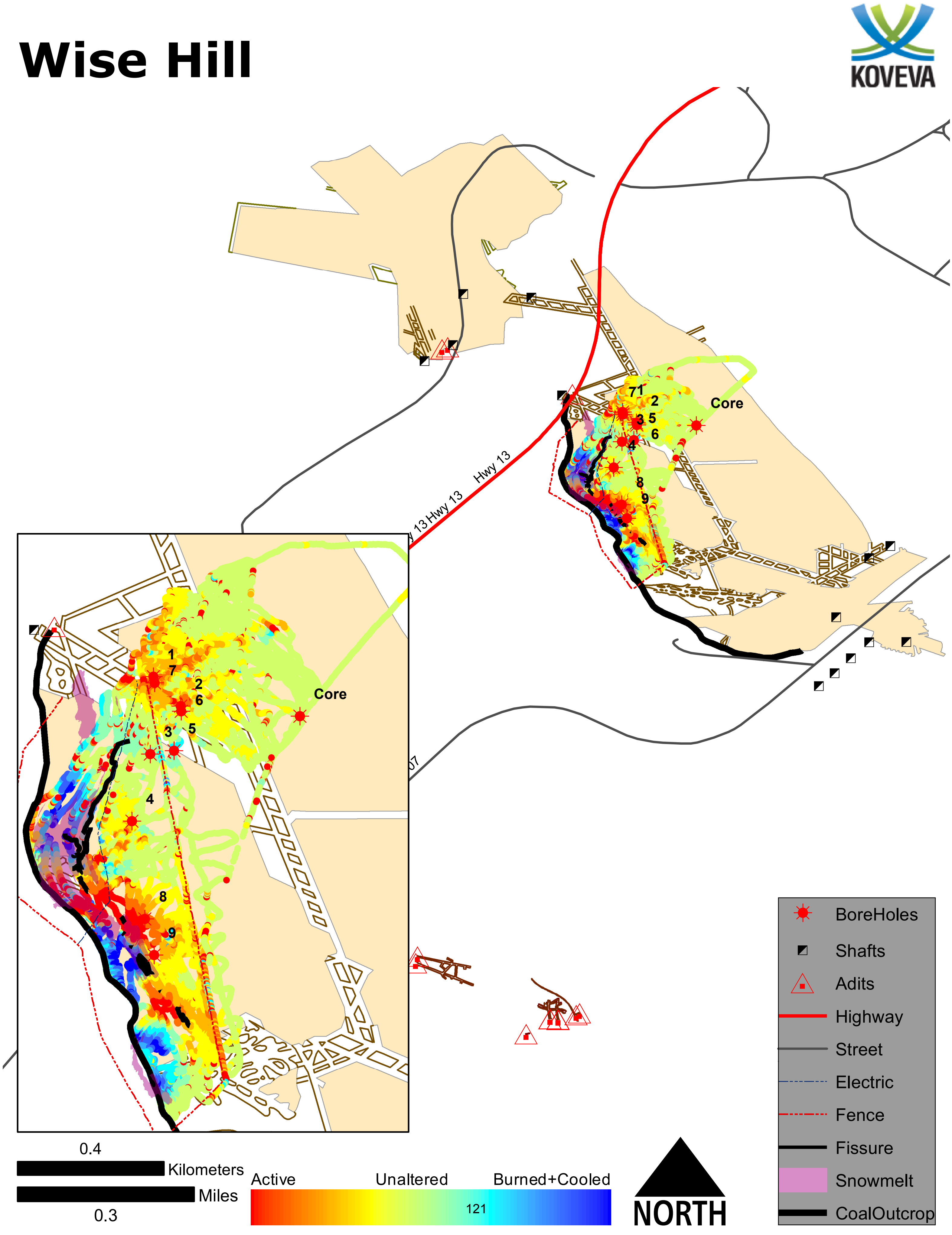
In an ideal world, the trench dimension would be approximately 1,300ft parallel to the strike, 5ft wide, and between 30ft to 100ft deep, (depth depends on the coal seam being targeted). Such a trench would require a volume of roughly 7,200 yd^3 to 22,000 yd^3 of earth to be moved, cooled, and refilled. In reality, digging a 5ft wide trench 100 ft would be illegal, if not structurally impossible, and more earth will surely have to be removed.

Thus trenching thus may be an expensive option. The simplest solution may be to excavate the coal fire at Wise Hill. The high concentrations of methane at the surface suggest that capturing methane down dip of this fire may help slow down the fire.

A satellite image of the Wise Hill fire, north is up

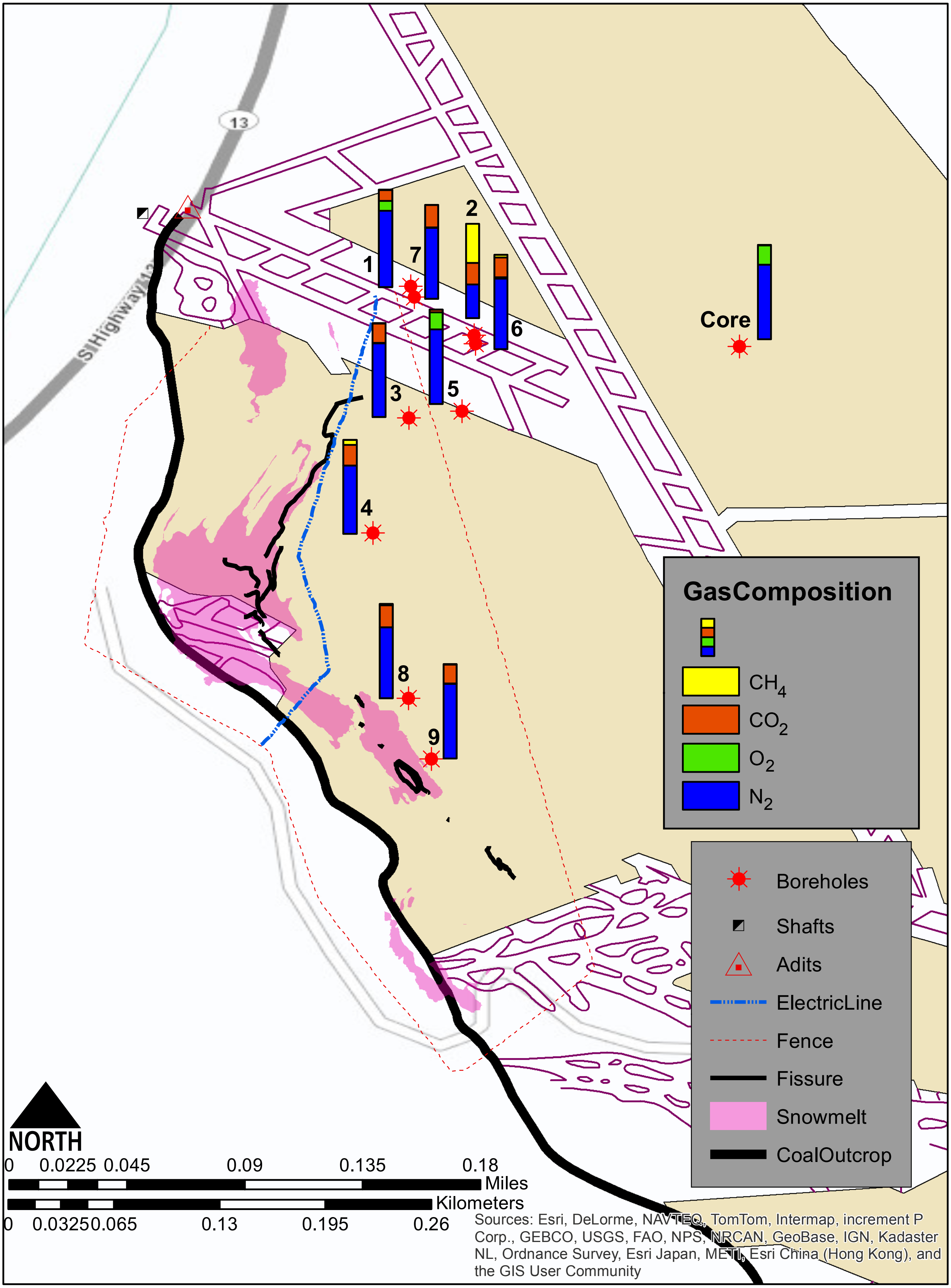
A picture of a borehole connecting the surface to the burning coal seam.

Wise Hill



KOVEVA
Hwy 13
Hwy 13
Hwy 13
Core
1
7
2
6
3
5
4
8
9
0.4
Kilometers
Miles
0.3
Active
Unaltered
Burned+Cooled
121
NORTH
BoreHoles
Shafts
Adits
Highway
Street
Electric
Fence
Fissure
Snowmelt
CoalOutcrop

Wise Hill



13
S Highway 13
1
7
2
6
3
5
4
8
9
Core
GasComposition
CH4
CO2
O2
N2
Boreholes
Shafts
Adits
ElectricLine
Fence
Fissure
Snowmelt
CoalOutcrop
NORTH
0 0.0225 0.045 0.09 0.135 0.18
Miles
Kilometers
0 0.0325 0.065 0.13 0.195 0.26
Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), and the GIS User Community

Double Dick Vicinity

Summary:

Location (lat/long): 38.2908 / -105.1669
Region / Coal field: Canon City / no data
Formation: Vermljo
Seam: Brookside
Mining method: Drift
Strike / Dip: N5E / 4^{o}
Coal Rank: no data
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: no data

Elk Creek

Summary:

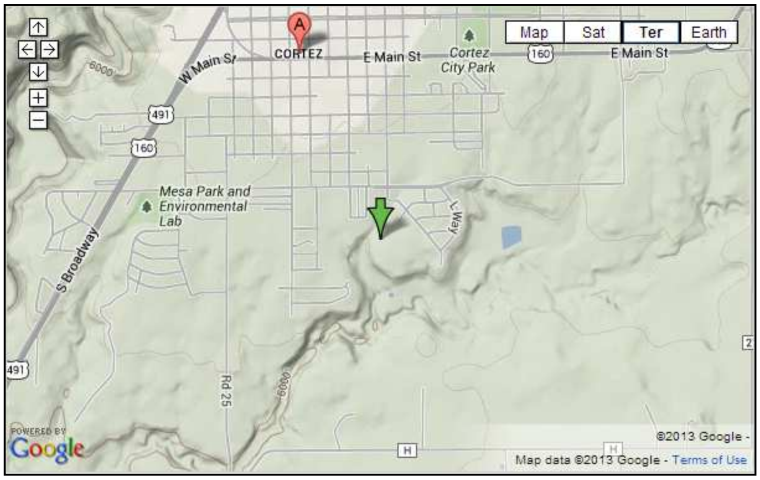
Location (lat/long): 39.5889 / -107.5877
Region / Coal field: Uinta / Grand Hogback
Formation: no data
Seam: no data
Mining method: Drift
Strike / Dip: N73W / 54^{o}
Coal Rank: HvA
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: Active

Garfield

Summary:

Location (lat/long): 39.1271 / -108.3813
Region / Coal field: Uinta / Book Cliffs
Formation: Mount Garfield
Seam: Palisade
Mining method: Drift
Strike / Dip: N20W / 11^{o}
Coal Rank: HvC
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: Active

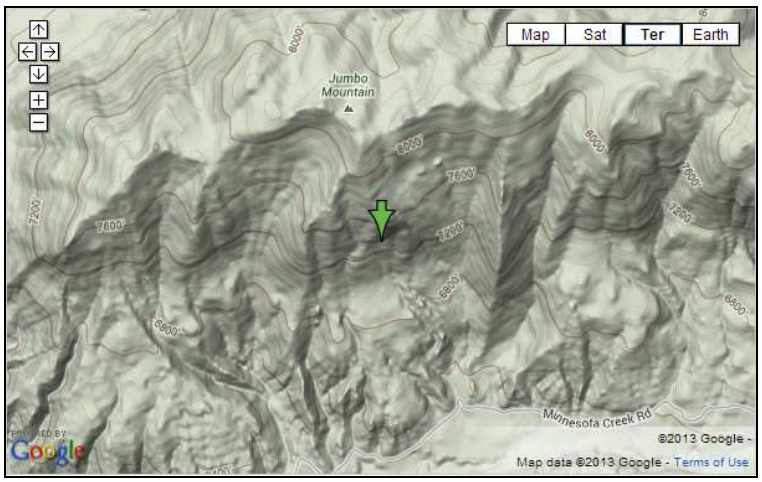
McElmo



Summary:

Location (lat/long): 37.3386 / -108.5802
Region: San Juan River
Coal field: Nucla-Naturita
Formation: Dakota
Seam: Unnamed
Mining method: Drift
Strike / Dip: no data / 4^{o}
Coal Rank: no data
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: no data

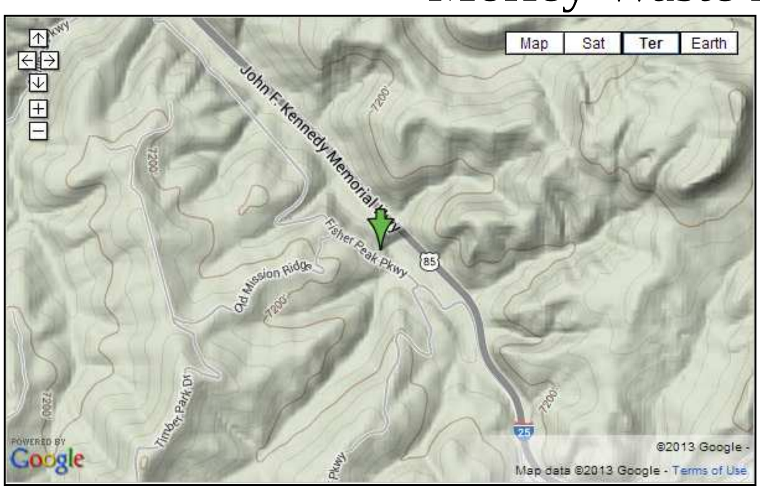
Minnesota Creek



Summary:

Location (lat/long): 38.8816 / -107.5233
Region / Coal field: Uinta / Somerset
Formation: no data
Seam: no data
Mining method: no data
Strike / Dip: no data
Coal Rank: HvB/HvA
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: no data

Morley Waste Dump



Summary:

Location (lat/long): 37.0344 / -104.5075
Region / Coal field: Raton Mesa / no data
Formation: no data
Seam: no data
Mining method: no data
Strike / Dip: no data
Coal Rank: no data
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: no data

Morgan

Summary:

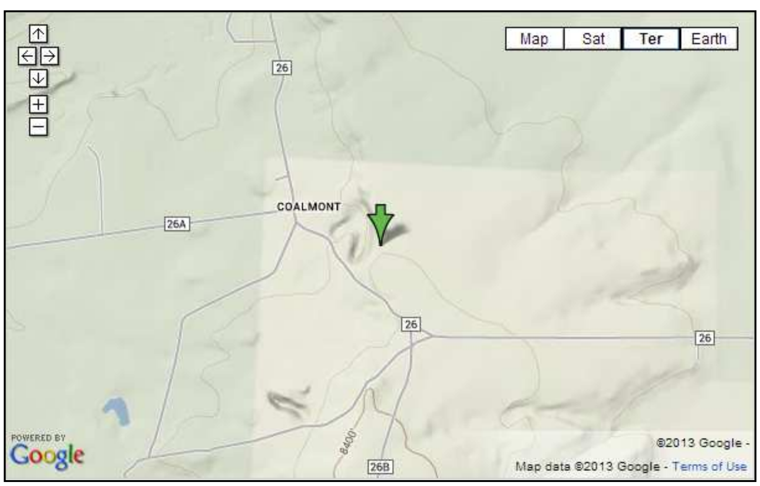
Location (lat/long): 39.5940 / -107.6033
Region / Coal field: Uinta / Grand Hogback
Formation: Williams Fork
Seam: Wheeler
Mining method: Stope
Strike / Dip: N45W / 53°
Coal Rank: HvA
Coal Thickness Affected (ft): <50
Area Affected (ft^2): no data
Status: Active

Oliver

Summary:

Location (lat/long): 38.9247 / -107.4316
Region / Coal field: Uinta / Somerset
Formation: no data
Seam: Oliver
Mining method: no data
Strike / Dip: N90W / 3°
Coal Rank: HvB/HvA
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: no data

Riach



Summary:

Location (lat/long): 40.5603 / -106.4395
Region / Coal field: North Park / Coalmont
Formation: Coalmont
Seam: Riach
Mining method: Slope
Strike / Dip: no data
Coal Rank: SubC/SubB
Coal Thickness Affected (ft): <80
Area Affected (ft^2): no data
Status: Active

Rienau

Summary:

Location (lat/long): 40.1124 / -107.8470
Region / Coal field: Uinta / Danforth
Formation: Williams Fork
Seam: Fairfield, Goff, or Lion
Mining method: Drift
Strike / Dip: N30W / 18^{o}
Coal Rank: HvC/HvB
Coal Thickness Affected (ft): <10
Area Affected (ft^2): no data
Status: Active

Slagle

Summary:

Location (lat/long): 38.2705 / -107.6622
Region: San Juan River
Coal field: Tongue Mesa
Formation: no data
Seam: no data
Mining method: Drift
Strike / Dip: no data
Coal Rank: SubC/SubB
Coal Thickness Affected (ft): no data
Area Affected (ft^2): no data
Status: Active

Chapter 6

CONCLUSIONS

In this report, general characteristics of coal fires that are shared with the majority of the fires were presented. While there are over 30 known fires in Colorado, almost all of them burn at the edge of a coal bearing basin. This suggested that coal fires likely ignite at or close to outcrops, where air is easily accessible. If the fire burns into the formation away from the outcrop, air and combustion gases circulate under natural convection forces within abandoned mines. The mine workings bear resemblance to chimneys. Air can enter the subsurface and combustion gases can leave the combustion zone through old mine workings. In addition to old mine workings, cracks in the ground that appear when subsidence occurs (referred to as fissures in the report) can facilitate the exchange of air and combustion gases between the surface and the subsurface combustion.

A number of field measurements that help characterize coal fires were presented next. Only a small subset of the measurement methods presented in Chapter 2 may be applicable at a specific coal fire depending on both geology and site specific conditions. Both the measurements' purpose and limitations were outlined in Table 3. A single type of data is often not enough to understand key characteristics of a fire such as the extent of the fire in the subsurface, the direction of fire propagation, the intensity of the fire, and the rate of fire propagation. By integrating many forms of data, it is possible to develop a holistic understanding of a fire.

Based on observations, surveys, and historical accounts of approximately 30 fires in Colorado, a schematic diagram detailing how an underground combustion can continue to burn was presented. The schematic presented in Chapter 3 is representative of the majority of the fires burning in Colorado. The four main ideas were that first, air that is drawn in to the subsurface is heated by previously burned zones. Second, the warmed air can react with the char (carbon portion of the coal that is left behind) to produce carbon monoxide or carbon dioxide. Third, the air also has the ability to react with volatile gas species such as methane, hydrogen, and carbon monoxide that evolve from the coal upon heating. These gas phase reactions are important because they are very rapid (about five orders of magnitude faster than air-char reactions), and release a lot of heat. It is believed that the heat from these reactions helps keeps the coal fires burning in the subsurface. Lastly, any unburned carbon monoxide, hydrogen, and methane can burn inside of a fissure as they travel upwards towards the surface. If hydrogen and methane are observed at the surface, this signifies an oxygen lean environment. Oxygen concentrations can be low at the leading edge of the fire, since all of the oxygen has been used up before it reached the front of the combustion zone.

In order to extinguish or control underground fires, one of the following three elements, fuel source, oxygen, or heat, must be removed from active fire regions. In this report, a number of methods were discussed. A fire must be properly characterized in order to determine which fire extinguishing method is most applicable. Sometimes, a combination of methods may be most effective.

Finally, the statuses of coal fires that are burning in Colorado were discussed. Out of the 35 known fires, 19 of them are active. Out of these 19 active fires, 11 are highly active, emitting combustion gases through fissures, and showing signs of spreading. Surface temperatures are highly elevated as well. Fires that are dormant today show no signs of fire, evidenced by snow accumulation over presumed coal fire areas. The fire's current dormancy does not necessarily mean that the fire will stay inactive in the future. Periodic monitoring is recommended.

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