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Meteorite impact craters as hotspots for mineral resources and energy fuels: A global review

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ABSTRACT

The ever-increasing recovery rate of natural resources from terrestrial impact craters over the last few decades across the globe offers new avenues for further exploration of mineral and hydrocarbon resources in such settings. As of today, 60 of the 208 terrestrial craters have been identified to host diverse resources such as hydrocarbons, metals and construction materials. The potential of craters as plausible resource contributors to the energy sector is therefore, worthy of consideration, as 42 (70%) of the 60 craters host energy resources such as oil, gas, coal, uranium, mercury, critical and major minerals as well as hydropower resources. Among others, 19 craters are of well-developed hydrocarbon reserves. Mineral deposits associated with craters are also classified similar to other mineral resources such as progenetic, syngenetic and epigenetic sources. Of these, the progenetic and syngenetic mineralization are confined to the early and late excavation stage of impact crater evolution, respectively, whereas epigenetic deposits are formed during and after the modification stage of crater formation. Thus, progenetic and syngenetic mineral deposits (like Fe, Ni, Pb, Zn and Cu) associated with craters are formed as a direct result of the impact event, whereas epigenetic deposits (e.g. hydrocarbon) are hosted by the impact structure and result from post-impact processes. In the progenetic and syngenetic deposits, the shock-wave induced fracturing and melting aid the formation of deposits, whereas in the epigenetic deposits, the highly fractured lithostratigraphic units of higher porosity and permeability, like the central elevated area (CEA) or the rim, act as traps. In this review, we provide a holistic view of the mineral and energy resources associated with impact craters, and use some of the remote sensing techniques to identify the mineral deposits as supplemented by a schematic model of the types of deposits formed during cratering process.

1. Introduction

The 208 meteorite impact craters discovered on Earth (Kenkmann, 2021) (Fig. 1) have provided insights into some of the fundamental geological processes of the Solar System (Shoemaker, 1983; French, 1998; Osinski and Pierazzo, 2013; Osinski et al., 2013; Li et al., 2018; Keerthy et al., 2019; Gottwald et al., 2020; Chandran et al., 2021; Indu et al., 2021) including the origin of the Moon (Canup and Asphaug, 2001; Daly, 1946), and the Cretaceous-Paleogene (K-Pg) mass extinction (Alvarez et al., 1980; Smit and Hertogen, 1980; Schulte et al., 2010; Barnosky et al., 2011).

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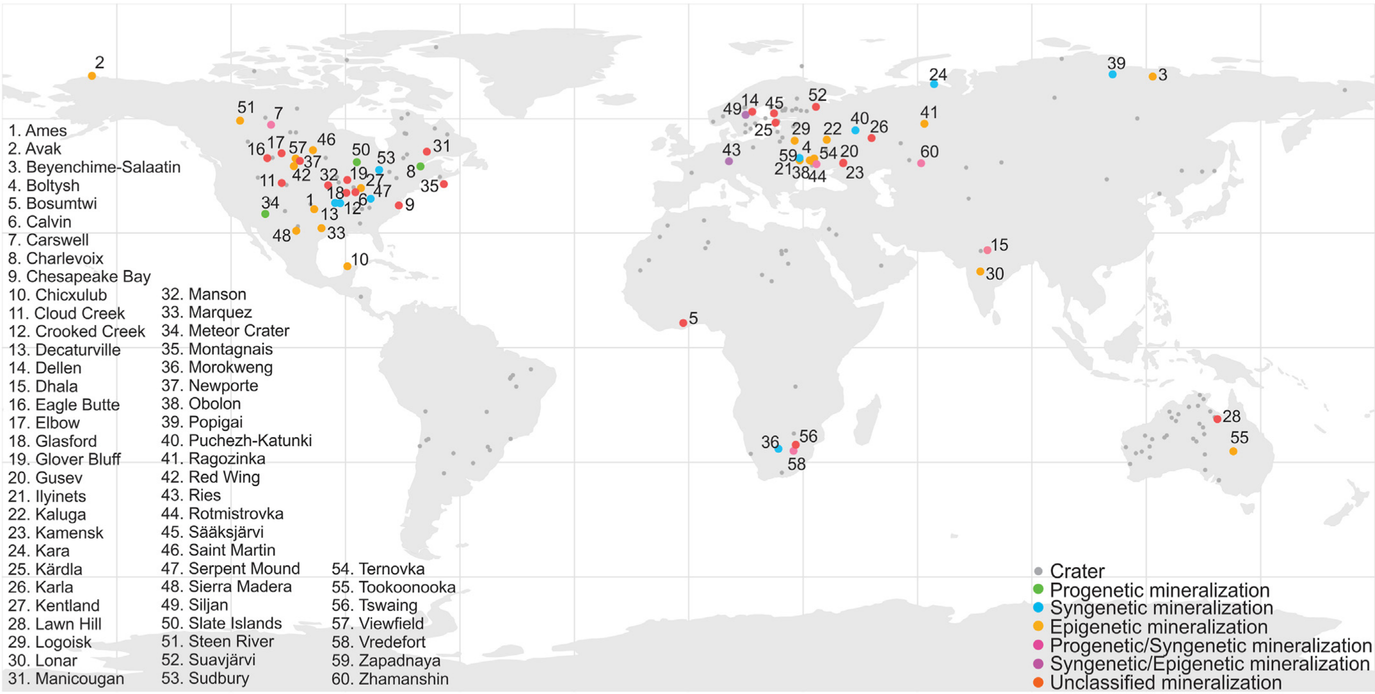

Fig. 1. Global inventory of meteorite impact craters. Craters with reported mineralization are annotated with numbers (1–60). Craters 1 to 60 are listed in Table 1.

Terrestrial impact craters are generally classified based on morphology as either simple or complex craters (Fig. 2) (French, 1998). A simple crater (Fig. 2a) is circular bowl-shaped depression with a rim (smooth/raised), in diameter less than 2 km (Hargitai and Watters; 2014). A typical complex crater (Fig. 2b) contains a central elevated area (CEA), surrounded by a relatively flat floor. A terraced rim circumscribes the flat region (Dence, 1968; Grieve et al., 1977, 1981; Grieve, 1991; French, 1998). Relative to a simple crater, a complex crater is of greater morphological complexity as attributed to the increasing size of the craters (Hargitai and Ohman, 2014). Within the complex craters, as the diameter increases, the complexity of the central uplift is also enhanced. The complex craters have been classified into three distinct types based on the morphology of the CEA, including central peak structure, central-peak-basin structure, and peak-ring basin structure (French, 1998, Grieve et al., 1981; Melosh, 1989; Spudis, 2005). The transition from simple to complex craters on Earth occurs within a diameter range of 2–3 km in sedimentary rocks and of 4–5 km in crystalline rocks (Grieve 1987, 2006).

Crater formation can be divided into three stages: (1) contact/compression stage, (2) excavation stage, and (3) modification stage (Melosh, 1989; French, 1998). In the contact stage, the projectile's kinetic energy is converted into shockwaves to impact and penetrate the target. In the excavation stage, the shockwaves initiate crater formation, while propagating and expanding rapidly into the target. The vertically and horizontally moving shockwaves fracture and eventually hurl parts of the target rock and sub-surface material outwards at high velocities (French, 1998). In the middle excavation stage, a prominent melt lining is developed in the transient cavity. This stage terminates when the transient crater reaches its maximum extent (French, 1998). The final crater results from the modification stage when the transient crater is modified by forces of gravity and rock mechanics. The modification processes in this stage slowly and progressively coalesce into an array of natural geological modification processes over time (French, 1998).

Similar to other terrestrial planets, the early Earth was also bombarded with numerous impacts, but most of them were erased owing to plate tectonics processes (Santosh et al., 2017; James et al., 2021) and/or denudation (Indu et al., 2021). For example, the Yarrabubba impact structure (2229 ± 5 Ma) is the oldest crater on Earth, with no physical signatures left today (Kring and Cohen; 2002; Johnson and Melosh, 2012; Erickson et al., 2020;

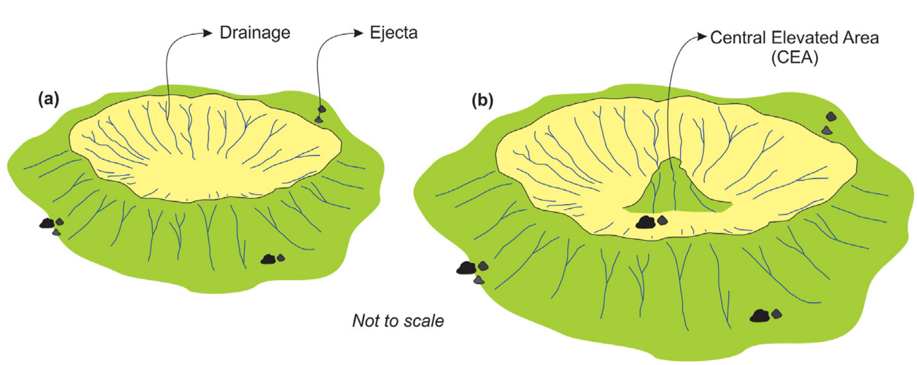

Fig. 2. Schematic sketch of meteorite impact craters: simple (a) and complex (b) (Modified after Indu et al. (2021)).

Schmieder and Kring, 2020). However, recent studies on meteorite impacts have unravelled the possibilities for existence of more impact craters (Kenkmann, 2021). One of the prime interests in identifying impact craters is its potential for hosting mineral deposits. This is exemplified by the giant nickel deposits associated with the Sudbury crater, Canada, which makes it an unparalleled economically-relevant crater (Grieve, 2005; Reimold et al., 2005).

The world population is projected to reach 8 billion by 2024 according to the UN (Roser et al., 2013). The unsustainable exploitation of mineral and natural resources in the wake of the industrial revolution has put unprecedented stress on the supply chain to meet the demands of the humongous global population. In such a scenario, major attempts are being made to identify new mineral deposits while charting out ways to ensure a sustainable and equity centric mode of resource distribution. Since impact craters are now recognized as potential hosts for valuable mineral deposits, they are becoming hot targets for mineral exploration. Kenkmann (2021) summarized that 53 impact craters are being harnessed for natural resources, although the count is not absolute. The scope of craters as potential loci of ore deposits is going to attain increased attention in the future due to the following factors: (1) detailed exploration at known crater locations, (2) discovery of the 100+ missing craters (Kenkmann, 2021), (3) confirmation of suspected craters such as Shiva (Chatterjee et al., 2006), Bedout (Becker et al., 2004) and several others, and (4) identification of submerged craters. Mineral exploration is an endeavour that often extend for decades, given the array of processes involved in the identification, delineation and estimation of the mineral resources. Irrespective of this, certain practices can accelerate exploration and thereby, extraction. Remote sensing and geophysical investigations are two such tools that can contribute to easier identification of craters with potential mineral resources. Therefore, in this study we focus on selecting craters under mineralization, while highlighting minerals used for energy resources and depicting a few mineral-hosting craters through remotely sensed images to narrate how these techniques can be useful in mineral exploration at craters.

2. Ore deposits in relation to impact craters

A total of 60 craters contain natural resources (Fig. 1). The resources range from minor to precious materials like gold, diamond, amber, to minerals with elements such as Co, Cu, Ni, Pb, Pt, U and Zn, and to ilmenite, agate, bauxite, gypsum, pyrite, mercury, iron, limestone, phosphorite, coal, hydrocarbons, salt, silica, trona and groundwater (Table 1).

2.1. Impact events as mineralization trigger

Several terrestrial craters contain/host natural resources, of which some are quantitatively and qualitatively viable enough to be economically exploited such as the nickel deposits at Sudbury (Mory et al., 2000; Grieve, 2005; Kenkmann, 2021). Ore deposits associated with terrestrial craters fall in one of the following three categories defined by Grieve and Masaitis (1994), and Grieve (2005): (1) progenetic, (2) syngenetic, and (3) epigenetic deposit/mineralization (terms used interchangeably). Though this classification is valid for all the terrestrial craters, only 39 craters mentioned by Grieve (2005) are classified accordingly while the rest are termed 'unclassified' in this review, to conform with the original classification due to varied interpretation of the classes by different workers (cf. Grieve and Masaitis, 1994; Grieve, 2005; Reimold et al., 2005). Among the crater deposit classes of Grieve (2005), three deposits are progenetic, four are progenetic/syngenetic, nine are syngenetic, two are syngenetic/epigenetic and 19 are epigenetic (Fig. 3).

2.1.1. Progenetic mineralization

In several instances, the target lithologies have hosted notable mineral deposits before the initiation of the impact event itself. The impact event simply exposes the deposits onto the surface where they can be recovered or converts them into recoverable forms (Reimold and Koeberl, 2014). The shockwave-initiated crustal and structural deformation can easily uplift the buried deposits to near-surface levels, which makes both the discovery and excavation of the deposits easier, or slumping the same further into the crust (Grieve, 2005). Progenetic deposits are best concentrated in the CEA and annular regions in a complex crater (Grieve, 2005). Gold and uranium ores at Vredefort (South Africa) and its vicinity, iron ores at Ternovka (Ukraine), and uranium mineralization at Carswell (Canada) are three of the major examples of progenetic mineralization (Grieve, 2005; Reimold et al., 2005).

The occurrence of exclusively progenetic mineralization is less common than the other two types of deposits. This trend can be directly related to the fewer pre-existing ore deposits at the craters. Additionally, considering the immense scale of impact events, it can actually obliterate the earlier mineral deposits through vaporization or melting. In such cases, the past deposits may become part of the melt itself, which in turn drives mineral enrichment, though an example of such obliterated deposits cannot be identified easily. In such cases, a combination of deposits corresponding to both progenetic and syngenetic mineralization can occur as shown by all the craters containing uranium resources (e.g., Carswell, Ternovka and Vredefort). For the formation of uranium deposits, a stable uranium source is needed. In impact events, it is difficult to determine whether the uranium present is a deposit prior to the impact or originally enriched in target rocks. Such scenarios can also lead to a doubtful or even dual-genetic type for a crater's resources.

2.1.2. Syngenetic mineralization

Ore deposits that are formed on mineralization from impact melt points to syngenetic mineralization (Grieve and Masaitis, 1994; Grieve, 2005; Reimold et al., 2005). As the name suggests, the mineralization is coeval with the crater formation process. The impact melt drives the mineralization at an accelerated and elevated scale, owing to the extremely high impact energies, overseeing metamorphic transformations or geochemical enrichment within the melt (Grieve, 2005; Reimold and Koeberl, 2014; Kenkmann, 2021). Syngenetic deposits are mainly found associated with the impact melt and suevitic units of a crater (Grieve, 2005). Grieve (2005) distinguished syngenetic mineralization as an energy-induced process since impact energies also establish a hydrothermal heat source at craters. Therefore, Grieve (2005) classified impact-derived hydrothermal deposits as syngenetic; while Grieve and Masaitis (1994), Naumov (2002, 2005) and Reimold et al. (2005) classified it as epigenetic.

A potential mineral system is formed due to the presence of a combination of factors like a source rock, driving energy, fluid pathways and a depositional gradient/trap (Wyborn et al., 1994; Knox-Robinson and Wyborn, 1997). Mineral deposits will form in impact structures if all these conditions are present. Terrestrial impact events can create many of these conditions, except the presence of a source rock, which solely depends on the presence of ore minerals in the target rocks. If the target rocks can provide the source for ore minerals, then the impact process is quite efficient in redistribution, remobilization, and enrichment of ore minerals during the progressing impact, which can in turn form a mineral deposit. Additionally, meteorites contribute significant amounts of siderophile elements to the melts, which then can drive mineralization at the craters. While extra-terrestrial contributions in melt are typically less than 1%, which can progress to higher

Table 1
Inventory of meteorite impact craters hosting mineral deposits with genetic types specified (after Grieve (2005), Reimold et al. (2005), and Kenkmann (2021)).

Sl.No	Crater	Latitude	Longitude	Diameter	Age (Ma)	Resources	Deposit Type
1	Ames	36°15′ N	98°12′ W	15	470	Oil, Gas	Epigenetic
2	Avak	71°15′ N	156°30′ W	12	90–94	Gas	Epigenetic
3	Beyenchime-Salaatin	71°03′29″ N	121°41′23″ E	8	<66	Pyrite (minor)	Epigenetic
4	Boltysh	48°57′30″ N	32°14′23″ E	24	65.17 ± 0.64	Oil Shale, Phosphorite	Epigenetic
5	Bosumtwi	06°30′09″ N	01°24′27″ W	10.5	1.07	Water Reservoir	Unclassified
6	Calvin	41°49′ 48″ N	85°57′00″ W	8.5	450	Oil	Epigenetic
7	Carswell	58°25′ N	109°31′ W	39	481.5 ± 0.8	U	Progenetic/Syngenetic
8	Charlevoix	47°32′ N	70°21′ W	55	450 ± 20	Ilmenite	Progenetic
9	Chesapeake Bay	37°14′ N	76°01′ W	85	35.2 ± 0.3	Groundwater	Unclassified
10	Chicxulub	21°20′ N	89°30′ W	180	66	Hydrocarbons	Epigenetic
11	Cloud Creek	43°10′36″ N	106°42′30″ W	7	190 ± 20	Oil	Unclassified
12	Crooked Creek	37°50′05″ N	91°23′44″ W	7	323–348	Pb, Zn, Ba, Fe	Syngenetic
13	Decaturville	37°53′33″ N	92°43′11″ W	6	<300	Pb, Zn	Syngenetic
14	Dellen	61°50′49″N	16°40′38″ E	20	140.82 ± 0.51	Hydropower Reservoir	Unclassified
15	Dhala	25°17′55″ N	78°08′33″ E	12	2240–2440	U	Unclassified
16	Eagle Butte	49°42′ N	110°30′ W	1	<66	Oil	Unclassified
17	Elbow	50°58′ N	106°45′ W	8	201–358	Oil	Unclassified
18	Glasford	40°36′06″ N	89°47′06″ W	10	455 ± 2	Gas Storage	Unclassified
19	Glover Bluff	43°58′12″ N	89°32′18″ W	10	455–459	Gravel, Mortar	Unclassified
20	Gusev	48°29′ N	40°32′ E	3	50.36 ± 0.33	Coal	Unclassified
21	Ilyinets	49°07′ N	29°06′ E	8.5	445 ± 10	Agate	Epigenetic
22	Kaluga	54°30′ N	36°12′ E	15	395 ± 4	Water	Epigenetic
23	Kamensk	48°21′ N	40°30′ E	25	50.36 ± 0.33	Coal	Unclassified
24	Kara	69°05′ N	64°20′ E	65	70.3 ± 2.2	Diamond, Zn, Pyrite (minor)	Syngenetic
25	Kärdla	58°58′26″ N	22°46′51″ E	4	455	Oil, Ore	Unclassified
26	Karla	54°57′23″ N	47°57′04″ E	10	<5	Mercury	Unclassified
27	Kentland	40°45′ N	87°24′ W	12.5	<107	Limestone, Gravel, Pb-Zn	Unclassified
28	Lawn Hill	18°41′19″ S	138°39′06″ E	20	472 ± 8	Zn, Pb, Ag	Unclassified
29	Logoisk	54°15′46″ N	27°47′10″ E	17	29.71 ± 0.48	Amber, Phosphate	Epigenetic
30	Lonar	19°58′36″ N	76°30′32″ E	1.88	0.570 ± 0.047	Salt	Epigenetic
31	Manicouagan	51°23′ N	68°41′ W	100	214	Water and Hydropower	Unclassified
32	Manson	42°35′ N	94°33′ W	35	74.1 ± 0.1	Groundwater	Unclassified
33	Marquez	31°17′00″ N	96°17′30″ W	15	58.3 ± 3.1	Gas	Epigenetic
34	Meteor Crater	35°01′39″ N	111°01′20″ W	1.2	0.049	Silica	Progenetic
35	Montagnais	42°53′ N	64°13′ W	45	50.5 ± 0.8	Oil	Unclassified
36	Morokweng	26°28′ S	23°32′ E	70	145 ± 2	Ni	Syngenetic
37	Newporte	48°58′ N	101°58′ W	3	500	Oil Sand	Unclassified
38	Obolon	49°35′48″ N	32°54′3″ E	18	169	Oil Shale	Epigenetic
39	Popigai	71°38′ N	111°11′ E	100	35.7 ± 0.2	Diamond	Syngenetic
40	Puchezh-Katunki	56°58′ N	43°43′ E	40	192–196	Diamond, Mercury, Zeolite	Syngenetic
41	Ragozinka	58°42′17″ N	61°47′50″ E	9	50	Diatomite	Epigenetic
42	Red Wing	47°36′ N	103°33′ W	9	200–220	Oil, Gas	Epigenetic
43	Ries	48°52′09″ N	10°34′41″ E	26	14.8	Cement, Gravel	Syngenetic/Epigenetic
44	Rotmistrovka	49°08′00″ N	31°44′52″ E	2.7	95–145	Oil Shale	Epigenetic
45	Sääksjärvi	61°24′40″N	22°22′45″ E	6	<520-600	Agate (traces)	Unclassified
46	Saint Martin	51°47′ N	98°32′ W	40	227.4 ± 0.8	Gypsum, Anhydrite	Epigenetic
47	Serpent Mound	39°01′56″ N	83°240′10″ W	8	256–290	Pb, Zn	Syngenetic
48	Sierra Madera	30°35′44″ N	102°54′42″ W	12	<100	Gas	Epigenetic
49	Siljan	61°01′ N	14°56′ E	65	380.9 ± 4.6	Cement, Oil, Pb, Zn	Syngenetic/Epigenetic
50	Slate Islands	48°39′ N	87°01′ W	30	436 ± 3	Au	Progenetic
51	Steen River	59°30′ N	117°38′ W	22	108	Oil, Gas	Epigenetic
52	Suavjärvi	63°07′21″ N	33°22′24″ E	16	2090–2700	Ore	Unclassified
53	Sudbury	46°36′ N	81°11′ W	200	1849.3 ± 0.3	Cu, Ni, Co, Pt	Syngenetic
54	Ternovka	48°07′48″ N	33°31′12″ E	11	280 ± 10	Iron Ore, U	Progenetic/Syngenetic
55	Tookoonooka	27°07′ S	142°50′ E	66	128 ± 5	Oil	Epigenetic
56	Tswaing	25°24′ 31″ S	28°04′ 57″ E	1.13	0.220 ± 0.052	Trona, Salt	Unclassified
57	Viewfield	49°35′ N	103°04′ W	2.5	190	Oil, Gas	Epigenetic
58	Vredefort	27°00′ S	27°30′ E	275	2023 ± 4	Au, U	Progenetic/Syngenetic
59	Zapadnaya	49°44′00″ N	29°03′15″ E	3.2	165 ± 5	Diamond	Syngenetic
60	Zhamanshin	48°21′38″ N	60°56′12″ E	14	0.75–1.10	Bauxite, Glass	Progenetic/Syngenetic

concentrations of 5% (Morokweng). This can lead to significant increase in siderophile element content despite the fact that smaller projectiles favour homogenous melt production due to the lower chance of target variations across smaller distances, whereas larger projectiles enhance the chances of non-homogenous melting as target lithology varies across greater distances (Maier et al., 2006; Koeberl, 2014; Lightfoot, 2017). Variation also arises from the type of projectile/meteorite class since chondrites have higher siderophile concentrations than achondrites; yet for the most part siderophile concentrations across meteorite classes are highly variable (Koeberl, 2014). Though the siderophile concentration in melt results from cumulative contributions of projectile properties, target lithologies and shock modifications, the mineral deposits need not reflect the same due to potential dominance of one contributor over the other (Koeberl, 2014). So, most of the major mineral deposits are syngenetic in nature.

As many as 10 craters contain major minerals like Cu, Fe, Ni, Pb and Zn. Deposits containing Ni, Cu and platinum-group elements (PGE) in the Sudbury crater (Canada) are prime examples of syngenetic deposits (Lightfoot, 2017; Kawohl et al., 2020) while Pb-Zn

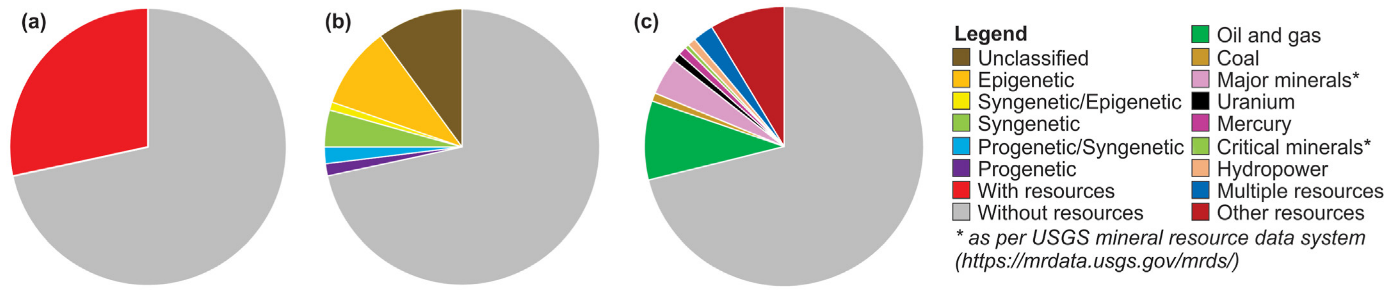

Fig. 3. Pie chart showing the percentage of craters with mineralization (a), types of deposits (b), and energy fuels (c) (Source: Collated from various references cited within this paper).

mineralization at Crooked Creek and Decaturville (USA) are hydrothermal syngenetic deposits (Grieve, 2005; Reimold et al., 2005; Kenkmann, 2021). Except for Lawn Hill and Kentland, Grieve (2005) classified seven of the remaining eight deposits as syngenetic, with Siljan being the sole syngenetic/epigenetic deposit.

2.1.3. *Epigenetic mineralization*

The epigenetic mineralization largely occurs along the morphological and structural units of a crater (Grieve, 2005), that is, in crater basin or subsurface through fluid circulation along the different units of the crater (Grieve, 2005; Kenkmann, 2021). Hydrocarbon deposits linked to craters are epigenetic in nature like the one at Ames and Avak craters in the USA (Reimold et al., 2005; Curtiss and Wavrek, 1998) and coal deposits in Gusev and Kamensk craters. A total of 21 craters have oil/gas/hydrocarbon/coal resources, of which 19 host oil and/or gas. The structural modifications from cratering events are necessary to put in place hydrocarbon-supporting trap systems. As the structural deformation, components and arrangements stabilize much later than the actual impact event, it is essentially a post-impact process. Therefore, deposits formed with the aid of the structural units are classified as epigenetic. Craters with water/groundwater resources such as Bosumtwi, Chesapeake Bay, Dellen, Manicouagan and Manson also host epigenetic deposits, since the drainage networks are established post-impact over several millions of years.

There are several craters that host fossil fuels, with the submarine Chicxulub impact crater being a case in point (Urrutia-Fucugauchi et al., 2013). The deformation due to the impact has been directly linked to the formation of carbonate breccias in the Gulf of Mexico, which host hydrocarbons. The typical bowl-shaped topography and raised rim acts as a potential target for entrapment of hydrocarbons (Donofrio, 1981). From a structural viewpoint, the elevated rim at the crater basin can contain hydrocarbon in the presence of a hydrocarbon-rich lithological seal like at Ames (USA) or the fractured rocks of CEA can itself act as a trap like at Red Wing (USA) (Grieve, 2005; Reimold et al., 2005). Red Wing crater is characterized by three oilfields, of which the Red Wing Creek field occupies the CEA whereas the Bowline and Little Tank fields occupy the rims of the crater (Fig. 4). As per Reimold et al. (2005), the crater acts only as a structural trap for the hydrocarbons, especially the central uplift where the Red Wing Creek field is centred. The cratering-induced structural traps have efficiently established an isolated high-potential hydrocarbon reservoir at the crater centre.

The Jebel Hadid structure in the Al Kufrah Basin (SE Libya) has been postulated to be an impact structure with potential hydrocarbon trap, since the basin is located in an area with high hydrocarbon potential, and the impact could have provided routes and traps for hydrocarbon migration and accumulation in the Nubian Sandstone Series (Schmieder et al., 2009). In the Canadian Alberta Basin, impact structures with hydrocarbon production include

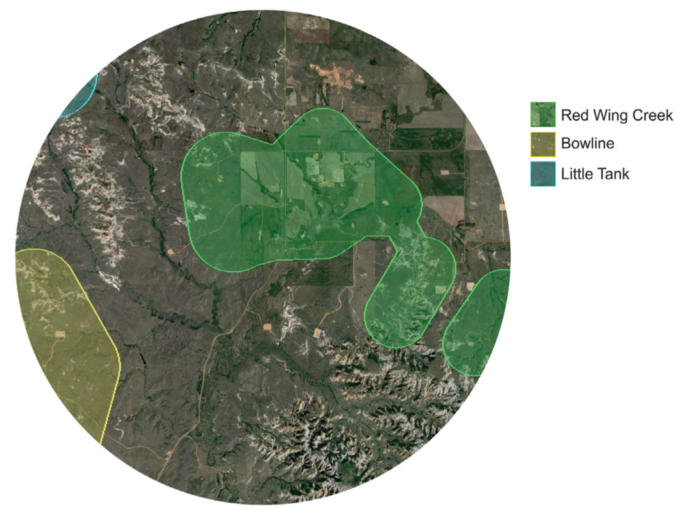

Fig. 4. Oil fields in the Red Wing Crater. Both CEA and the raised rim host oil. (Source: Background image-Google Earth; Shapefile of oilfields, https://www.eia.gov/maps/maps.htm).

Steen River (Robertson, 1997; Mazur et al., 1999), Eagle Butte (Sawatzky, 1976; Hanova et al., 2005), and Bow City (Glombick et al., 2014). The latter structure is postulated to represent a complex impact structure in a mature hydrocarbon-producing basin. The sequence of events leading up to hydrocarbon generation through entrapment following meteorite impact has been established for the Ames structure by Curtiss and Wavrek (1998). This sequence could be taken as the general path in the formation of hydrocarbons, in the event of meteorite impact, especially in marine or other water bodies or even in terrestrial locations (Fig. 5). Crater excavation through fracturing and brecciation of the carbonates and granites was followed by flooding, leading to a contained body of anoxic waters. Algae and other organic debris generated the potential hydrocarbon source rock, which was subsequently buried by thick sequences of sediments. Kerogen to petroleum transformation occurred millions of years later and at the ‘critical moment’ in this transformation, hydrocarbon generation occurred (Curtiss and Wavrek, 1998; Grieve, 2005).

Nineteen craters that host oil and/or gas resources of varying potential are shown in Fig. 5. None of the craters is older than 500 Ma and therefore fits well into the Petroleum System Events timelines. In craters such as Ames (470 Ma) and Red Wing (220-200 Ma), the trap formation deviates from the Ordovician age, probably due to dominance of the shock-induced structural trap formation during the impact event that occurred in different geologic ages, and essentially deviates from the conventional trap formation events. In a similar manner, potential deviations can

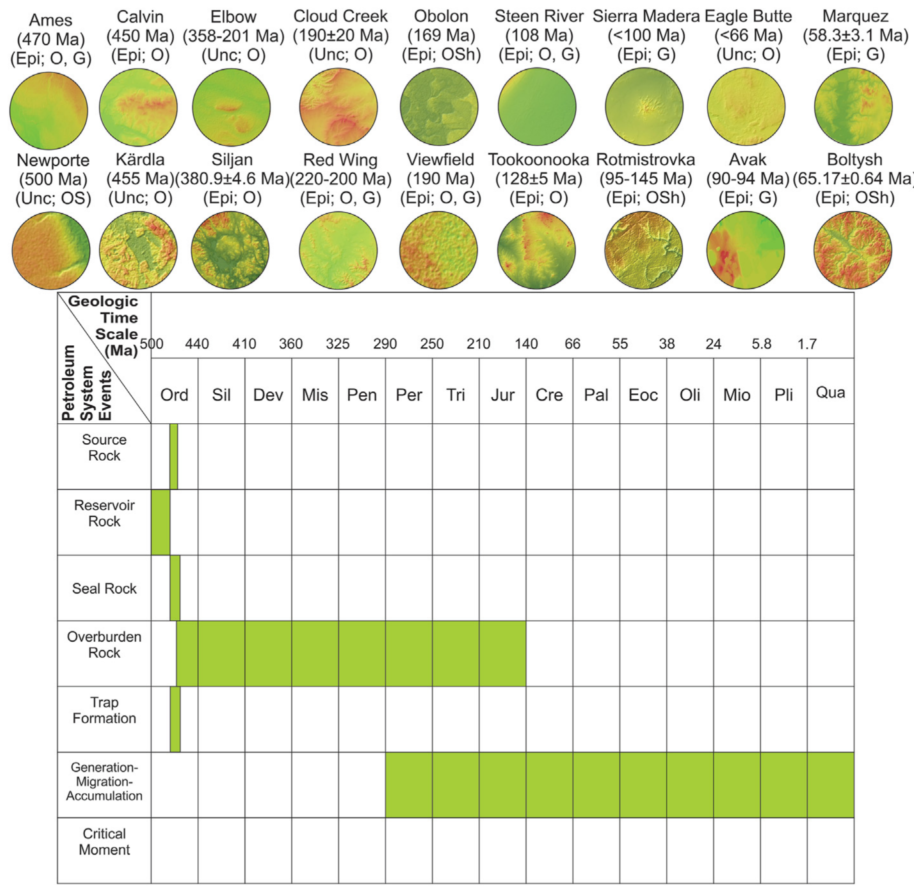

Fig. 5. A petroleum system events chart (Source: Curtiss and Wavrek, 1998) with the impact crater hosting hydrocarbon (Source: ALOS PALSAR elevation data). Montagnais is a marine impact crater and hence not shown. Notes: Ord-Ordovician; Sil-Silurian; Dev-Devonian; Mis-Mississippian; Pen-Pennsylvanian; Per-Permian; Tri-Triassic; Jur-Jurassic; Cret-Cretaceous; Pal-Paleocene; Eoc-Eocene; Oli-Oligocene; Mio-Miocene; Pli-Pliocene; Qua-Quaternary; Epi-Epigenetic; Syn-Syngenetic; Unc-Unclassified; O-Oil; G-Gas; OS-Oil sand; OSh-Oil shale.

occur in different craters, which require additional scientific studies to ascertain the events.

Impact crater hydrocarbon has been likened to unconventional sources like shale gas, tight gas and coal bed methane by Gryga et al. (2016), who also established that the oil and gas potential of the Rotmistrovka impact structure in Ukraine is associated with the hydrocarbon accumulation at the crater rims. Impact cratering events have high potential to establish hydrocarbon reservoirs and trap systems, though the events do not favour formation of source rocks since impacts increase rock permeability, which decreases the chances of hydrocarbon maturation. Impact-induced fracturing and brecciation can enhance the porosity and permeability of the rocks in and around the crater, which can further promote hydrocarbon migration and formation of promising hydrocarbon reservoirs (Grieve, 2005; Reimold et al., 2005). Evans et al. (2005) summarized that the target rock porosity, fault systems, crater burial and ensuing upward migration of hydrocarbons are determinants in establishing a hydrocarbon deposit. There are many more case-specific instances depicting the trapping mechanisms at craters (Grieve, 2005; Reimold et al., 2005). Barton et al. (2009) cautioned that impacts could destroy hydrocarbon reservoirs, as has happened at the Mjølnir marine impact crater in the Barents Sea following which porosity increased immediately after impact by 6.3% on the periphery of the brecciated crater, whereas porosity decreased by 1% in the CEA (Tsikalas et al., 2002). The lithology at the site of impact is often decisive in the development of subsequent economic mineralization. This is especially evident at the Siljan impact structure of the Late Devonian, where the impact triggered the mobilization of the hydrocarbons residing in mature shales and further to microbial metabolism, methanogenesis and gas accumulation under sedimentary cap rock within the crater (Drake et al., 2019). Siljan crater was the site of drilling for hydrocarbons, subsequent to the current discredited theory of Gold and Soter (1980, 1982) on impact fractures facilitating the buoyant movement of mantle-derived methane to the surface, to form hydrocarbons and petroleum. Thus, impact craters have emerged as a topic of potential interest in the hydrocarbon and energy literature.

2.1.4. Multiple modes of mineralization

Impact cratering is almost an instantaneous event, occurring within a fraction of a second (French, 1998). As a result, the different stages of crater formation can either occur simultaneously or even overlap. In this regard, the three mineralization modes can either occur in isolation or act together. Thus, the natural resources as we see at a crater might be a progenetic-syngenetic or syngenetic-epigenetic deposit. Vredefort deposits are dominantly progenetic with notable syngenetic contributions (Grieve, 2005; Reimold et al., 2005), while Siljan Pb-Zn and oil resources are syngenetic-epigenetic deposits (Grieve, 2005). Additionally, the genetic type of crater deposits can vary with the classification adopted, as Sudbury is a syngenetic deposit for Grieve (2005) whereas it is a syngenetic-epigenetic deposit as per Reimold et al. (2005). The difference results from varied views on hydrothermal events as a syn- or post-impact process, and the extremely fast sequence of cratering events do not help resolve it either. While this review follows Grieve (2005), the other ore deposit classifications for impact craters are equally valid.

3. Discussion and conclusion

Though impact craters are potential sites for mineral deposits, identification of minerals that are confined to the structural-morphological features of a crater can help in identifying a crater. Thus, studying mineralization associated with impact craters has an equally-matched function: mineral deposits can aid the recognition of impact craters and craters in turn can also help identify more deposits.

3.1. Crater identification as aided by mineral deposits

Mineral deposits in association with terrestrial craters show two characteristics corresponding to: (1) deposit distribution and orientation and (2) deposit associations. The deposit distribution and orientation have strong links to morphology of a potential crater. The spatial distribution of deposits can either manifest in a circular or near-circular form (aerially) or in a hemispherical/basin form (in 3D), which can taper identically in all directions with depth. Such deposits can be used to identify impact craters. The Cuddapah Basin in India has vast mineral resources and is crescent-shaped. Krishna Brahmam and Dutt (1985), and Krishna Brahmam (1992) suggested an impact origin for this basin , though unequivocal impact origin has not been established. Thus, when mineral deposits are distributed in a radial, circular or crescent shape, the possibility of impact origin is high. Such mineral occurrences showing these patterns need to be investigated, even in the absence of a clear-cut basin structure with or without the CEA. Similarly, mineral deposits oriented either along a concentric fault system or along the length of listric faults also aid in crater identification. For example, confirmation of the Chicxulub crater was made possible through the identification of slump faulting and fracturing near the rim, giving way to a circular cenote (water-filled sinkholes) ring in karst topography (Hildebrand et al., 1995). Yet, the deposit orientations can be misleading at times as the above stated physical signatures can also be reflective of mineral deposits formed by other geological features such as intra-cratonic basins (e.g., Vindhyan Basin in India), wherein the resultant listric and concentric faults can also accommodate mineralization. Such a scenario can result in misinterpretation of the field observation, but it has to be noted that a standalone mineralization along fault is not indicative of a crater's presence because to establish the presence of a crater, multiple evidences from field, geophysical and remote sensing surveys are required. Hence, the deposit distributions and orientations only provide a very preliminary or rather indirect evidence of a crater's presence.

The association of the mineral deposits with direct and spallation components of the impact event is detrimental in crater identification. The direct components occur as physical units but with chemical changes. If mineral deposits occur in the vicinity of a melting layer and/or brecciated rock or shattered cones, then the probability of a crater is conceivable. Unlike the direct physical manifestation of impact shock near the crater, the metamorphic effects from it can continue till the shockwave is attenuated. Therefore, target rocks imbibe the shock metamorphic signatures, which decrease with distance from the centre of the crater. So, observing mineral deposits adjacent to lithology that shows systematic decrease in shock metamorphic effects can be a potential indicator of a crater, but might be less robust than the physical derivatives. The spallation components include proximal ejecta, near which the mineral deposits can indicate crater presence. Distal ejecta, however, is not reliable in crater identification, since with distance, the physical influence of craters dies out, precluding the possibility of mineralization. The Chicxulub impact crater has global ejecta but its oil production is limited to the fields of Campeche marine platform, 350–600 km away from the crater centre (Grajales-Nishimura et al., 2000; Schmieder and Kring, 2020). Additionally, it is difficult to identify the source crater of distal ejecta, which makes it unreliable. The above-stated standalone observations will not indicate crater presence; instead a combination of the observations with each other can serve to discover craters at times at/near mineral deposits.

3.2. Mineral deposits accommodated in impact craters

Craters play an important role in the three processes related to economic mineralization namely formation, preservation and exposure. The cratering process catalyses the mineralization process both physically and chemically. The structural deformation at the crater and target produces physical drivers for mineralization. The formation of new concentric and listric faults, brecciation and reactivation of faults from pre-impact mineralization, generate pathways for fluid mobility (e.g., Carswell) (Baudemont and Fedorowich, 1996; Grieve, 2005). The brecciation and fracturing at the target elevate its porosity and permeability, which becomes quite detrimental to hydrocarbon entrapment (e.g., Ames) (Grieve, 2005; Reimold et al., 2005). The huge volume of impact melt can enrich minerals through processes such as magmatic differentiation, which leads to mineralization (e.g., Sudbury) (Grieve, 2005; Reimold and Koeberl, 2014). Shock metamorphism induces mineral transformation, which in turn aids mineralization. The maturation of hydrocarbons is the best example of chemical transformation assisted by structural and morphological elements of craters.

While all these summarize the individual events facilitating mineralization, it is to be noted that the events fall into one of the three crater formation stages, namely contact/compression, excavation and modification (French, 1998) (Fig. 6a). Firstly, the contact/compression stage marks the projectile destruction and initiation of shockwave expansion (French, 1998). The excavation stage showing visible effects of the progressing shockwaves, can be divided into early-, mid-, and late-excavation sub-stages (French, 1998). The released waves provide enough kinetic energy to eject large fragments of the brecciated and fractured target rocks at high velocities, in addition to uplifting and deforming the target region; which in turn deforms, displaces and exposes the near-surface mineral deposits onto the visible ground levels (Fig. 6b). Hence, progenetic deposits form in the early-excavation sub-stage, with new orientations relative to the ones prior to the impact event. As cratering progresses, so does the melt formation due to greater material interaction, aided by high temperatures released by shockwave energies. By the mid-excavation sub-stage, the crater has a significant quantity of melt, which increase with further material interaction and flow. The elements of greater concentration in the target rock before impact, undergo enrichment in the newly formed melt as the melt ensures greater energy for fluid and elemental mobility, along with activation of enrichment processes such as fractionation, assimilation, secondary alteration or magmatic differentiation (Koeberl, 2014; Reimold et al., 2014; Latypov et al., 2019). The brecciated rocks and fracture systems provide the required permeability for diverse material interaction and create melt flow pathways. Eventually, the melt is enriched with ore forming minerals (Fig. 6c). The melt ensures mineralization within itself and along all its flow paths. As the melt is the prime mineralization agent, deposits forming in the mid-late excavation sub-stages are syngenetic in nature. As the melt forms, the brecciation and structural damage at the target continue,

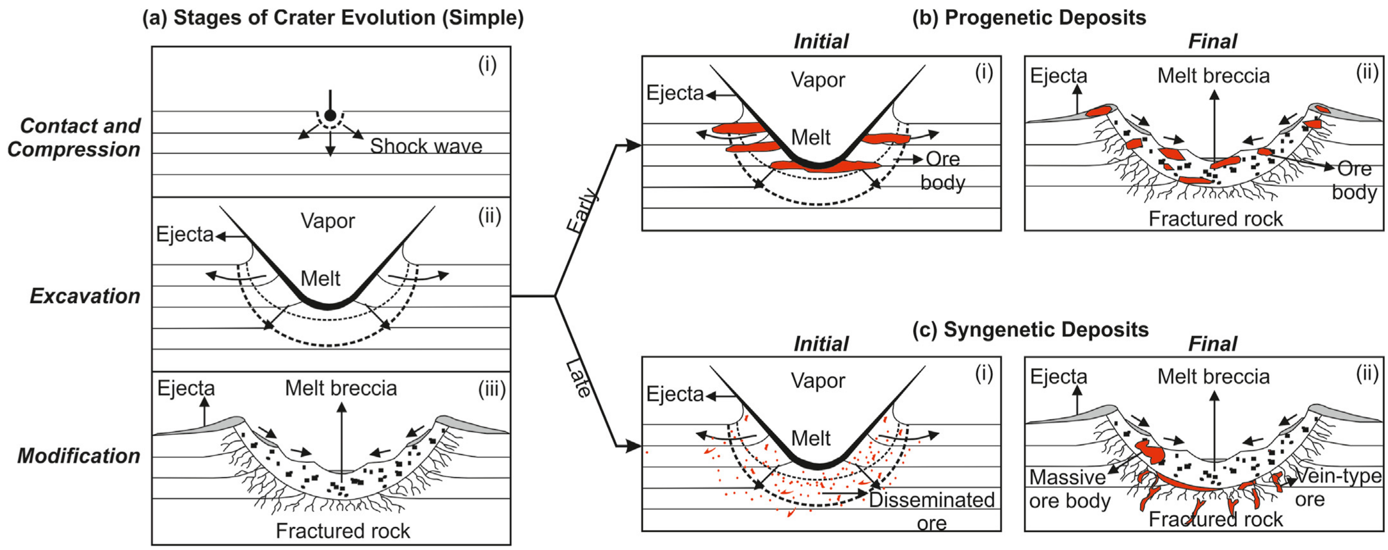

Fig. 6. Schematic sketch showing different stages of simple crater formation (a) (i- Contact and Compression; ii-Excavation; iii-Modification stages), stage of progenetic mineral deposit formation (b) (i-Initial; ii-Final) and syngenetic mineral deposit formation (c) (i-Initial; ii-Final) (Modified from French, 1998).

which in turn facilitates remobilization and enrichment of ore minerals with the aid of circulating fluids, which results in the formation of the hydrothermal deposits. Hence, hydrothermal deposits are also initiated at the mid-excavation sub-stage and the process continues through the late-excavation sub-stage. But networks ensuring hydrothermal mineralization can later change due to events of the crater modification stage. Lastly, the crater attains its final form in the modification stage. As crater morphology is the dominant factor influencing mineralization (Grieve, 2005), it is right to say that epigenetic deposits form in the modification stage and sustain into the post-modification stages of the impact crater.

The preservation of mineral deposits is another major function of craters. Ames crater is an example of terrestrial craters favouring the formation of hydrocarbon system, wherein the Middle Ordovician Oil Creek shale acts both as the source and cap rock for the hydrocarbons, though hydrocarbons get accumulated in the brecciated units (Curtiss and Wavrek, 1998; Grieve, 2005). While impact events might be quite weak in facilitating source rock formation, the formation of reservoir rocks/units, migration pathways (fractures, breccia) and structural traps can be greatly attributed to impact events. Impact craters preserve resources especially hydrocarbon, while the morphological units act as hydrocarbon reservoirs. The reservoirs in terrestrial craters occur along CEA, crater rim and floor, and brecciated units (Mazur et al., 1999). Fig. 7a shows the formation stages of a complex crater and its associated CEA. Fig. 6b depicts the fracture and brecciated zones generating both vertical and lateral hydrocarbon migration pathways, owing to elevated porosity and permeability of the target; which in turn facilitates significant hydrocarbon accumulation in and along different parts of the crater. This establishes the hydrocarbon reservoir, when impact-induced fault alignments favour the formation of structural traps for hydrocarbons. The combination of different morphological and structural units generates structural traps for hydrocarbons (e.g., Red Wing) (Grieve, 2005; Reimold et al., 2005) (Fig. 7b), along with stratigraphic traps such as Tookoonooka and slump block traps (Mazur et al., 1999), which restrict the flow of hydrocarbon within the reservoir units. Additional impact-induced structural modifications such as concentric anticlines and synclines can preserve mineral deposits (e.g., Vredefort) (McCarthy et al., 1986, 1990; Grieve, 2005). Lastly, the terrestrial impact events force the exposure of otherwise buried mineral deposits to surface or near surface levels where extraction of the deposits can be easier (e.g., Ternovka). The impact event displaces and modifies a large extent of rocks and sediments to accomplish it.

3.3. Remote sensing-fostered mineral identification

Remote sensing is an essential tool aiding mineral exploration as it allows investigation of inaccessible regions, reduces the time, resources and investments required for initial investigation to a great extent and lastly, provides an array of sophisticated techniques to aid resource identification. Multispectral, hyperspectral and multi-temporal coverages help delineate metallogenic provinces by utilizing different material properties (Rajesh, 2004). Following this, a combination of image interpretation and analysis techniques is also used to decipher mineral deposits.

Sudbury is quite relevant as an impact crater site of ore deposits of high Ni-Cu concentration. The Frood-Stobie mine is one of the most prominent mines in Sudbury. The deposits of the Frood-Stobie mine are still being mined, which leaves a near arcuate and seemingly clawed-out structure (Fig. 8a). The False Colour Composite (FCC) image derived using high resolution (3 m) Planet Lab images (Fig. 8a) shows the mines in Sudbury. The hyperspectral analysis, using EO-1 Hyperion images containing 242 bands, downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/), shows the presence of chalcopyrite from the absorption band around 400 nm (Fig. 8b), bornite around 600 nm and pyrrhotite from the presence of absorption bands around 2100 nm.

Manicouagan reservoir is an ideal example of epigenetic deposits, since the reservoir system mostly results from post-impact drainage modification over several years. The Manicouagan reservoir and its sub-basins extend outside the crater rim and depict the extensive spatial reach of the post-impact modification. The Google Earth image (Fig. 9) shows the water-covered Manicouagan reservoir near the Daniel-Johnson Dam and the Manic-5 Generating Station. The sprawling vegetation indicates the fertility of soil due to the Manicouagan reservoir's influence. The surrounding water bodies can also be linked to the reservoir. The dam channels the water to power plants and different other locations. This shows that the uninterrupted flow of the Manicouagan reservoir/river provides favourable conditions for establishing large-scale hydropower plants such as the Manic-5 generating station.

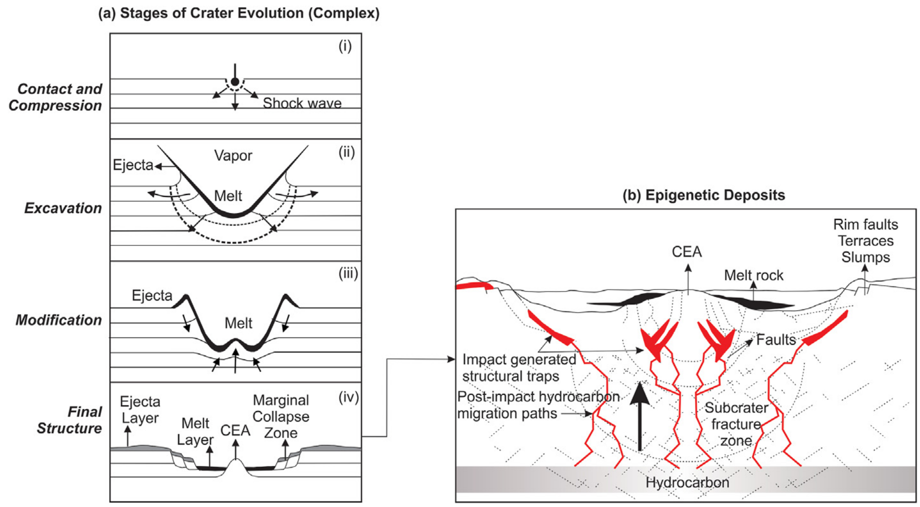

Fig. 7. Schematic sketch showing different stages of complex crater formation (a) (i-Contact and Compression; ii-Excavation; iii-Modification stages; iv-Final structure) (Modified from French, 1998), and epigenetic mineral deposit (hydrocarbon) formation (b) (Source: Modified from Schmieder et al., 2009). (Note: Hydrocarbon deposits can be syngenetic or epigenetic, and we have illustrated only epigenetic)

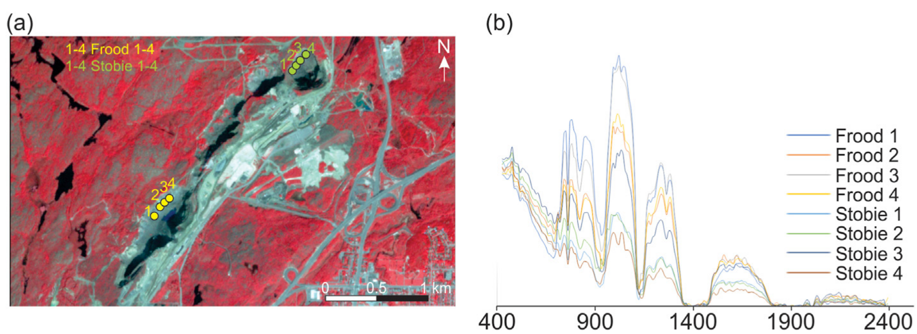

Fig. 8. False Colour Composite image, derived from 3 m resolution Planet Lab images, of Frood and Stobie mines of Sudbury crater (a), and spectra from Hyperion hyperspectral images (b). Spectra has matching peaks with pyrrhotite, bornite and chalcopyrite.

3.4. Constraints on crater and deposit discovery

Several factors reduce the potential of crater and ore deposit discovery. The absence of a complete crater dataset with the impending discovery of 100+ craters (Kenkmann, 2021) has put mineral exploration on hold. Exploration is not to be undertaken at craters at higher latitudes (poles) in permafrost regions, or in submerged craters (James et al., 2021). In known craters, the deformation events can add further complexity to mineral extraction or destroy the deposits to varying degrees, like the loss of past hydrocarbon accumulations due to impact, as at the Avak crater (Grieve, 2005). The presence of human settlements on unidentified craters and deposits can complicate economic utilization of the same due to issues pertaining to displacement of people and cities altogether. On a similar note, even if one of the mentioned characteristics does imply a crater or deposit, the confirmation and economic exploration take years, which can delay the reach of the resource to the supply chains. Hence, remote sensing techniques, which will help augment global exploration efforts to satisfy the energy demand on the planet, need to be applied extensively to identify terrestrial craters and mineral deposits.

Fig. 9. High-resolution Google Earth image of Manicouagan Crater showing the Daniel Johnson Dam and its reservoir. The dam has an installed capacity, totalling 2660 MW.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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