Geoscience Canada

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Volume 15, Number 2, June 1988

URI: https://id.erudit.org/iderudit/geocan15_2art03

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

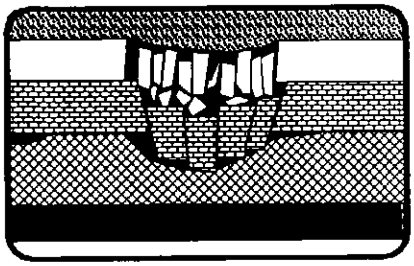
Explore this journal

Cite this article

Simpson, F. (1988). Solution-Generated Collapse (SGC) Structures Associated with Bedded Evaporites: Significance to base-metal and hydro-carbon localization. *Geoscience Canada*, *15*(2), 89–93.

Article abstract

Localized solution removal of bedded salt ofthe cratonic interior has given rise to characteristic collapse structures in the overlying strata. Solution-generated collapse (SGC) structures comprise (1) fault-bounded subsidence troughs, (2) anomalous thickness increases of lithostratigraphic units, (3) collapse breccias resting on solution residues, and (4) local absence or thickness reduction of an evaporite unit at depth. SGC structures are potential conduits for cross-formational flow of fluids (ground water and hydrocarbons) and may have served as free-ways of easy migration for brines enriched in base metals. Reconstruction of the hydro-geologic environments and ground-water regimes has potential as a strategy for location of commercial accumulations of hydro-carbons and base metals.



Solution-Generated Collapse (SGC) Structures Associated with Bedded Evaporites: Significance to base-metal and hydrocarbon localization

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Summary

Localized solution removal of bedded salt of the cratonic interior has given rise to characteristic collapse structures in the overlying strata. Solution-generated collapse (SGC) structures comprise (1) fault-bounded subsidence troughs, (2) anomalous thickness increases of lithostratigraphic units, (3) collapse breccias resting on solution residues, and (4) local absence or thickness reduction of an evaporite unit at depth. SGC structures are potential conduits for cross-formational flow of fluids (ground water and hydrocarbons) and may have served as freeways of easy migration for brines enriched in base metals. Reconstruction of the hydrogeologic environments and ground-water regimes has potential as a strategy for location of commercial accumulations of hydrocarbons and base metals.

Introduction

Solution-generated collapse (SGC) structures associated with bedded evaporites in cratonic-interior settings originated as a result of subsidence, attendant upon localized removal of salt by circulating ground water undersaturated in sodium chloride. SGC structures commonly are mapped as fracture-bounded subsidence sinks, spatially coincident with strata which exhibit differing degrees of brecciation, where an underlying evaporite sequence is locally reduced in thickness or absent. The breccias occur in bodies referable to a limited number of types on the basis of external geometry, and, to some extent, characterizing particular, generally local, hydrogeologic environments.

Specific ground-water regimes showing considerable variation in scale gave rise to solution at the superface, lateral termination or salt margin, and subface of the evaporite-bearing sequence. These ground-water regimes were not mutually exclusive regionally, but tended to be associated with inter-related hydrogeologic environments occupying different parts of the sedimentary basin. In a recent exposition of the generalized hydraulic theory of petroleum migration, Tóth (1980) concluded that both ascending ground-water flow and stagnant conditions, obtained where adjacent flow systems meet or move apart, are associated with oil and gas pools. It follows that recognition of geological features, such as SGC structures, which owe their origins in part or entirely to upward, cross-formational patterns of ground-water flow, forms an important part of an exploration strategy aimed at reconstruction of hydrogeologic environments governing the migration paths of hydrocarbons from source rock to reservoir.

Reconstruction of hydrogeologic environments related to the formation of SGC structures also is likely to aid exploration for, and development of, a wide range of mineral resources which owe their origin to cross-formational flow of ground water. These include Mississippi Valley-type (MVT) lead-zinc deposits, which are hosted typically in parts of carbonate sequences displaying extensive brecciation. Furthermore, prediction of trends for SGC structures in relation to modern ground-water flow systems is of vital importance to the safe and economic mining of potash and rock salt, as well as to the assessment of environmental impacts for waste-injection and underground-storage operations.

This account outlines a systematic approach to description and interpretation of evaporite-associated SGC structures, and suggests how this might form part of an exploration strategy aimed at location of commercial accumulations of mineral resources, with special emphasis on MVT deposits. Attention is focussed on SGC structures resulting from localized solution of the Middle Devonian Prairie Evaporite of the northern Williston Basin region of southern Saskatchewan. The regional setting was described by Christopher *et al.* (1971, 1973); and the special problems posed by SGC structures for operators of waste-injection wells were considered by Simpson and Dennison (1975) and Simpson *et al.* (1987). These accounts have extensive bibliographies.

SGC Breccias and Related Features: Description

Figure 1 shows the lateral terminations of salt and anhydrite referable to the Prairie Evaporite of southern Saskatchewan, presented by Fuzesy (1982), as well as some of the best documented SGC structures. Table 1 gives the author's scheme for systematic description of SGC structures. The scheme is of general applicability to karstification features in carbonate-evaporite sequences.

Texture. (1) The size of fragments in SGC breccias ranges from clay through to blocks to more extensive bodies of foundered strata. Breccias commonly exhibit an upward-coarsening arrangement of grain sizes, with anhydrite-rich mudstone at the base succeeded by polymictic breccias with upward-decreasing matrix support, giving way to oligomictic breccias with grain support increasing in importance upward, replaced by continuous, superjacent strata,

Table 1 Solution-generated collapse (SGC) structures: descriptive format.

Texture	Size:	framework *versus* matrix
	Shape:	mechanical *versus* chemical rounding mechanical breakage, bounding fractures, internal fractures
	Orientation:	rotated *versus* unrotated
	Packing:	matrix *versus* grain support, jig-saw fit
	Porosity:	microporosity/intergranular/fracture
Composition	Framework related to enclosing strata Interstice/fracture infilling Clay content	
Structure	Original Layering:	continuity across structure, into enclosing strata, etc.
	Deformation	incl. fluid-escape structures,
Structures:	flow banding	
Internal Geometry	Plan:	Simple *versus* multiple
	Elevation:	upward-coarsening, upward increase in continuity of strata
External Geometry	Plan:	circular, linear, blanket
	Elevation:	pipe, sink dome blanket/wedge

fractured to varying degrees. (2) Breccia fragments may exhibit minor shape modification resulting from solution. In general, however, fragments are angular. The degree of mechanical breakage in the relatively undisturbed strata decreases upward. (3) The degree of rotation of fracture-bounded blocks and foundered strata decreases upward. (4) Matrix support of breccia fragments is progressively replaced upward by grain support. In the relatively undisturbed material, adjacent, fracture-bounded blocks commonly exhibit a jig-saw fit. (5) Microporosity in the basal, clay-rich lithologies passes upward into intergranular porosity, which in turn gives way to fracture porosity. These porosity types are augmented to varying degrees by original porosity in breccia blocks and fracture-bounded blocks.

Composition. (1) The lithologic contrast between breccia clasts and the undisturbed enveloping strata around the breccia body decreases upward. (2) The proportion of fragments of pre-existing breccia, reflecting two or more phases of collapse, decreases upward within the polymictic breccia. (3) Variable induration of breccias reflects differences in the proportion of cement introduced into interstices and fractures. (4) The amount of anhydrite-rich clay decreases upward.

Structure. (1) A sharp, solution-formed base is typical for SGC breccia bodies. This may occur within the evaporite sequence or at the top of the subjacent lithostratigraphic unit. (2) There is an upward-increasing tendency for breccia and broken rock to be replaced by undisturbed strata, circumscribed by fractures but in continuity with layering in the enveloping rocks. (3) Deformation structures in the relatively fine-grained parts of breccia accumulations include contorted layering, which is evidence for plastic flow of clay-rich material and possibly fluid expulsion during compaction.

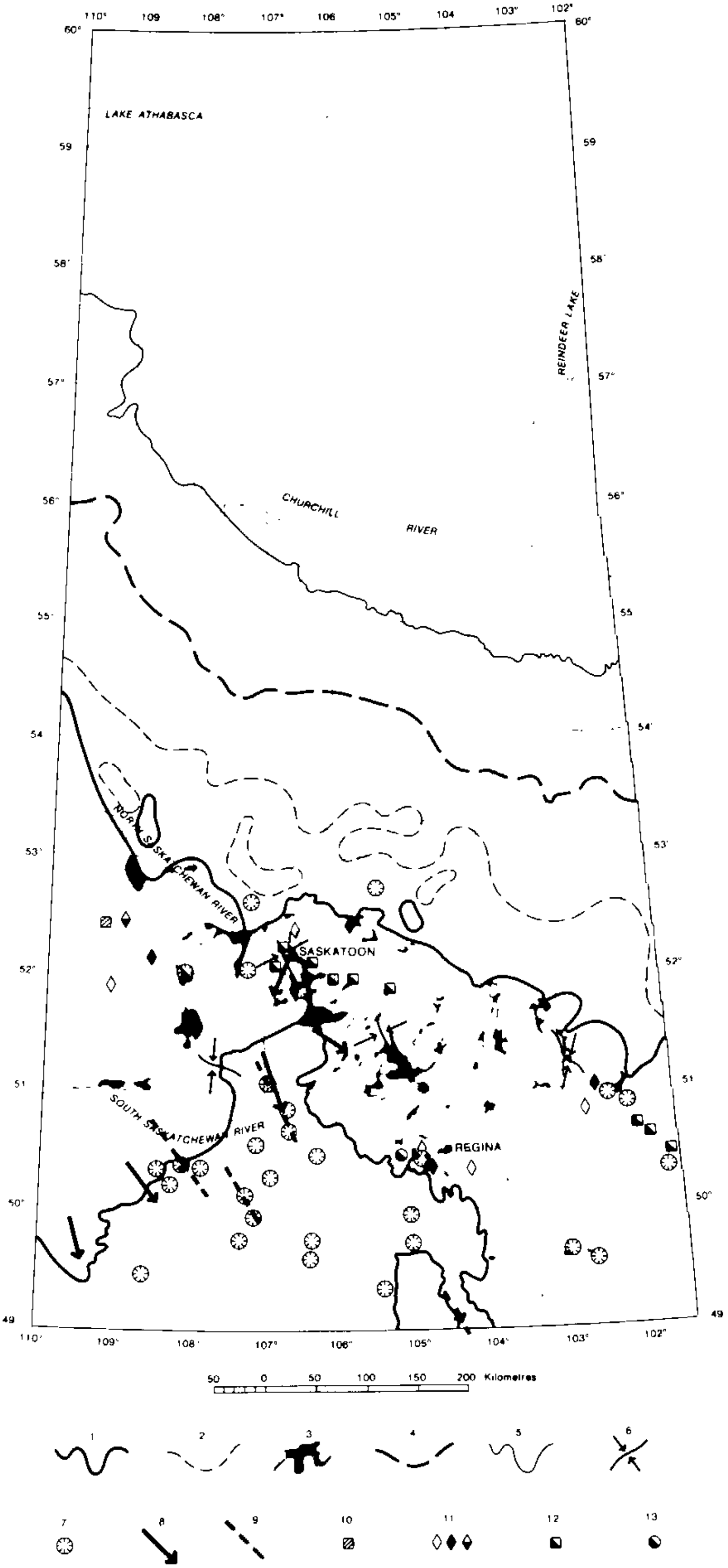

Figure 1 *Solution-generated collapse (SGC) structures associated with the Prairie Evaporite (Middle Devonian) in southern Saskatchewan. (After Fuzesy, 1982; Simpson and Dennison, 1975; Simpson and Connolly, 1982).*

***1**, edge of Prairie Evaporite salt; **2**, edge of Prairie Evaporite anhydrite; **3**, local salt solution (seismic anomaly); **4**, northern limit of Colorado Group (Cretaceous); **5**, southern perimeter of Precambrian Shield; **6**, linear solution features; **7**, sinks and large-scale circular structures; **8**, trend of multi-stage salt solution structures; **9**, major seismic positive elements; **10**, aquifer natural-gas storage; **11**, LPG storage cavern, natural gas storage cavern, chemical-plant facility; **12**, shaft mining; **13**, solution mining.*

Internal Geometry. (1) In plan and elevation, concentric patterns of fractures commonly reflect multi-stage collapse, associated with two or more phases of salt removal. (2) The frequently anhydritic mudstones and mud-supported breccias at the base of a given SGC breccia body are, to a large extent, solution-formed residues comprising material originating within the evaporite sequence. (3) Breccias and fractured rock in the upper parts of SGC structures have resulted from collapse of strata above the evaporite sequence. (4) There is an upward increase in continuity of strata within SGC structures. The lowermost continuous strata may exhibit downwarping.

External Geometry. (1) In plan view, SGC structures exhibit circular, linear and less regular, wedge- and blanket-like configurations (Figure 1). All of these forms are found at locations which are internal, marginal and external with respect to the area of evaporite occurrence. The linear structures tend to be associated with re-entrants along the evaporite margin, where they make high angles with the overall trend of the solution edge. Some linear structures reflect successive stages in the retreat of the salt margin. (2) In elevation, the main configurations are pipes or chimneys, broader sinks and domes, all commonly bounded by fractures, as well as wedge and blanket shapes.

Associated Hydrogeologic Environments and Ground-water Regimes

The SGC breccia bodies described above and elsewhere by the author (Simpson, 1987, Table 2) are similar in external geometry to the prismatic and tabular karst accumulations associated with MVT lead-zing deposits at Pine Point, NWT (Table 2), described by Rhodes *et al.* (1984). The possibility that the presence of evaporites is critical to the origin of MVT deposits, as suggested by fluid-inclusion studies, was considered by Anderson and Macqueen (1982). The relationships between SGS structures and patterns of hydrocarbon migration and entrapment were discussed by Simpson (1987). These connections between mineral-resource accumulations and SGC structures strongly suggest that reconstruction of the associated hydrogeologic environments and ground-water regimes might form a useful starting point for somewhat related exploration strategies.

Solution at the Salt Superface. SGC breccia was first formed through initial collapse over caverns and tunnels at the salt superface. Subsequent development took the form of (1) lateral expansion as the salt edge retreated, and (2) growth from below through increments of solution residue. The SGC breccia body thus formed was an extensive blanket, incorporating pipe and linear bodies at locations external to the area of salt occurrence. Drawdown associated with major river systems and the downward and lateral flow associated with recharge areas were related ground-water movement patterns.

Solution at the Salt Margin. SGC structures resulted mainly from solution by recharge waters directed at the salt margin, and comprised wedge forms extending beneath the salt and linear bodies at re-entrants along the crenulated solution edge. These marginal bodies passed into breccia blankets at external locations.

Solution at the Salt Subface. Access to the salt subface was gained by ground water undersaturated in sodium chloride through conduits permitting relatively easy upward migration. These conduits were (1) carbonate mounds referable to the subjacent Winnipegosis Formation and structurally high with respect to the salt subface in general; and (2) pervasive fractures penetrating the sedimentary sequence from the crystalline basement. The pattern of ground-water circulation at the salt subface initially was controlled by brine density flow (Anderson and Kirkland, 1980), involving (1) upward motion of relatively fresh ground water, impelled by the regional potentiometric gradient, to the salt subface; (2) downward displacement of the more dense brines produced by salt solution, moving in the same conduit; and (3) movement of the brines in hydrostratigraphic units below the salt toward the discharge area. Brine density flow was replaced to a large extent by true cross-formational flow after the salt-bearing sequence had been breached as a result of cavern collapse and breccia formation. SGC pipes formed in this way are similar in morphology to features formed through collapse of artificial caverns produced during solution mining of salt (Ege, 1984).

Accelerated Salt-Solution Episodes. Although solution of the Prairie Evaporite has taken place from Devonian time up to the present day, episodes of intensified, possibly accelerated salt solution are reflected in single-stage SGC structures and parts of multi-stage SGC features, referable to several time ranges: Late Devonian, Late Mississippian to Early Jurassic, Late Jurassic to Early Cretaceous, and Paleocene to Holocene. These episodes of intensified salt solution correspond to periods of cratonic emergence (Simpson, 1978), arising in response to plate interaction at the western margin of North America. The resulting uplift of recharge areas in the ancestral Cordilleran region and other western locations produced an increase in potentiometric gradient across the western Canadian sedimentary basin, which gave rise to increased solution removal of salt. The less subsident regional arches and other large-scale basement linear features may also have had a role in facilitating salt solution by causing localized, upward deflection of ground-water flow systems, possibly up compaction-related fractures in the overlying strata and along the pervasive faults considered above.

Regional Perspectives. As indicated above, basement linear features appear to have played a significant role in the formation of SGC structures. Indeed, basement structures exerted a major influence on the distribution of hydrocarbons in Paleozoic reservoirs (Kent, 1973), and, in conjunction with commonly related SGC structures, they influenced the trends of depositional systems up to the present day. The work of Christopher (1974, 1980) shows a clear connection between younger depositional systems (including modern drainage systems) and antecedent facies trends, with deep-seated control by SGC structures and basement linear features. For example, Figure 2 shows the spatial coincidence between Dina (Early Cretaceous) valley fill mapped by Christopher (1980) and SGC structures associated with the Prairie Evaporite, as presented by Fuzesy (1982). Trends may be predicted for SGC structures by extrapolation along the axes of Dina valleys (Simpson and Connolly, 1982). Furthermore, the high fluid pressures and artesian conditions encountered in sandstones of the Early

Table 2 Main types of breccia accumulation associated with Pb-Zn mineralization, Pine Point, NWT (Rhodes *et al.*, 1984).

Breccia	Remarks
Prismatic Karst	Chimney-like structures at intervals along tabular solution channels, through 30-100 m of strata (Watt Mtn and Sulphur Pt Formations).
Tabular Karst	Linear solution channels continuous along strike of barrier (Presqu'ile Dol), over depositional ridges at top of Pine Point Formation, 1-15 m thick, 15-220 m wide.
Abnormal Prismatic Karst	Collapse structures penetrating below stratigraphic level of dominant paleokarst network by 90 m or more, block displacement up to 150 m, breccias unconsolidated.
B Spongy-Type Karst	Moldic vuggy porosity, fine crackle-breccia porosity, no larger cavity features with internal sediments.

Cretaceous Mannville Group, which include the Dina valley-fill deposits, almost certainly reflect pressurization as a result of hydraulic continuity with older hydrostratigraphic units transected by the same SGC structures. Indeed, Mannville fluid pressures may have resulted from the influx of deep ground water from below the salt subface.

Application to Mineral-Resource Exploration and Development

Evidence for possible migration of ground water and hydrocarbons within SGC structures presented by Simpson (1987) includes a favourable distribution of porosity types in many SGC breccias; the approximate coincidence of high-pressure potentiometric cells with SGC structures, on the basis of limited study of potentiometric surfaces based on drill-stem tests; the occurrence of hydrocarbon showings in the matrix of SGC breccias; the presence of oil pools trapped within SGC structures, and the occurrence of old oil in younger reservoirs, where the sedimentary sequence from source rock to reservoir is transected by SGC structures. Reconstruction of the hydrogeologic environments and ground-water regimes genetically related to SGC structures is therefore strongly recommended as a starting point in exploration for mineral resources which owe their origins to the cross-formational migration of formation fluids, including hydrocarbons and MVT lead-zinc accumulations. In such reconstructions, it is necessary to consider the evolution of basin hydrodynamics in the context of stages in the depositional and structural history of a sedimentary basin, as is presented in Table 3 (after Coustau *et al.*, 1975).

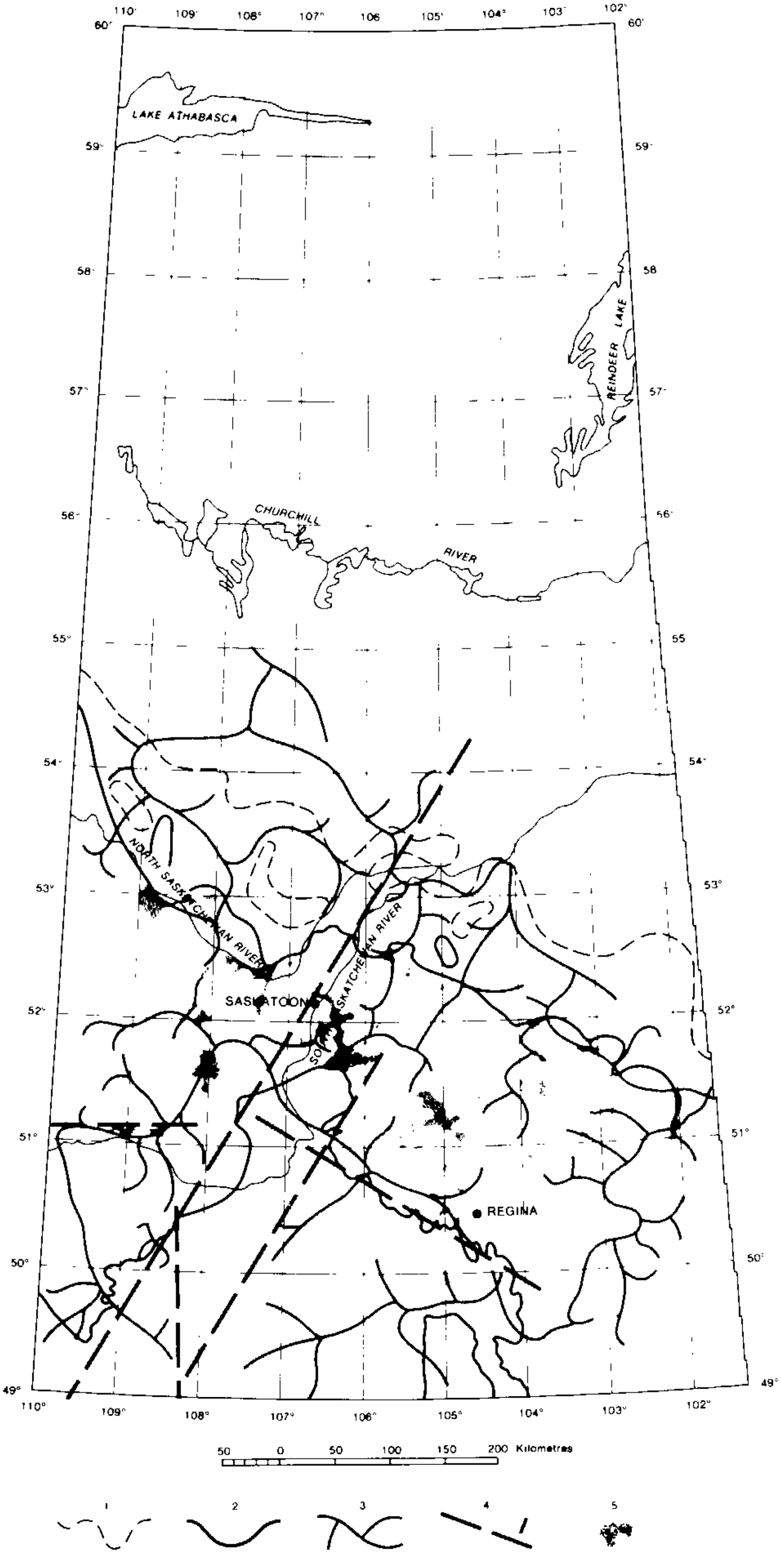

Figure 2 *Solution-generated collapse (SGC) structures associated with the Prairie Evaporite (Middle Devonian) and axes of Dina Formation (Lower Cretaceous) valley fill in southern Saskatchewan. (After Christopher, 1980, Fuzesy, 1982; Simpson and Connolly, 1982).*

1, edge of Prairie Evaporite anhydrite; 2, edge of Prairie Evaporite salt; 3, axis of Dina Formation valley fill deposits; 4, structural linear; 5, local salt solution (seismic anomaly).

Although schemes of hydrodynamic classification of sedimentary basins (*e.g.*, Table 3) commonly assume widespread continuity of hydrostratigraphic units, it is clear the SGC structures may provide vertical conduits linking deep and shallow aquifers. SGC structures may also provide connections between regional, intermediate and local flow systems, in juvenile, intermediate and possibly senile basin types (Table 3).

The forecasting of trends for SGC structures in hydrocarbon exploration (Simpson, 1987) should take into account the following alternative relationships: (1) Sites of hydrocarbon accumulation are coincident with the SGC structure, *e.g.*, at associated dip reversals in the superjacent strata. Improved porosity and permeability resulting from dolomitization along the fractures associated with SGC structures (Kent, 1968) is a variant of condition 1; (2) Hydrocarbons migrated up the SGC structure to accumulate in the transected strata, *e.g.*, at updip locations; (3) Hydrocarbons migrated up the SGC structure to the surface, where they were degraded or lost; (4) The sites of hydrocarbon accumulation are relatively young depositional systems, laid down along trends controlled by SGC structures; (5) SGC structures are indicators of potential reservoirs in the deeper subsurface, *e.g.*, in subjacent reef prominences. With the exception of condition 3, above, these relationships may also favour the precipitation of MVT lead-zinc deposits. Although it is not known whether MVT deposits can be formed by precipitation from the same fluids which transport petroleum from source rock to reservoir (Anderson and Macqueen, 1982), parallel exploration rationales may be applicable to these dissimilar resource types.

Acknowledgements

Observations presented above were made in part during the course of separate research projects suppported by Saskatchewan Energy and Mines and Manitoba Energy and Mines and, more recently, in a project funded by the Geological Survey of Canada through a Research Agreement.

Table 3 **Hydrodynamic classification of sedimentary basins. (After Coustau *et al.*, 1975).**

Basin Type	**Remarks**
Juvenile	Centrifugal water movement. No uplift/ deformation. Basin fluids moved by compaction upward and outward, limited meteoric input, Deep-basin waters hypersaline and stagnant.
Intermediate	Centripetal water movement. Uplift and erosion. Surface waters enter around basin margins, migrate toward centre. Lateral vertical flow.
Senile	Hydrostatic conditions. Aquifers distant from recharge areas and enveloped by impermeable strata are invaded. Formation fluids driven upward and outward to give reversed hydrologic profiles.

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