Diamonds in komatiites and some contemporary views about this gem-carbon

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Diamond, known in India since the Vedic times (2000 BC), is pure carbon formed at high pressure that exists in the earth's mantle zone. When subjected to pressure >5 GPa (>50,000 atmospheres) and temperature of 1600 K (2400°F), prevailing at depths of 200 km, the carbon is transformed to diamond, and it remains stable there for millions of years. A number of processes are envisaged to operate for diamond nucleation from methane, carbon dioxide or particulate carbon under favourable pressure and temperature conditions aided by catalysts (COS, CS_2, N_2)[1]. From the diamond stability zone in the mantle, they are brought later to the surface by plumes of mantle melt material that ascend with explosive rapidity (Figure 1). This rapid ascent prevents diamond to return to graphite structure or its oxidation. Weathering of the host rocks liberates the diamonds, which soon get dispersed by streams and rivers to form alluvial deposits. Diamonds of non-mantle origin (crustal diamonds) are observed within garnets and zircons in calc-silicate rocks, amphibolites and pyroxenites. Here, diamonds are believed to have formed *in situ* at high pressure from carbon derived from the recycled (subducted) crust[2,3]. Microscopic diamonds are seen in some meteorites and their impact craters as well as within larger diamondiferous pipes along with macrodiamonds. Some consider that these crystals had little time to grow to macro-size, before transportation to the surface or they may have evolved under sparse carbon availability leading to stunted growth or due to resorption of larger diamonds[4].

Archaean period was notable for intense magmatism, which brought about development of large metallogenic provinces and diamond genesis. Continental crustal formation during early Archaean was negligible and whatever formed was recycled back into the convecting mantle. The few that survived either retained or built up thick Archaean mantle keels (between 200 and 400 km) which served as repositories (Figure 1) for the early formed diamonds[1,5–7]. Some of these Archaean crusts or cratons have remained unaffected for billions of years by orogenic activities like subduction. Typical of these Archaean cratons are greenstone belts (mainly rocks of ultrabasic and basic magmatism) and granitoids (products of younger magmatism). Peridotites, eclogites, komatiites, kimberlites, lamproites, basalts, andesites, and dacites are the usual intrusive rock groups in these greenstone belts and graded volcanoclastic sediments and greywacke are the sedimentary sequences noted here. Considerable thickness of such geological terrains lie scattered in a number of countries like Western Australia, Canada, South Africa, Norway and Greenland, while in India, the Dharwar craton and the Singhbhum craton are the two classic occurrences.

Most of the world's diamonds come from kimberlites, intrusive into the Archaean cratons. Lamproites (volcanic lamprophyres), another class of intrusive rocks, also carry diamonds and they have been more associated with Proterozoic mobile belts adjacent to some of these cratons[8] (Figure 1). About 500 diamondiferous kimberlites are known all over the world and 15 among them are reported to be active mines with hopes of new ones coming up in Canada, Eastern Europe and Russia[8]. Indian kimberlites and lamproites, worked for diamonds are Proterozoic volcanic intrusions between 846 and 1446 m. y. ago[8–10]. Notable occurrences are in Andhra Pradesh (Wajra Karur, Lattavaram), Madhya Pradesh (Majhgawan and Hiṇota near Panna), Uttar Pradesh (Jungel valley), and Orissa (Sambalpur). At Majhgawan is the only mine working lamproites for diamonds, while the others in Andhra Pradesh and Orissa are alluvial deposits of Krishna and Mahanadi rivers. Microdiamonds occur in lamproite dykes at Chelima, Andhra

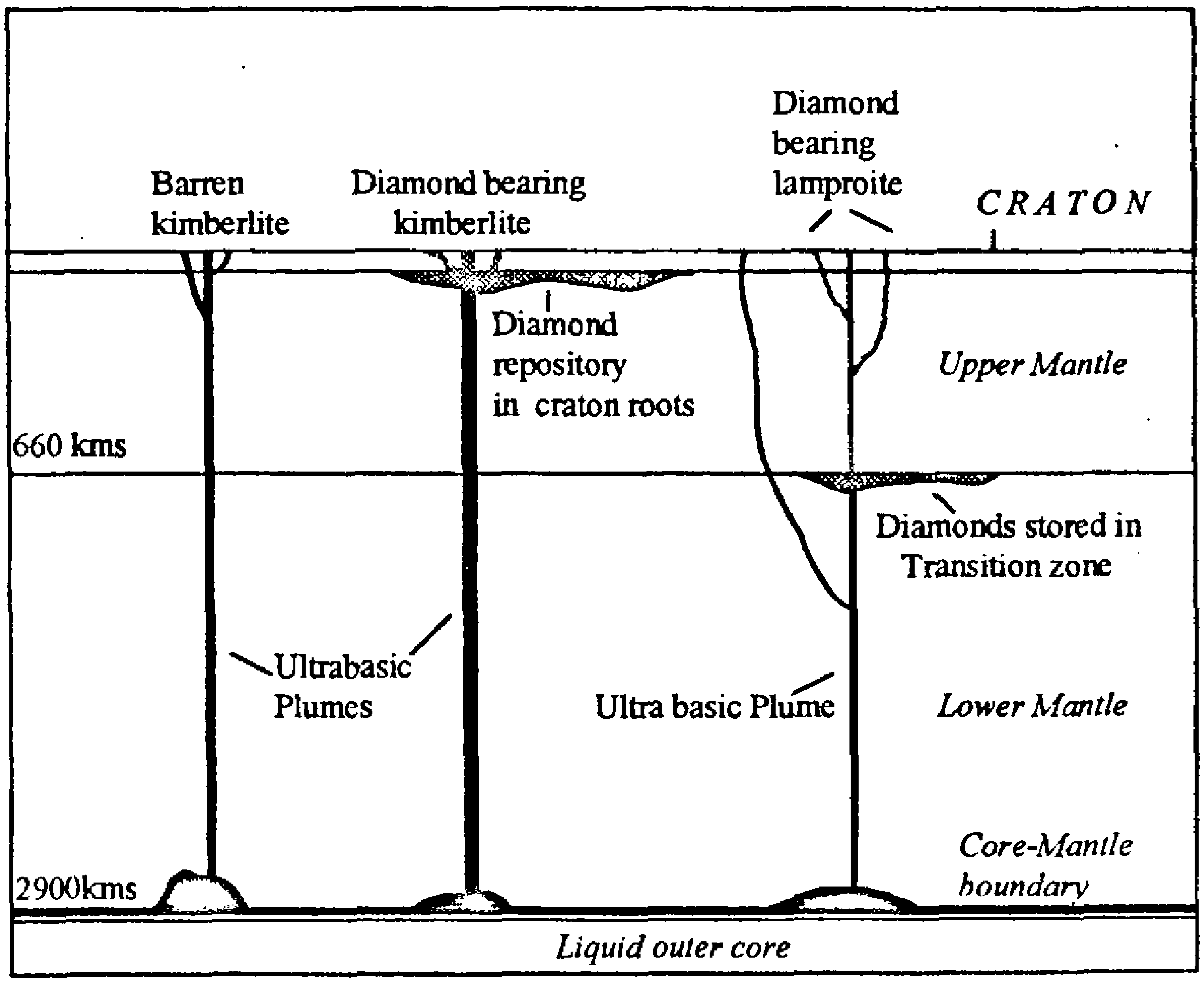

Figure 1. Idealized kimberlite and lamproite dykes, barren and diamondiferous, originating from the core–mantle boundary or the transition zone.

Pradesh. Bulk of world's diamond production comes from Africa, Australia, Russia and the recently discovered new deposit from the Canadian Arctic region. China, Borneo, Brazil and India produce smaller amounts. Now a new type of diamond occurrence has been reported[11] from komatiites, which like kimberlites are early ultrabasic lavas generated by partial melting of mantle. This reported occurrence of diamonds adds a new dimension to diamond prospecting in Archaean terrains where komatiites are predominant.

During the late 1960s, geologists working in one of the ancient cratons in South Africa – the Barberton Mountain Land greenstone belt came across certain interesting ultrabasic intrusives within the 3.49 b.y. old Komati Formations of the Onverwacht Group. These showed unusual chemistry, pillowed structure and a distinct spinifex texture (radiating bladed olivine crystals) that develops during quench crystallization of highly magnesian high temperature lava. They had high MgO, very high MgO/FeO ratio, low alkalies and TiO_2, Al_2O_3/CaO ratio less than unity, a chemical composition quite unlike that of average basalt and peridotite. These rare chemical and mineralogical features warranted classifying them as a separate rock group – 'komatiites'[12], named after the Komati river formations where they were first noticed. These were further classified as basaltic komatiites (with MgO 10–20%) and peridotitic komatiites (with MgO >20%). Discoveries of komatiites were soon reported from Western Australia (Pilbara craton)[13,14], India (Kulamara, Singhbhum Thrust Belt and the Kolar Schist Belt)[15,16], Canada (Abitibi Belt)[17–19], Finland (Satasvaara greenstones)[20], Norway (Karasjok belt)[21], Columbia (Gorgonia Island)[22] and French Guiana (Inini greenstone belt)[11]. Petrological, geochemical and isotopic investigations have indicated that komatiites are products of high degree melting (typically 50–100%) of mantle peridotite and those with high ages around 3 b.y. are found to be alumina depleted (e.g. Barberton, Pilbara) while those with younger ages, around 2.7 b.y., are alumina undepleted (e.g. Abitibi, Kolar Schist Belt)[23]. There exists a view regarding a decline in komatiite abundance (and the average MgO contents) and increase in kimberlite occurrence with time; however, examination of some 40 greenstone belts worldwide does not support this view; the study, however, has indicated peaking of these rocks in late Archaean greenstone belts[6].

The new komatiitic occurrence of diamonds has now been reported from the Proterozoic Formation in French Guiana, South America[11]. Geologists of French Geological Survey and Guyanor Resources (SA) had located in the Dachine deposit of this region alluvial diamonds ranging from microdiamond size up to 4 mm. Bulk samples of the volcanoclastic komatiite here contained <1 to 77 diamonds per kg. The komatiite xenoliths, of sizes 1–3 cm (maximum 20 cm) with relict olivine phenocrysts form part of the Inini greenstone belt. Studies have shown that this komatiitic magma is eclogitic in origin, from depths greater than 250 km (ref. 11). The magma picked up the diamonds (from >150 km depth) along with mantle xenoliths while ascending rapidly as narrow intrusions through the hydrated lithosphere to the surface, around 2.1 b.y. ago.

The stability of diamonds plus their remote age (most of the diamonds show ages >2.5 b.y.) make them ideal time capsules to study early mantle geochemistry and mineral genesis. In fact, few minerals have locked up within them so much information about early mantle, its mineralogy, chemistry and about volatiles as diamonds have and this has led to a lot of experimental work and lengthy debates about diamond genesis and distribution. It is interesting to note that most of the diamonds in the world were formed around 2.8–3 b.y. and were emplaced by the volcanic pipes in rocks of age group >1 b.y. which strongly suggests that conditions specific to diamond genesis as well their subsequent emplacement must have prevailed globally at these times in the earth's interior[7]. This inference emerges from extensive studies made not only on mantle xenoliths caught up in kimberlites and associated lamproitic rocks but also from mineral inclusions such as sulphides, garnet, olivine, pyrite, chromite in the diamonds[24], trace element patterns (K, Na, Ba, Sr, REE, Ti, Zr, Nb and P)[7] and radiogenic isotopes[25,26]. Based on similarity of inclusions to olivine-bearing peridotites or eclogites, diamonds are grouped as P-type (peridotitic) or E-type (eclogitic). While the former shows $\delta^{13}C$ values within a limited range, in agreement with that of lithospheric mantle, the E-type shows variable $\delta^{13}C$ which has given rise to speculation about its derivation. Recent studies[27] on the latter type diamonds attributed the different $\delta^{13}C$ ranges in them to different evolutionary trends taken by the carbonatitic melts from which diamonds crystallize. The nature of the mineral inclusions, Fe or Ni rich sulphides, is also found to be helpful in deducing the principal host rocks, peridotite or eclogite[1] as well as the depths from which diamonds were sampled, whether from the transition zone or deeper.

Considerable debate about the relation between diamonds and early mantle melt of kimberlite or komatiite composition has appeared in literature[5,7,24–26]. They point out that diamond genesis could be contemporaneous with early melt or their presence in these host rocks might be accidental, collected by them from the diamond stability zone[25]. In fact, Sm–Nd and Rb–Sr isotopic studies on inclusions in diamond from kimberlites from two different cratons – Kapvaal (South Africa) and Udachnaya (Siberia)[25,26], have concluded that no connection exists between genesis of diamonds and host kimberlite and that the two were separate events. Experiments[5,24] have also shown that diamonds that formed early at the base of the transition zone (410–660 km) and lower mantle float in the melt and accumulate within the transition zone (Figure 1). Here the diamond population may be of mixed ages (Archaean and Proterozoic) and parentage (peridotitic or eclogitic) and they remain stored in deep continental mantle for long periods before being sampled by kimberlite and other magmatic plumes of much younger ages[27,28].

Association of diamond-bearing plumes with superplume events has been noticed worldwide. Seven such superplume episodes have been recognized in the geologic past at ~1000 m.y. (Africa, Brazil, Australia, India, Greenland, Siberia), between ~450 and 500 m.y. (China, Canada, South Africa, Zimbabwe), 370 to 410 m.y. (Siberia, United States), ~200 m.y. (Botswana, Canada, Swaziland, Tanzania), 80 to 120 m.y. (Africa, Canada, India, Brazil, Siberia, United States), ~50 m.y. (Canada, Tanzania) and 22 m.y. (North-Western Australia)[29]. The superplume episode during Mesozoic, between 180 and 130 m.y ago, synchronizing with the break-up of Pangea was responsible for hundreds of diamondiferous plumes apart from eruption of flood basalts[30,31]. Five of the seven superplume events listed are believed to be controlled by changes in the earth's polarity, i.e. geomagnetic reversals – the periods that have been termed 'superchrons'[30–32] occurring with a periodicity of about 200 m.y. (ref. 33). According to one view, an inverse relationship is seen between rate of crust formation by plume volcanism and the earth's geomagnetic reversals[31,32]. According to this model, the movements of convective currents within the earth's outer core of molten iron, known to generate the earth's magnetic field (geodynamo), liberates considerable heat that remains trapped in the lower mantle at the core–mantle boundary. The progressive build-up of this heat results in reduction of mantle density here and an increase in buoyancy enough to overcome viscosity of the mantle lying above to trigger rapid ascent of molten material through the upper mantle and lithosphere. Vast amounts of magma thus generated erupt as volcanic plumes (kimberlites, komatiites and other ultrabasic and basic intrusives) and flood basalts[31]. It appears logical, therefore, to expect diamonds in deep mantle derived intrusives other than kimberlites also provided their passage to the surface had taken place rapidly through the zones preserving diamonds[34].

Presence or absence of diamonds in the ultramafic plumes – kimberlitic or komatiitic, may be linked to lithospheric development and continental drift. A developing lithosphere, undergoing isostatic compensation, may have vertical transitions in and out of the diamond stability field, which will affect the diamonds at the diamond–graphite transition boundary[1]. Continental drifts propelling the lithosphere through the highly convective, oxidized asthenosphere can disturb and disrupt the diamond layers or repositories at the roots of the cratons due to the torque forces on the lower lithosphere[1]. Fortunately, repositories of diamonds that formed during early Archaean had remained undisturbed since all kimberlitic or komatiitic intrusions in this region carrying diamonds to the surface of ancient continental crusts took place prior to continental drift. In this context, Africa had remained stationary when Gondwanaland fragmented ~200 m.y. ago. The diamond zones at the roots of this continent's cratons (South, Central and West African) were, therefore, undisturbed. However, this was not the case with North America, India, Antarctica and Australia, inasmuch as these continents had drifted with breakup of Gondwanaland, thereby exposing the diamonds in the cratonic roots for damage. Proof of such disruptions is evident in recent osmium isotopic studies carried out in Kerguelen Islands (southern Indian Ocean) where subcontinental lithospheric mantle xenoliths of Proterozoic age are found in the newly forming Indian Ocean lithosphere, evidently incorporated during rifting of eastern Gondwana continents[35].

Over 5000 diamondiferous kimberlites and lamproites are already known globally, and new ones with good potential are being feverishly worked out in Canadian N.W. territories, Norway, Sweden, Ukraine, Finland, Eastern Europe and Russia[8]. Therefore, the hitherto unreported occurrence of diamonds in komatiites could be a pointer to undertake integrated search in Archaean komatiitic areas using geological, geophysical, morphological and structural prospecting methods which have been successfully employed earlier in locating primary diamondiferous kimberlites. Komatiite finds were great news during the 1960s and 70s for their unusual petrology, geochemistry and mineralogy and potential to interpret early mantle magmatism. Now, this rock may come into limelight again if the reported association of diamonds in them sets a wave of commercial hunt in the established occurrences. Likewise, hypabyssal intrusives (often diamond-bearing themselves), nephelinites, carbonatites, monchiquites which are found to be associated with larger diamondiferous pipes in Africa[34], should prompt searches in such areas in other countries.

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Emerging trends in agricultural biotechnology research: Use of abiotic stress-induced promoter to drive expression of a stress resistance gene in the transgenic system leads to high level stress tolerance associated with minimal negative effects on growth

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Abiotic stresses (such as those imposed by excess salts, reduced water supply leading to drought stress, excess water leading to submergence and anoxia stress, sub-optimal ambient temperature leading to low temperature stress, supra-optimal ambient temperature leading to high temperature stress, oxidative stress caused by different abiotic stresses in conjunction with high light intensity, heavy metal stress, air pollutants stress, etc.) negatively affect processes associated with biomass production and grain yield, in almost all major field-grown crops. In recent years, plant genetic engineering science has successfully risen to the challenge of producing plants tolerant to several abiotic stresses. A host of genes encoding different structural and regulatory proteins have been employed over the past 5–6 years, for production of a range of abiotic stress-tolerant transgenic plants[1–7]. The appreciation is growing that the usage of regulatory genes is a more effective approach for producing stress-tolerant plants. This is based on the observations that single regulatory gene leads to altered expression of a number of different downstream structural genes, thus leading to a wide-arrayed altered response[8–10]. Liu *et al.*[11] isolated cDNA encoding DRE (dehydration responsive element)-binding proteins, DREB1A and DREB2A, and showed that both of these proteins specifically bind and activate transcription of genes containing the DRE sequences in *Arabidopsis*. This group was then prompted to over-express cDNA of DREB1A under the control of 35S

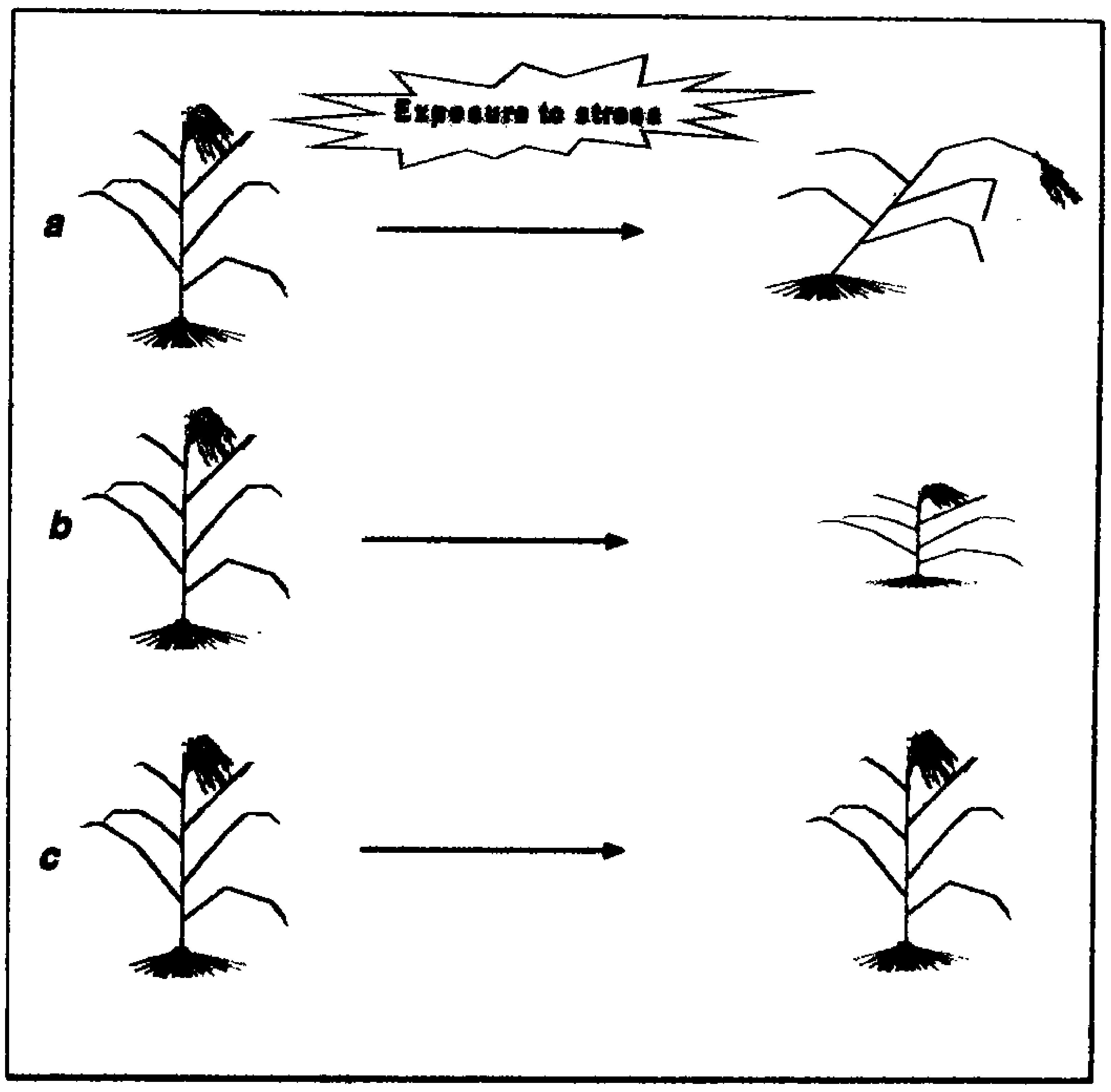

Figure 1. A model showing how the abiotic stress-induced promoter is useful in production of abiotic stress-tolerant transgenic plants. Three possible options shown above are as follows: ***a***, Non-transgenic plant exposed to stress lacks the requisite expression of the stress tolerance gene and therefore succumbs; ***b***, Transgenic plant expressing the requisite stress tolerance gene driven by a constitutive promoter overcomes the injurious effects of stress but the plant is short with conspicuous phenotypic differences; ***c***, Transgenic plant expressing the requisite stress tolerance gene driven by stress-induced promoter overcomes the injurious effects of stress and additionally is phenotypically similar to non-transgenic counterpart in terms of height, etc. The option *c* is the most desired research goal.