The occurrence of Li-Fe-Mn phosphate minerals in granitic pegmatites of Namibia

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This is the first comprehensive account of Li-Fe-Mn phosphates (triphylite-lithiophilite and the topotactic alteration products ferrisicklerite-sicklerite and heterosite-purpurite) from 46 granitic pegmatites of the Damara Sequence (Namibia). The Li-Fe-Mn phosphates display a wide range of Fe/(Fe+Mn) ratios. Preliminary ratios $0.125 \leq Fe/(Fe+Mn) \leq 0.845$ have been determined by wet chemical and microprobe analyses. Relationships appear to be developed between the Fe/(Fe+Mn) ratios and the observed economic minerals, e.g. beryl, Ta-Nb oxides, petalite, and gem tourmaline. There is evidence for regional distribution patterns of Fe/(Fe+Mn) ratios regarding 8 portions and swarms of 4 pegmatite belts. There is fairly good accordance between the degree of fractionation, and differentiation, and the Fe/(Fe+Mn) ratio (hypothesis of Ginsburg) for a great number of pegmatites, although conspicuous deviations from that hypothesis were also noted. From the occurrence of arborescent Li-Fe-Mn phosphates, seen in 22 pegmatites, important arguments could be found for both the mode of the pegmatite evolution and for their economic mineralisation. Recent field observations prove that thermal undercooling is predominantly responsible for the arborescent shape of Li-Fe-Mn phosphates in most of the Damaran pegmatites.

Introduction

The Precambrian Damara Sequence of Namibia is well known for its numerous granitic pegmatites (Wagner, 1916, 1921; Reuning, 1923; Gevers & Frommurze, 1929; De Kock, 1932; Haughton *et al.*, 1939; Frommurze *et al.*, 1942; Cameron, 1955; Roering & Gevers, 1964; Roering, 1966; Diehl, 1986, 1991). Most of the pegmatites lack any valuable minerals, but several hundred are of economic interest. During this century, they have been extensively mined for tin, lithium, beryllium, niobium-tantalum, caesium, multicoloured gem tourmaline and beryl, mica, quartz and feldspar. Although only a few mines are still active, increasing demand by modem technology for rare elements and especially for pegmatitic minerals with specific properties (e.g. petalite, spodumene, quartz of high purity, and feldspar for industrial ceramics) makes these pegmatites potential resources.

The economic pegmatites are also of particular mineralogical interest due to their associations of phosphate minerals. However, with the exception of amblygonite-montebrasite, pegmatitic phosphates are without any economic value. Although phosphates are important constituents in a few granitic pegmatites, up to several thousand tons, they are usually rather exotic accessories.

This publication deals with the Li-Fe-Mn phosphates, where the Fe/(Fe+Mn) ratio and the dendritic morphology are of particular interest. Mostly preliminary results are presented in this first comprehensive description which is part of a research program on the phosphate minerals from pegmatites in the Damara Sequence of Namibia. This study aims to: (i) determine the evolution of phosphate minerals, (ii) specify the mineralogical and geochemical role of phosphate minerals in the evolutionary processes of the granitic pegmatites, and (iii) point out possible relationships between phosphate minerals and economically important pegmatite min-erals (Keller, 1974, 1980, 1985, 1987, 1988; Keller & von Knorring, 1985, 1989; Fransolet, Keller & Fontan, 1986).

General description of Damaran pegmatites

The pegmatites without any economic minerals consist of microcline and microcline-perthite, varying quantities of albite, quartz and locally of large amounts of muscovite, schorl or almandine. These pegmatites were emplaced in various magmatic and metamorphic rocks. With regard to the latter, they are commonly concordant. The pegmatites are related to both syntectonic and post-tectonic granites (Gevers, 1963; Smith, 1965; Haack & Gohn, 1988; Diehl, 1991).

Most of the economic pegmatites have intruded into tightly folded mica schists, dolomitic marbles or quartzites (in order of frequency) and only a few are situated within granites. These pegmatites are usually dyke- or pod-like in appearance and usually more or less concordant, but occasionally clearly discordant to the host rock foliation. They are unmetamorphosed and evidently post-tectonic, but it is usually not possible to relate the pegmatites to a distinct post-tectonic parent granite body (Gevers, 1963; Smith, 1965; Hawkesworth *et al.*, 1981; Martin, 1983; Winkler, 1983; Haack *et al.*, 1983; Haack & Gohn, 1988).

Internal zoning is well developed in most pegmatites and prominent quartz cores are seen in many deposits. It must be stressed, however, that the important tin pegmatites of the Uis swarm as well as some other economic pegmatites are poorly zoned to unzoned. Although quartz cores and core margins are often mineralised, economic minerals are also confined to other pegmatite zones at several localities. Many pegmatites carry an assortment of beryl, columbite-tantalite and/or other Ta-Nb oxides, lepidolite, amblygonite-montebrasite, cassiterite, petalite, gem tourmaline, pollucite, microlite, spodumene, bismuth minerals, and a variety

TABLE 1: List of identified phosphate minerals from pegmatites in Namibia.

The minerals may be subdivided into three groups, due to their genesis, namely: (i) primary minerals (triphylite to triplite), (ii) metasomatic and early hydrothermal replacement products (alluaudite to phosphoferrite), and (iii) late hydrothermal alteration and weathering products (barbosalite to brushite). No distinct lines are drawn to define these groups, because several minerals clearly belong to different groups and for several other minerals the genesis is still under discussion. The sequence within one of these groups represents approximately the abundance of the phosphate minerals. - s - : solid solution series are known between the minerals given on one line.

Mineral name	Formula		Mineral name	Formula
triphylite	$Li(Fe,Mn)PO_4$	- s -	lithiophilite	$Li(Mn,Fe)PO_4$
amblygonite	$LiAl(F,OH)PO_4$	- s -	montebrasite	$LiAl(OH,F)PO_4$
fluorapatite	$(Ca,Mn)_5(F,OH)(PO_4)_3$			
graftonite	$Ca(Fe,Mn)_2(PO_4)_2$	- s -	beusite	$Ca(Mn,Fe)_2(PO_4)_2$
sarcopside	$(Fe,Mn)_3(PO_4)_2$			
monazite	$(Ce,...)PO_4$		brabantite	$CaTh(PO_4)_2$
triplite	$(Mn,Fe,Mg)_2(F,OH)PO_4$	- s -	zwieselite	$(Fe,Mn,Mg)_2(F,OH)PO_4$
ferrisicklerite	$Li_{1-x}(Fe^{3+}_x Mn^{2+}_{1-x})PO_4$	- s -	sickelerite	$Li_{1-x}(Mn^{2+}_{1-x} Fe^{3+}_x)PO_4$
heterosite	$(Fe,Mn)PO_4$	- s -	purpurite	$(Mn,Fe)PO_4$
alluaudite	$(Na,Ca)_{2-1}Mn(Fe,Al)_2(PO_4)_3$		hagendorfite	$Na_2Mn(Fe^{2+},Fe^{3+})_2(PO_4)_3$
triploidite	$(Mn,Fe)_2(OH)PO_4$	- s -	wolfeite	$(Fe,Mn)_2(OH)PO_4$
kryzhanovskite	$(Fe^{3+}_x,Mn^{2+})_3(OH)_x(PO_4)_2.(3-x)H_2O$	- s -	landesite	$Mn^{2+},Fe^{3+}_x)_3(OH)_x(PO_4)_2.(3-x)H_2O$
childrenite	$(Fe,Mn)Al(OH)_2(PO_4).H_2O$	- s -	eosphorite	$(Mn,Fe)Al(OH)_2PO_4.H_2O$
arrojadite	$K(Na,Ca)_5(Fe,Mn,Mg)_{14}Al(OH,F)_2(PO_4)_{12}$			
phosphoferrite	$(Fe,Mn)_3(PO_4)_2.3H_2O$	- s -	reddingite	$(Mn,Fe)_3(PO_4)_2.3H_2O$
tavorite	$LiFe(OH)PO_4$	-	barbosalite	$Fe^{2+}Fe^{3+}_2(OH)_2(PO_4)_2$
hureaulite	$Mn_5(HOPO_3)_2(PO_4)_2.4H_2O$		jahnsite	$CaMn(Mg,Fe)_2Fe^{3+}_2(OH)_2(PO_4)_4 8H_2O$
rockbridgeite	$(Fe,Mn)^{2+}Fe^{3+}_4(OH)_5(PO_4)_3$	- s -	frondelite	$(Mn,Fe)^{2+}Fe^{3+}_4(OH)_5(PO_4)_3$
lipscombite	$(Fe,Mn)^{2+}Fe^{3+}_2(OH)_2(PO_4)_2$		leucophosphite	$KFe^{3+}_2(OH)(PO_4)_2.2H_2O$
phosphosiderite	$FePO_4.2H_2O$		bermanite	$Mn^{2+}Mn^{3+}_2(OH)_2(PO_4)_2.4H_2O$
laueite	$MnFe^{3+}_2(OH)_2(PO_4)_2.8h_2O$		strunzite	$MnFe^{3+}_2(OH)_2(PO_4)_2.6H_2O$
stewartite	$MnFe^{3+}_2(OH)_2(PO_4)_2.8h_2O$		cyrilovite	$NaFe_3(OH)_4(PO_4)_2.2H_2O$
melonjosephite	$CaFe^{2+}Fe^{3+}(OH)(PO_4)_2$		giniite	$Fe^{2+}Fe^{3+}_4(H_2O)_2(OH)_2(PO_4)_4$
mitridatite	$Ca_3(Fe,Mn)^{3+}_4(OH)_6(PO_4)_4.3H_2O$		vivianite	$Fe_3(PO_4)_2.8H_2O$
herderite	$CaBeF(PO)_4$		moraesite	$Be_2(OH)(PO_4).4H_2O$
scorzalite	$(Fe,Mg)Al_2(OH)_2(PO_4)_2$		gormanite	$(Fe,Mg)_3(Al,Fe)_4(OH)_6(PO_4)_4.2H_2O$
ernstite	$(Mn^{2+}_{1-x}Fe^{3+}_x)Al(OH)_{2-x}O_x(PO_4)$		collinsite	$Ca_2(Mg,Fe)(PO_4)_2.2H_2O$
kidwellite	$NaFe^{3+}_9(PO_4)_6(OH)_{10}.5H_2O$		dufrenite	$CaFe^{2+}_2Fe^{3+}_{10}(OH)_{12}(PO_4)_8.4H_2O$
cacoxenite	$Fe^{3+}_9(OH)_{15}(PO_4)_4.18H_2O$		strengite	$FePO_4.2H_2O$
brazilianite	$NaAl_3(OH)_4(PO_4)_2$		wavellite	$Al_3(OH)_3(PO_4)_2.5H_2O$
morinite	$NaCa_2Al_2(F,OH)_5(PO_4)_2.2H_2O$			
whitlockite	$Ca_9(Mg,Fe)H(PO_4)_7$		sampleite	$NaCaCu_5(PO_4)Cl.5H_2O$
variscite	$AlPO_4.2H_2O$		montgomeriite	$Ca_2Al_2(OH)(PO_4)_3.7H_2O$
monetite	$CaHPO_4$		brushite	$CaHPO_2.2H_2O$

of Li-Fe-Mn and Fe-Mn phosphates and their alteration products.

Li-Fe-Mn phosphates

A total of 64 phosphate minerals has been identified from Namibian pegmatites (Table 1) by Keller (1974, 1985), von Knorring (1976, 1985a), Fransolet *et al.* (1986) and Keller & von Knorring (1989). Three phosphate minerals were first described from Namibian type localities, namely ernstite (Seeliger & Mücke, 1970), giniite (Keller, 1980a, 1980b), and brabantite (Rose, 1980).

This paper deals with the triphylite-lithiophilite solid solution members and their alteration products ferrisick-lerite-sicklerite and heterosite-purpurite. The occurrence of the other primary phosphates known from Damaran pegmatites, such as amblygonite-montebrasite, triplite-zwieselite and graftonite-beusite, and their role in the evolution of granitic pegmatites will be reviewed in subsequent publications. Detailed descriptions of single occurrences are given by Fransolet *et al.* (1986) and Keller & von Knorring (1989).

In contrast to all other alteration products of triphylite-lithiophilite, the solid solution members of ferrisicklerite-sicklerite and heterosite-purpurite are developed through topotactic transformation processes. The occurrence of these minerals is positive evidence for initial crystallisation of triphylite-lithiophilite, even if the primary mineral is not preserved. For that reason, the term Li-Fe-Mn phosphate is also used for the topotactic alteration products, even if they are free of lithium.

Although several non-topotactic alteration products of primary triphylite-lithiophilite, e.g. members of the alluaudite group, wolfeite-triploidite, kryzhanovskite-landesite and arrojadite, are usually related to metasomatic replacement processes during the pegmatite evolution and thus of genetic interest, they are not considered in this paper, but listed in Tables 1 and 2.

Occurrence of skeletal and arborescent Li-Fe-Mn phosphates

The Li-Fe-Mn phosphates are most commonly developed as rounded polycrystalline nodules which consist usually of a few equant-shaped crystals. However, single crystals with subhedral to rough euhedral outlines are fairly commonly seen, e.g. Sandamap, Strathmore "Petalite" (Fig. 1). The nodules, as well as the single crystals of triphylite-lithiophilite, display great variation in size from 1 cm up to 1.5 m in diameter.

Massive equant-shaped triphylite-lithiophilite is a characteristic constituent of the intermediate zone of pegmatites, preferentially confined to the core margin (Table 2). However, exceptions are also known, e.g. Clementine II at Okatjimukuju (Keller & von Knorring, 1989).

Skeletal and arborescent Li-Fe-Mn phosphates have

Fig. 1: Triphylite (dark grey) in a section approximately parallel to (100) with a typically arborescent texture in the centre and a rough euhedral outline in the upper left. The matrix consists of an albite(-quartz-muscovite) rock (light grey). The length of the hammer is 17 cm. Dan Patch, Black Hills, USA.
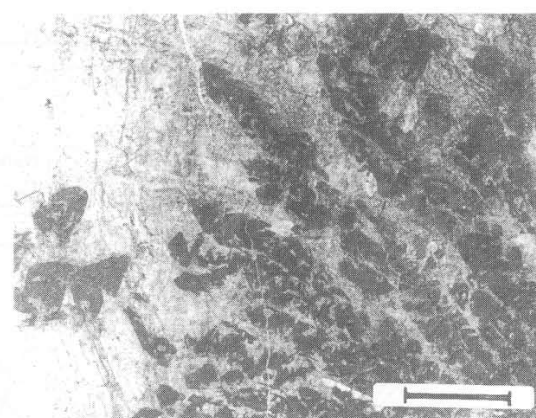

Fig. 2: Ferrisicklerite (dark grey) with an arborescent texture consisting of skeletal crystals in a section parallel to (100). Bar is 1 cm long. Karlsbrunn, Karibib, Namibia.
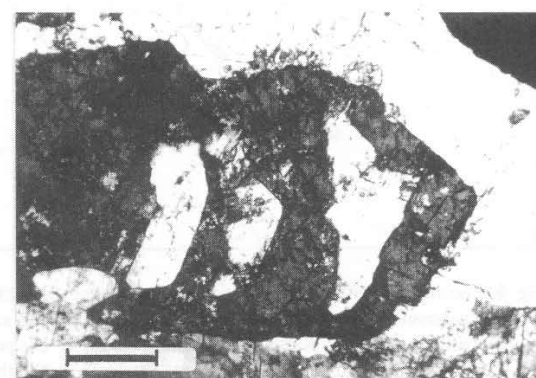
Fig. 3: Photomicrograph of a typically lantern-like skeleton of triphylite (dark grey) in a section parallel to (001). Crossed nicols. The bar, indicating the direction of the c-axis, is 1 mm long. Karlsbrunn, Karibib, Namibia.

been recently described (Keller, 1988). Up to this time, the true character of the dendritic texture of pegmatitic phosphates was simply overlooked and its genetic consequences not realised (Moore & Ito, 1973; Uebel, 1977). Dendritic phosphates are widely distributed in pegmatites of Namibia and of the Black Hills, USA.

They have also been observed in pegmatites of Finland (Viitaniemi; Seppalanranta, Orijärvi; Surmasuo, Tohllajärvi, von Knorring, pers. comm., 1988), Sweden (Varutrask), Rwanda (Gatumba), USA (Twin mountain, New Hampshire), Brazil (Lavra de Boa Vista, Mincipe Galileia) (Fransolet, pers. comm., 1988), and China (Koktokay, Altai). Arborescent phosphates have further been reported from pegmatites in the USSR (Kalba, Kazachstan; Kester, Yacutia - Y. Marin, pers. comm., 1990).

Subsequent to the publication of Keller (1988), the occurrence of dendritic phosphates has been indicated for many additional Damaran pegmatites by the author. In contrast to nearly all other occurrences, the dendritic texture has been seen *in situ* in Namibian pegmatites, thus providing the best opportunity for future investigations.

The shape and the growth habit of skeletal and arborescent Li-Fe-Mn phosphates are described in full detail by Keller (1988) where several typical figures are given. In this paper only a few impressive illustrations are added (Figs 1 to 3). To clarify the nomenclature, the term *dendritic* (e.g. dendritic crystal, dendritic mineral, dendritic morphology) is used as a comprehensive term, while *skeletal* (skeletal crystal, skeleton - Figs 2 and 3) and *arborescent* (arborescent mineral, arborescent texture - Figs 1 and 2) are used as specific sub-terms.

Fe/(Fe+Mn) ratio of the Li-Fe-Mn phosphates

According to an hypothesis introduced by Ginsburg (1960), the Fe/(Fe+Mn) ratio of triphylite-lithiophilite depends on the availability of iron and manganese from the pegmatitic melt and/or fluid phase. In a great number of cases, there is some evidence that: (i) the Fe/(Fe+Mn) ratio decreases with an increasing degree of fractionation of the initial pegmatitic melt, and (ii) the initial Fe/(Fe+Mn) ratio decreases successively during the crystallisation sequence of a pegmatite with increasing differentiation.
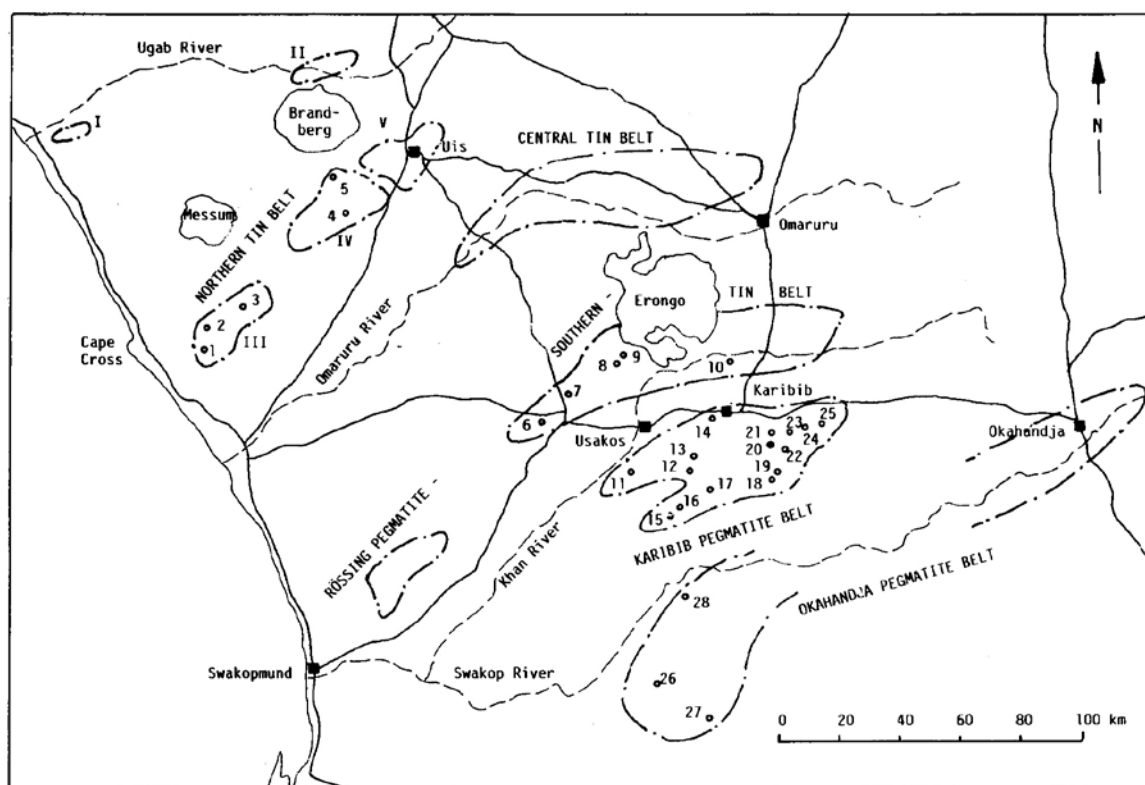

Fig. 4: Location map of the Damaran pegmatite province (Simplified from The Geological Map of South West Africa/Namibia, 1980). I: Ugabmond pegmatite swarm; II: De-Rust pegmatite swarm (Diehl and Schneider, pers. comm., 1991). III: Strathmore pegmatite swarm; IV: Karlowa pegmatite swarm; V: Uis pegmatite swarm (Diehl, 1991).
1: Strathmore No. SP48; *2*: Strathmore "Petalite"; *3*: Strathmore No. SP14; *4*: Karlowa, No. KPW2-13 and Engelbrecht's No. 2; *5*: Engelbrecht's tourmaline pegmatite; *6*: Black range, Cillier's; *7*: Sandamap, "Petalite" and pegmatite No. 3; *8*: Davib-Ost 61, Ariakas and Jooste's; *9*: Davib-Ost 61, Herbst's tourmaline pegmatite, pegmatites No. 2 and No. 3; *10*: Daheim 106, pegmatite No. 1 and No. 3; *11*: Naob 65; *12*: Abbabis 70, pegmatite No. 1; *13*: Abbabis 70, pegmatite No. 3; *14*: Dernburg (on Karibib 54), Henckert's beryl pegmatite; *15*: Etusis 75, Henckert's; *16*: Etusis 75, Prinz' tourmaline pegmatite and Simon's; *17*: Etusis 75, Berger's and Macdonald's; *18*: Okongava-Ost 72, Henckert's; *19*: Okongava-Ost 72, Rubicon No. 1, No. 2 and No. 3; *20*: Okatjimukuju 55, Clementine I and II; *21*: Okatjimukuju 55, Fricke's, "Petalite", pegmatite No. 3.3, No. 3.5, No. 6, and No. 10; *22*: Okongava-Ost 72, Helikon I and II; *23*: Okakoara 43, pegmatite No. 1; *24*: Karlsbrunn 42; *25*: Johann-Albrecht's 44, Berger's tourmaline pegmatite No. 2 and Kaliombo 119, Brockmann's; *26*: Onanis mountain, pegmatite No. 1; *27*: Donkerhuk 91, pegmatite No. 2; *28*: Tsaobismund.

TABLE 2.1: Pegmatites of the Okahandja pegmatite belt, western portion, with Li-Fe-Mn phosphate minerals.

Economic minerals: all minerals are given which may be valuable, even if they are too scarce to be mined; phosphates: only the primary minerals and the very early metasomatic products are given, except apatite, which is usually a constituent of each pegmatite; Fe/(Fe+Mn): the Fe/(Fe+Mn) ratio is calculated on the basis of wt %. If no indication is given, electron microprobe data are used. #: data of wet chemical analyses, for detail see Table 3; the shape, the Fe/(Fe+Mn) and the pegmat. zone refer to the Li-Fe-Mn phosphate minerals on the same line if no other indication is given.

ambl: amblygonite-montebrasite; allu: alluaudite; arr: arrojadite; Bi: bismuth minerals; cas: cassiterite; col: columbite; col-tant: columbite-tantalite solid solution members; euc: eucryptite; ferr: ferrisicklerite; graf: graftonite-beusite; het: heterosite; kryz: kryzhanovskite-landesite; Li-mica: lithium mica and lepidolite; lith: lithiophilite; Mn-col: manganocolumbite; pol: pollucite; pur: purpurite; qz: quartz; sar: sarcopside; sick: sicklerite; tap: tapiolite; trip: triplite-zwieselite; triph: triphylite; tripl: triploidite-wolfeite;

References (ref.): 1: Frommurze *et al.* (1942); 2: Roering (1966); 3: Keller (1988); 4: Diehl (1986, 1990); 5: von Knorring (1985a); 6: von Knorring (1985b); 7: Uebel (1977); Karnin (1980); Bergholz and Kubanek (1981); Fransolet, Keller and Fontan (1986); 8: Roering and Gevers (1964); 9: Keller and von Knorring (1985); 10: Keller and von Knorring (1989); 11: Smith (1965); 12: Keller (1974, 1985)

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Donkerhuk 91 pegmatite No. 2	beryl	lith, sick,	nodular	0.20 - 0.22	inn. intermed.	-.-
Onanis mountain, pegmatite No. 1	beryl, ambl	triph, ferr, het ambl, trip, allu	nodular	0.574#	inn. intermed.	-.-
Tsaobismund 85, Brockmann's	beryl, columb uraninite	triph, ferr, het	nodular (skelet.)	0.640, 0.655#	core margin	7
		triph (+trip) sar, trip, graf allu, kryz	granular	0.765	core margin	

Thus the Fe/(Fe+Mn) ratio of triphylite-lithiophilite is not only an important tool in interpreting the evolution of a pegmatite, but may possibly be useful for prospecting purposes as well.

Pegmatites bearing Li-Fe-Mn phosphates

For the purpose of this paper, it is possible to subdivide the pegmatites of the *Damaran province* into several distinct belts, striking approximately SW-NE to W-E (Fig. 4). Three of these belts were first mentioned by Gevers & Frommurze (1929) and Frommurze *et al.* (1942), namely the *Southern*, the *Central* and the *Northern tin belts*. As these three belts contain not only tin pegmatites, it may be convenient to follow a recommendation of Diehl & Schneider (pers. comm., 1991) to rename (i) the Northern tin belt to Cape Cross-Uis pegmatite belt, (ii) the Central tin belt to Nainais-Kohero pegmatite belt, and (iii) the Southern tin belt to Sandamap-Erongo pegmatite belt.

The belts can be subdivided into swarms if their geological and genetic relationships are sufficiently well known, e.g. the Northern tin belt (Diehl, 1991). Otherwise they are subdivided into portions containing groups of pegmatites which are usually named according to the places (farms) where they are exposed.

At present, the *Okahandja pegmatite belt*, the *Karibib pegmatite* belt, and the *Rössing portion* of the South-ern tin belt are introduced (Fig. 4). With regard to its distinct mineralisation and characteristic mode of emplacement, it may be accepted that the pegmatites of the Rössing portion represent a separate pegmatite belt.

The Okahandja pegmatite belt

The Okahandja pegmatite belt extends along the Okahandja lineament from east of Okahandja to the Onanis Mountain, Namib Naukluft Park. The pegmatites of the eastern and the middle portion lack any Li-Fe-Mn phosphates according to both personal observations and published information (Gevers, 1963).

The pegmatites of the western portion containing Li-Fe-Mn phosphates are given in Table 2.1. Only the phosphate associations of the Tsaobismund pegmatite are well described (Fransolet *et al.*, 1986). Whereas no Li-Fe-Mn phosphates are recorded from the well-known spodumene pegmatite on Donkerhuk (Cameron, 1955), a small pegmatite (termed Donkerhuk No. 2) some hundred metres west of the spodumene pegmatite, is rich in lithiophilite.

Although Onanis No.1 is situated south of the Okahandja lineament and Tsaobismund north of it, both pegmatites display primary Li-Fe-Mn phosphates that are intensively replaced by alluaudite due to strong metasomatic processes. This is not observed in any other Damaran pegmatite.

TABLE 2.2: Pegmatites of the Karibib pegmatite belt, Kaliombo-Okongava portion, with Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Kaliombo 119, Brockmann's	Li-mica, ambl, col-tant, beryl	tot. weathered Li-Fe-Mn phosph	arboresc.	unknown	unknown	2,11
Joh.-Albrecht's 44, Berger's No. 2	gem tourmaline	ferr	arboresc.	0.67 - 0.68	intermed.	-.-
Karlsbrunn 42	pet, ambl, qz, Li-mica, beryl, cass, Mn-col	triph, ferr	arboresc.	0.520-0.555	border and wall zone	2,3,6,8,11
Okakoara 43, pegmatite No. 1	-.-	triph, ferr	nodular	0.695-0.70	unknown	-.-
Okatjimukuju 55, pegmatite No. 6	beryl, Li-mica	ferr, het	nodular	0.59-0.595	unknown	-.-
Okatjimukuju 55, pegmatite No. 10	pet, col-tant	ferr, het	nodular	0.575-0.58	intermed.	-.-
Okatjimukuju 55, Fricke's	beryl, Li-mica, col-tant, ambl, mica, qz, pet	triph, ferr, het lith, sickl ambl, tripl	arboresc. nodular	0.635-0.655 0.319#	intermed. core marg.	3,9,11
Okatjimukuju 55, "Petalite"	pet	het ferr, het	arboresc. nodular	0.69-0.695 0.654#	out. interm. intermed. (?)	-.-
Okatjimukuju 55, pegmatite No. 3.3	-.-	ferr, allu, kryz	nodular	0.535-0.55	core marg.	-.-
Okatjimukuju 55, pegmatite No. 3.5	-.-	triph, ferr, het	nodular	0.52-0.525	intermed.	-.-
Okatjimukuju 55, Clementine I	beryl, Li-mica qz, col-tant,	ferr lith, sickl, tripl	arboresc. nodular	0.560 0.351#	out. interm. core marg.?	3,5
Okatjimukuju 55, Clementine II	beryl, col, ambl, Li-mica	ferr, het fer, het (+trip) ferr, het triph, ferr, het lith, sick, pur ambl, trip, kryz, arr, allu	arborec. granular arb.+nod. nodular nodular	0.78 0.72-0.76 0.607, 0.675# 0.587-0.595# 0.492-0.495	intercal. intermed. intermed. inn. interm.	6,9,10
Okongava 72, Helikon No. 2	pet, pol, ambl, beryl, Mn-col, Bi	lith, sick	nodular arboresc.	0.17 unknown	unknown intermed.	5,6
Okongava 72, Helikon No. 1	pet, beryl, pol, Li-mica, ambl, col-tant	tot.weathered Li-Mn-Fe phos.	arboresc.	unknown	out. interm.	8
Okongava 72, Rubicon No. 1	pet, beryl, ambl, Li-mica, Mn-col, qz, Bi	lith, sick lith, sick	arboresc. nodular	0.125-0.13 0.173#	inn. interm. lepidolite	5,6,8
Okongava 72, Rubicon No. 3	qz	lith, sick, pur trip	nodular	0.300,0.350#	core marg.	-.-
Okongava 72, Rubicon No. 2	-.-	ferr, ferr, het	arboresc. granular	unknown 0.55-0.65	unknown unknown	-.-
Okongava 72, Henckert's	col	triph, ferr, het trip, graf, allu	nodular	0.494#	unknown	6

rocks.

All pegmatites with Li-Fe-Mn phosphates are listed in Tables 2.2 to 2.4. The location and/or name of a great number of these pegmatites are given by former publications (Cameron, 1955; Roering & Gevers, 1964; Roering, 1966; Keller, 1988; Keller & von Knorring, 1989) or

The Karibib pegmatite belt

This belt extends from Kaliombo in a southwesterly direction and is terminated by two branches, a northward branch at Naob and a southward branch at Etusis (Fig. 4). The Karibib pegmatite belt contains many economically important pegmatites, an exceptionally great number of them with Li-Fe-Mn phosphates. Subdivision into the *Kaliombo-Okongava*, the *Etusis*, and the *Dernburg-Abbabis-Naob portions* seems to be convenient, not only territorially but also in respect of their mineralisation and/or country rocks.

All pegmatites with Li-Fe-Mn phosphates are listed in Tables 2.2 to 2.4. The location and/or name of a great number of these pegmatites are given by former publications (Cameron, 1955; Roering & Gevers, 1964; Roering, 1966; Keller, 1988; Keller & von Knorring, 1989) or marked on the map of Smith (1966).

The Southern tin belt

The Southern tin belt, as defined by Gevers & Frommurze (1929) and Frommurze *et al.* (1942), is subdivided into three portions: the *Omapyu-Otjimbojo, Etiro-Daheim* and *Ameib-Davib-Sandamap portions*.

The tin and/or tourmaline pegmatites of the Omapyu-Otjimbojo portion lack any Li-Fe-Mn phosphates according to my field observations. But at Daheim, Li-Fe-Mn phosphates occur sporadically (Table 2.5). Although, the pegmatites of Jooste on Etiro (Miller, 1969) are rich in triplite, no Li-Fe-Mn phosphates occur.

Within the Ameib-Davib-Sandamap portion, several pegmatites with an important Li-Fe-Mn phosphate mineralisation are exposed (Table 2.6). Most of the pegmatites of this paper are described to some extent by Frommurze *et al.* (1942). While no Li-Fe-Mn phosphates have been observed in the pegmatites of Ameib and Brabant, the pegmatites at Goabeb, Davib- West and Kudubis have yet to be visited by the author. However, Frommurze *et al.* (1942) have described the occurrence of Li-Fe-Mn phosphates at Cameroon and Sidney's on Goabeb as well as at Schimanski's and Drew's on Kudubis.

The Northern tin belt

Whereas the pegmatites of the *Uis swarm* are very poor in Li-Fe-Mn phosphates, several pegmatites of the *Karlowa* and *Strathmore swarms* are typically miner-

TABLE 2.3: Pegmatites of the Karibib pegmatite belt, Etusis portion, with Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Etusis 75, Berger's	pet, ambl, beryl, Li-mica, Bi	ferr, het ambl	arboresc.	0.59-0.595	intermed.	-.-
Etusis 75, Macdonald's	Li-mica	ferr, het	arboresc.	0.60	unknown	11
Etusis 75, Prinz' No. 1	gem-tourm., ambl	ferr, het triph, ferr, het ambl	arboresc. nodular	0.58-0.585 0.545-0.555	out. interm. intermed.	-.-
Etusis 75, Simon's	beryl, ambl.	ferr, het triph, ferr, het ambl, kryz	arboresc. nodular	0.745-0.75 0.548#	out. interm. core marg.	-.-
Etusis 75, Henckert's	beryl, mica, cass, col-tant	ferr, het ferr, het, kryz	arboresc. nodular	0.795-0.805 0.80	inn. interm. inn. interm.	-.-

TABLE 2.4: Pegmatites of the Karibib pegmatite belt, Dernburg-Abbabis-Naob portion, wiht Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Dernburg (on 54) Henckert's beryl	beryl	triph, ferr, het	nodular	0.57	unknown	-.-
Abbabis 70, pegmatite No. 3	beryl, col-tant	ferr, het allu, arr	nodular	0.55-0.56	unknown	-.-
Abbabis 70, pegmatite No. 1	beryl, mica col-tant	het ferr, het arr	arboresc. nodular	unknown 0.835-0.845	intermed. intermed.	-.-

TABLE 2.5: Pegmatites of the Southern tin belt, Etiro-Daheim portion, with Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Daheim 106, pegmatite No. 1	pet, Li-mica, ambl, col-tant	sick, allu ambl	nodular	0.205-0.21	unknown	5,6
Daheim 106, pegmatite No. 3	unknown	lith, sick	nodular	0.195-0.205	intermed.	-.-

TABLE 2.6: Pegmatites of the Southern tin belt, Ameib-David-Sandamap portion, with Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
David-Ost 61, Herbst's	gem-tourm.,	ferr, het triph, ferr, het	arboresc. nodular	0.64-0.645 0.645-0.650	out. interm. inn. interm.	-.-
David-Ost 61, pegmatite No. 2	-.-	ferr, het, kryz	nodular	0.69-0.695	core margin	-.-
David-Ost 61, pegmatite No. 3	-.-	ferr, het, kryz	nodular	0.75-0.76	core margin	-.-
David-Ost 61, Ariakas	cas, col, ambl	ferr, het graf, trip	nodular	0.64	intermed.	1
David-Ost 61, Ariakas No. 2	cas, col-tant	het	arboresc.	0.68-0.69	intermed.	1
Davib-Ost 61, Jooste's	Li-mica, cas, col-tant	het	nodular	0.64-0.655	unknown	-.-
Sandamap "Petalite"	pet, cas, col Li-mica	ferr, het triph, ferr, het	arboresc. nodular	0.665 0.714,0.778#	intermed.? core margin	1,3,6, 12
Sandamap pegmatite No. 3	-.-	het	nodular	0.620#	unknown	-.-
Black Range Cillier's	cas, tant beryl	triph, ferr, het	nodular	0.70-0.705	unknown	1

alised, dendritic phosphates being more frequent than nodular phosphates. The pegmatites described in this paper (Tables 2.7 and 2.8) are classified according to Diehl (1986, 1991), except the small cassiterite prospect Engelbrecht's No.2 that could not be identified by Diehl (pers. comm., 1991).

The other belts

The *Rössing portion* of the Southern tin belt (or the Rössing pegmatite belt) is represented by the mineralised pegmatites within the Rössing mountains and their northern vicinity. From several pegmatites of this belt, Fe-Mn phosphates have been collected, but Li- Fe-Mn phosphates have not been observed.

During several field trips, no Li-Fe-Mn phosphates were seen in pegmatites of the *Central tin belt*, although amblygonite-montebrasite does occur (Fig. 4).

The pegmatites of the *Ugabmond pegmatite swarm* and the *De-Rust pegmatite swarm* are situated north of the Brandberg (Diehl and Schneider, pers. comm., 1991). This area has not been visited by the author.

Occurrences of dendritic Li-Fe-Mn phosphates

The arborescent Li-Fe-Mn phosphates are exclusively developed in 'albite(-quartz-muscovite) rocks, occasionally together with accessory manganoan apatite, tourmaline and/or distinct ore minerals, described below. The albite generally displays the cleavelandite shape, but is also seen with an equant habit. Arborescent Li-Fe-Mn phosphates were not observed in primary intergrowth with saccharoidal albite or together with K-feldspar.

Beryl, Ta-Nb oxides and cassiterite typically occur in association with arborescent Li-Fe-Mn phosphates, possibly in paragenesis - at least, in the same pegmatitic unit. (The term *pegmatitic unit* is used for distinct portions of a pegmatitic zone). The pegmatites with arborescent phosphates have been mined for the economic

minerals mentioned above, as well as for petalite, amblygonite-montebrasite, lithium mica, pollucite and/or gem tourmaline. However, the minerals of the latter most group are, in respect of their genesis, not directly related to the arborescent phosphates.

Whereas the nodular triphylite-lithiophilite and their alteration products usually occur in the inner intermediate zone, most commonly along the core margin, the dendritic Li-Fe-Mn phosphates have been seen in all pegmatite zones (Table 2). Furthermore, whereas the occurrence of nodular Li-Fe-Mn phosphates, with few exceptions, is confined to well-zoned pegmatites, arborescent phosphates have also been observed in poorly zoned pegmatites.

Occurrences in the border and wall zone

Typically, but not most commonly, arborescent Li-Fe-Mn phosphates occur in the wall zone (and border zone), as observed in the pegmatites of Karlsbrunn, Strathmore "Petalite" and Strathmore No. SP14 (Table 2). These pegmatite bodies are well described, Karlsbrunn by Roering & Gevers (1964), the Strathmore pegmatites by Diehl (1991). The arborescent phosphate minerals of Karlsbrunn have been incorrectly attributed to a fracture-filling unit by Keller (1988), but according to recent field observations they clearly belong to the border and wall zone.

The arborescent phosphates consist of triphylite, ferrisicklerite or heterosite with different Fe/(Fe+Mn) ratios (Table 2). Their primary branches, determining the direction of fastest growth velocity, are orientated perpendicular to the pegmatite contact. Due to a thermal gradient, prismatic to slightly fan-shaped beryl and cassiterite display the same orientation as the arborescent phosphates. For these reasons, the arborescent growth habit is obviously the result of thermal undercooling (Keller, 1988).

Occurrences in the intermediate zone

Arborescent Li-Fe-Mn phosphates are most commonly developed within the intermediate zones, usually in their outer and/or middle portions, but rather seldom along the core margin. In the latter unit, the phosphates commonly display a nodular to blocky shape and occasionally skeletal crystals are observed. In moderately dipping pegmatites, the arborescent phosphates occur more frequently in the hanging wall than in the footwall.

At some well-exposed pegmatites, e.g. Strathmore No. SP48 and Simon's on Etusis, it is easy to observe that the arborescent phosphates have grown from the outer parts of the intermediate zone in such a manner that the primary branch of the dendrites points toward the core. Consequently, in a hanging wall the arborescent phosphates grow downwards and in the footwall upwards, following the direction of the most probable cooling front of a crystallising pegmatite. This observation confirms that in the discussed pegmatites, the arborescent shape is predominantly the result of thermal undercooling as opposed to constitutional supercooling.

TABLE 2.7: Pegmatites of the Northern tin belt, Karlowa swarm, with Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Engelbrecht's tourmaline	gem-tourm, col-tant, beryl	ferr, het	nodular	0.73	intermed.	-.-
Karlowa pegmatite KWP 2-13	cas, col-tant Li-mica	ferr, het triph, fer, het	skelet. nodular	0.660-0.670# 0.665#	core marg. core marg.	3,4
Karlowa Engelbrecht's No. 2	cas	het	nodular	0.795-0.80	unknown	-.-

TABLE 2.8: Pegmatites of the Northern tin belt, Strathmore swarm, with Li-Fe-Mn phosphate minerals (for explanation see Table 2.1).

Farm, area name of pegmatite	economic minerals	phosphates	shape	Fe/(Fe+Mn)	pegmat. zone	ref.
Strathmore pegmatite No. SP14	cas, col-tant, tap, ambl, beryl	ferr, het	arboresc.	0.71-0.72	wall zone	4
Strathmore "Petalite"	pet, col-tant, cas, beryl, euc, mica	ferr, het ferr, het	arboresc. nodular	0.80 0.786#	wall zone inn. interm.	3,4
Strathmore pegmatite No. SP48	cas, col-tant beryl	ferr, het	arboresc.	0.745	intermed.	-.-

The arborescent Li-Fe-Mn phosphates display nearly the full range of variation of Fe/(Fe+Mn) ratios obtained from all occurrences reported here, disregarding their shape and position within the pegmatite zonation, namely $0.125 \leq$ Fe/(Fe+Mn) ≤ 0.805 (Table 2).

With respect to their economic minerals, the pegmatites may be subdivided into four groups:

1. Pegmatites with cassiterite and columbite-tantalite: Strathmore No. SP48; Ariakas No.2, Davib-Ost.

2. Pegmatites with beryl and minor columbite-tantalite: (i) without lithium mineralisation: Henckert's, Etusis; Abbabis No. 1; (ii) with minor lithium mineralisation: Fricke's and Clementine I, Okatjimukuju; Simon's, Etusis.

3. Pegmatites with lithium minerals (petalite, lepidolite and amblygonite-montebrasite): (i) low to medium fractionated: "Petalite", Sandamap; "Petalite", Okatjimukuju; Berger's and Macdonald's, Etusis; (ii) highly fractionated: Rubicon No. 1, Helikon No.1 and No.2, Okongava-Ost.

4. Pegmatites with gem tourmaline: Berger's No.2, Johann-Albrecht'shöhe; Prinz' No.1, Etusis; Herbst's,

Davib-Ost.

Occurrences along the quartz core

Skeletal crystals are developed together with massive nodules of Li-Fe-Mn phosphates typically along the margin of the quartz core within the inner intermediate zone and the quartz core itself at Brockmann's, Tsaobismund, "Petalite", Sandamap, and Karlowa No. KWP2-13. At Tsaobismund, the skeletal crystals are associated with beryl and columbite. A detailed description is given by Fransolet *et al.* (1986).

Arborescent Li-Fe-Mn phosphates, exposed mainly in the intermediate zone but partly reaching the core margin, have already been described.

Occurrences in units of uncertain origin

Arborescent Li-Fe-Mn phosphates of "Petalite" at Sandamap and Rubicon No.1 are of uncertain origin and may possibly be parts of replacement units.

Between the outer and the inner intermediate zones of

TABLE 3.1: Chemical compositions of Li-Fe-Mn phosphates from Damara pegmatites.

The cation proportions of the wet chemical analyses are calculated on the basis of 16 oxygens. *: Fe calculated as FeO for triphylite-lithiophilite or as Fe_2O_3 for ferrisicklerite-sicklerite and heterosite-purpurite; #: Mn calculated as MnO for triphylite-lithiophilite and for ferrisicklerite-sicklerite or as Mn_2O_3 for heterosite-purpurite; -.-: not determined; 0: less than 0.005. a: Wet chemical analyses performed by J.-M. Speetjens; b: "bulk composition" of impure minerals; c: including H_2O; d: including SiO_2.

| | Onanis | Tsaobismund | | Okatjimukuju | | | | |
| | No. 1 lithioph. | Brockmann's | | Fricke's lithioph. | "Petalite" ferris. | Clement. I lithioph. | Clementine II | |
		triph. 1	triph.2				ferris. 3	ferris. 4
P_2O_5	44.87	44.55[a,b]	44.30[a,b]	44.85	43.07[b]	44.63	43.43[b]	42.94[b]
Al_2O_3	0.	-.-	-.-	-.-	0.06	-.-	-.-	-.-
Fe_2O_3	-*-	0.	0.47	-*-	33.09	-*-	34.33	31.33
FeO	26.04	28.22	26.80	14.55	-*-	15.56	-*-	-*-
Mn_2O_3	-#-	-#-	-#-	-#-	-#-	-#-	-#-	-#-
MnO	19.33	14.84	15.32	31.11	15.68	28.75	14.86	18.20
MgO	0.05	0.93	1.79	0.11	2.02	0.60	0.84	0.48
ZnO	0.08	0.	0.05	0.01	0.08	0.08	0.20	0.36
CaO	0.07	0.	0.	0.08	0.08	0.19	0.59	0.94
Li_2O	9.45	9.06	9.00	9.17	2.87	9.54	3.21	3.14
Na_2O	0.06	0.33	0.20	0.11	0.64	0.09	0.14	0.20
K_2O	0.	0.14	0.05	0.01	0.14	0.01	0.36	0.56
Total	99.95	98.05	97.98	100.90[d]	98.73	99.52[d]	97.96	98.15
Cations per formula unit								
P	3.99	4.01	3.99	3.98	3.82	3.97	3.86	3.86
Al	-.-	-.-	-.-	-.-	0.01	-.-	-.-	-.-
Fe	2.29	2.51	2.39	1.28	2.61	1.37	2.71	2.50
Mn	1.72	1.34	1.39	2.78	1.39	2.56	1.32	1.64
Mg	0.	0.15	0.29	0.02	0.32	0.09	0.13	0.08
Zn	0.	0.	0.	0.01	0.01	0.01	0.02	0.03
Ca	0.	0.	0.	0.	0.12	0.02	0.06	0.11
Li	4.02	3.88	3.88	3.89	1.21	4.03	1.35	1.36
Na	0.01	0.07	0.04	0.002	0.13	0.01	0.01	0.04
K	0.	0.	0.01	0.	0.02	0.	0.02	0.08
Fe/(Fe+Mn)	0.574	0.655	0.640	0.319	0.654	0.351	0.675	0.607

Clementine II, Okatjimukuju, a zone of uncertain origin is intercalated on both sides of the nearly symmetrical pegmatite body, containing arborescent Li-Fe-Mn phosphates. Beryl and columbite have been mined from this intercalated zone. A full description is given by Keller & von Knorring (1989).

The Fe/(Fe+Mn) ratio

The Li-Fe-Mn phosphates of Damaran pegmatites display a wide range of Fe/(Fe+Mn) ratios. Values of $0.125 \leq$ Fe/(Fe+Mn) ≤ 0.845 have been obtained by microprobe study and wet chemical analyses (Tables 2 and 3).

With respect to both the relatively small number of preliminary analytical data and the possibility of unconsidered pegmatites with Li-Fe-Mn phosphates, care must be taken to avoid misinterpretation. However, it can be reasonably inferred that regional distribution patterns of Fe/(Fe+Mn) ratios are developed.

The Li-Fe-Mn phosphates with the lowest ratio Fe/(Fe+Mn) = 0.125 have been collected at Rubicon No. 1. Taking the pegmatite with the lowest Fe/(Fe+Mn) ratio from each portion into account, increasing values are obtained from the centre of the Kaliombo-Okongava portion in all directions within this portion itself, but also between different portions (Table 2). Systematically increasing ratios are obtained in a northerly direction, including the Etiro-Daheim portion (0.195), the Ameib-Davib-Sandamap portion (0.62), the Karlowa portion (0.66), and the Strathmore portion (0.71).

On the other hand, a very small variation of $0.765 \leq$ Fe/(Fe+Mn) ≤ 0.845 is obtained by comparing the highest value of Fe/(Fe+Mn) ratio of each portion, if the Etiro-Daheim portion with only two Li-Fe-Mn phosphate-bearing pegmatites is excluded.

The pegmatites of the whole Northern tin belt and of each portion of the Southern tin belt display relatively constant Fe/(Fe+Mn) ratios. In contrast, pegmatites with remarkably different Fe/(Fe+Mn) ratios are exposed within each portion of the remaining southern belts.

There is an apparent relationship if the Fe/(Fe+Mn) ratio of nodular phosphates is compared with the economic minerals from pegmatites of a restricted area, e.g. a portion (Table 2). This relationship is less obvious for the Fe/(Fe+Mn) ratio of arborescent phosphates only.

The following sequence considers the Fe/(Fe+Mn) ratios of nodular Li-Fe-Mn phosphates of all Damaran pegmatites. (The valuable minerals, which have been mined, are given in italics, their order represents the mineral abundance): $0.125 \leq$ Fe/(Fe+Mn) ≤ 0.22: *petal-*

TABLE 3.2: Chemical composition of Li-Fe-Mn phosphates from Damara pegmatites (for explanation see Table 3.1).

	Okatjimukuju					Okongava-Ost		
	Clementine II					Rubicon 1	Rubicon No. 3	
	hetero. 4	triph. 5	hetero. 5	lithioph. 6	sickl. 6	lithioph.	lithioph. 1	lithioph. 1
P₂O₅	43.67[b]	44.35[a]	42.36[b]	44.51[a]	46.40[b]	45.25	44.38	45.04
Al₂O₃	-.-	0.	-.-	0.	-.-	-.-	0.	0.13
Fe₂O₃	31.71	2.06	30.94	3.43	24.33	-*-	-*-	-*-
FeO	-*-	24.60	-*-	19.22	-*-	7.77	15.84	13.83
Mn₂O₃	20.63	-#-	21.09	-#-	-#-	-#-	-#-	-#-
MnO	-#-	18.56	-#-	22.78	22.54	37.19	29.44	32.31
MgO	0.64	0.06	0.51	0.02	1.10	0.01	0.17	0.06
ZnO	0.36	0.38	0.42	0.32	0.34	0.03	0.02	0.04
CaO	1.30	0.08	2.08	0.08	2.06	0.29	0.08	0.10
Li₂O	0.80	9.60	0.44	9.48	3.35	9.56	9.53	9.43
Na₂O	0.10	0.	0.18	0.	0.13	0.02	0.02	0.04
K₂O	0.44	0.01	0.34	0.	0.13	0.	0.	0.02
Total	99.65	99.95[c]	98.36	100.17[c]	100.38	100.12	99.48	101.00
Cations per formula unit								
P	3.78	3.95	3.75	3.95	4.03	3.99	3.96	3.97
Al	-.-	-.-	-.-	-.-	-.-	-.-	0.	0.02
Fe	2.44	2.32	2.43	1.96	1.88	0.68	1.40	1.20
Mn	1.61	1.65	1.68	2.02	1.96	3.28	2.63	2.85
Mg	0.10	0.01	0.08	0.	0.17	0.	0.03	0.01
Zn	0.03	0.03	0.03	0.02	0.03	0.	0.	0.
Ca	0.14	0.01	0.23	0.01	0.23	0.03	0.01	0.01
Li	0.33	4.05	0.18	4.04	1.38	4.03	4.08	3.97
Na	0.02	0.	0.04	0.	0.03	0.	0.	0.01
K	0.06	0.	0.05	0.	0.02	0.	0.	0.
Fe/(Fe+Mn)	0.606	0.587	0.595	0.495	0.492	0.173	0.350	0.300

ite, Li-mica, amblygonite-montebrasite, beryl, mangano-columbite, *pollucite*, bismuth minerals;

$0.319 \leq Fe/(Fe+Mn) \leq 0.351$: *beryl, Li-mica*, petalite, columbite-tantalite, amblygonite-montebrasite;

$0.492 \leq Fe/(Fe+Mn) \leq 0.595$: *beryl, amblygonite-montebrasite*, Li-mica, *petalite, columbite-tantalite, gem tourmaline*, native bismuth;

$0.607 \leq Fe/(Fe+Mn) \leq 0.665$: *cassiterite, columbite-tantalite, beryl*, Li-mica, *gem tourmaline*, amblygonit-montebrasite, *petalite*, uraninite;

$0.70 \leq Fe/(Fe+Mn) \leq 0.745$: *cassiterite, columbite-tantalite*, beryl, tapiolite, amblygonite-montebrasite, *gem tourmaline, petalite*, Li-mica;

$0.778 \leq Fe/(Fe+Mn) \leq 0.845$: *cassiterite, columbite-tantalite, beryl*, Li-mica, *petalite*, eucryptite.

Inferences that can be made from the above results, if the hypothesis of Ginsburg (1960) is applied, are:

(i) All pegmatites with Li-Fe-Mn phosphates of the Northern tin belt and of the Ameib-Davib-Sandamap portion are rather poorly fractionated, with an almost constant degree of fractionation within each portion.

(ii) The pegmatites of the Karibib belt display very different degrees of fractionation and differentiation, ranging from a very low (Abbabis No. 1, $Fe/(Fe+Mn)$ = 0.835-0.845) to a very high degree (Rubicon No. 1, $Fe/(Fe+Mn)$ = 0.173), and Helikon No. 2, $Fe/(Fe+Mn)$ = 0.17).

(iii) For a great number of pegmatites, a general relationship exists between their economic minerals and the degree of fractionation and differentiation. As expected, lithium-pegmatites with minor beryl are highly fractionated and differentiated with respect to their very low $Fe/(Fe+Mn)$ ratio. The pegmatites with increasing beryl and decreasing lithium mineralisation, through to pegmatites containing only beryl (and columbite-tantalite), have successively lower degrees of fractionation and differentiation. The cassiterite pegmatites with beryl and/or lithium mineralisation display an intermediate degree of fractionation. Simple cassiterite pegmatites are usually very poorly fractionated.

(iv) If both arborescent and nodular Li-Fe-Mn phosphates occur in different units of a pegmatite, the degree of differentiation can be estimated from the $Fe/(Fe+Mn)$ ratios. For instance, the pegmatitic melt of Fricke's, Okatjimukuju, was rather moderately fractionated during crystallisation of the arborescent phosphates, $Fe/(Fe+Mn)$ = 0.675-0.78, but a relatively high degree of differentiation was reached during the course of pegmatite evolution at the time of crystallisation of the nodular lithiophilite, $Fe/(Fe+Mn)$ = 0.492.

Although the majority of observations support the hypothesis of Ginsburg (1960), several conspicuous exceptions are present. For instance, "Petalite" at Strathmore was an important lithium producer and thus it

TABLE 3.3: Chemical composition of Li-Fe-Mn phosphates from Damara pegmatites (for explanation see Table 3.1).

	Okongava-O.	Etusis	Sandamap		No. 3	Karlowa		Strathmore
	Henkert's	Simon's	"Petalite"			Engelbrecht's		"Petalite"
	lithioph.	triph.	triph. 1	triph. 2	hetero.	triph.	ferris.	ferris.
P_2O_5	44.76	44.36	45.58[a]	44.93	43.85	45.18	45.74	45.24
Al_2O_3	0.	0.	-.-	-.-	0.	-.-	-.-	-.-
Fe_2O_3	-*-	-*-	-*-	-*-	31.85	-*-	32.58	34.43
FeO	22.27	23.77	34.72	32.35	-*-	29.42	-*-	-*-
Mn_2O_3	-#-	-#-	-#-	-#-	19.56	-#-	-#-	-#-
MnO	22.82	19.62	9.89	12.94	-#-	14.81	14.37	8.42
MgO	0.03	0.09	0.04	0.68	0.37	0.33	0.49	1.27
ZnO	0.02	0.87	-.-	0.17	-.-	0.48	0.49	0.03
CaO	0.05	0.09	0.23	0.07	2.93	0.06	0.15	5.24
Li_2O	9.29	9.38	9.43	9.48	0.09	9.56	3.44	1.29
Na_2O	0.08	0.19	0.05	0.04	0.14	0.01	0.62	0.71
K_2O	0.01	0.01	0.09	0.03	0.27	0.	0.24	0.15
Total	99.33	99.38	100.03	100.69	99.07	99.99[d]	98.18[d]	96.78
Cations numbers								
P	4.00	3.93	4.03	3.96	3.82	4.00	4.00	4.01
Al	0.	0.	-.-	-.-	0.	-.-	-.-	-.-
Fe	1.96	2.04	2.32	2.82	2.47	2.57	2.54	2.71
Mn	2.04	1.70	0.88	1.15	1.54	1.31	1.26	0.75
Mg	0.	0.01	0.01	0.11	0.05	0.05	0.08	0.20
Zn	0.	0.06	-.-	0.	-.-	0.04	0.04	0.
Ca	0.01	0.01	0.03	0.01	0.32	0.01	0.02	0.59
Li	3.97	3.93	3.96	4.00	0.04	4.02	1.43	1.09
Na	0.02	0.04	0.01	0.	0.03	0.01	0.12	0.14
K	0.	0.	0.02	0.	0.04	0.	0.03	0.02
Fe/(Fe+Mn)	0.494	0.548	0.778	0.714	0.620	0.665	0.670	0.786

should be highly fractionated and differentiated. However, the Fe/(Fe+Mn) ratio of Li-Fe-Mn phosphates is very high. Furthermore, nodular and arborescent phosphates have approximately the same Fe/(Fe+Mn) ratio, although they occur in very different pegmatite units. Less striking, but similar, examples are Berger's at Etusis and "Petalite" at Okatjimukuju (Table 2).

Very careful and detailed investigation of these pegmatites is necessary to decide whether the hypothesis of Ginsburg (1960) needs some modification or other factors are responsible for the irregular results.

Conclusions

This is the first comprehensive account of the Li-Fe-Mn phosphates, namely triphylite-lithiophilite solid solution members and their topotactic alteration products ferrisicklerite-sicklerite and heterosite-purpurite from 46 granitic pegmatites of the Damara Sequence in Namibia. These pegmatites belong to 8 portions and swarms of 4 pegmatite belts.

The Li-Fe-Mn phosphates display different shapes which are not only of mineralogical interest, but an important tool in interpreting the course of the pegmatite development. Li-Fe-Mn phosphates with the well-known nodular to subhedral shape, which are usually seen in the inner intermediate zone, are reported from 37 pegmatites. Li-Fe-Mn phosphates with the particularly interesting arborescent shape are developed in 22 pegmatites. In 15 pegmatites, the Li-Fe-Mn phosphates display both a nodular and an arborescent shape. The arborescent Li-Fe-Mn phosphates are exclusively confined to albite-(quartz-muscovite) rocks, which may occur in all pegmatite units.

Arborescent phosphates, intergrown with silicate minerals, are evidence of paragenetic relationships between these minerals (Keller, 1988). Moreover, the occurrence of dendritic minerals is an indication of crystal growth under non-equilibrium conditions, a rather interesting phenomenon with respect to the evolution of pegmatites. It was not possible to decide whether thermal undercooling or constitutional supercooling was responsible for the dendritic growth (Keller, 1988). However, as a result of field observations presented here, thermal undercooling is considered to have been predominant causing the arborescent shape of Li-Fe-Mn phosphates in most of the Damaran pegmatites.

As a preliminary result of 24 wet chemical analyses (Table 3) and microprobe data (Table 2), the Fe/(Fe+Mn) ratios of the Li-Fe-Mn phosphates from Damaran pegmatites display a wide variation. Values of $0.125 \leq$ Fe/(Fe+Mn) ≤ 0.845 have been obtained.

There is some evidence for both (i) regional distribution patterns of the Fe/(Fe+Mn) ratios and (ii) a relationship between the economic minerals of a pegmatite and the Fe/(Fe+Mn) ratio of its Li-Fe-Mn phosphates. However, due to the preliminary state and paucity of present data, further investigations are necessary to cor-

roborate these genetically and economically important relationships.

According to the first detailed investigation of the pegmatite Clementine II at Okatjimukuju (Keller & von Knorring, 1989), the results of this publication and of some unpublished data, the hypothesis of Ginsburg (1960) needs some modification (Chapter 3.3 and 6). Attention must especially be focused on:

(i) The Fe/(Fe+Mn) ratio of triphylite-lithiophilite could be initially determined not only by the availability (activity) of iron and manganese from the pegmatitic melt but by partitioning between the melt (and/or vapor phase) and the solid phases. Under such conditions, the Fe/(Fe+Mn) ratio can be affected by temperature and/or pressure, even if the degree of fractionation is constant.

(ii) The position of occurrence within the pegmatite units may be responsible for the Fe/(Fe+Mn) ratio of Li-Fe-Mn phosphates as a result of the distinct degree of differentiation that may have occurred at the time of crystallisation during the pegmatite evolution.

(iii) The Fe/(Fe+Mn) ratio is not only dependent on the degree of fractionation and differentiation of a pegmatite, but also on the distribution of Fe^{2+} and Mn^{2+} between coexisting triphylite-lithiophilite and triplite-zwieselite and/or other Fe-Mn minerals, e.g. tourmaline and garnet. The tiny grains of Li-Fe-Mn phosphates of Tsaobismund, Clementine II and Rubicon II (Table 2) are obviously affected by such partitioning phenomenon.

(iv) The partitioning of iron and manganese between the vapor phase and the remaining silicate melt must be taken into account if the idea of Jahns & Burnham (Jahns, 1982) is adopted (Keller & von Knorring, 1989).

Accepting the modified hypothesis of Ginsburg (1960), the genetic position of albite-rich rocks in a pegmatite could be determined by the Fe/(Fe+Mn) ratio of their dendritic Li-Fe-Mn phosphates. If the' albite rocks are products of subsequent solidification of the intermediate zone, related arborescent Li-Fe-Mn phosphates are older than the nodular phosphates, which are exposed along the core margin. Thus, the nodular Li-Fe-Mn phosphates of the latter units would display a lower Fe/(Fe+Mn) ratio than the arborescent minerals. In contrast, if the albite rocks are younger replacement products, the arborescent Li-Fe-Mn phosphates would have a lower Fe/(Fe+Mn) ratio than the nodular types.

As another consequence of the arguments discussed above, the Li-Fe-Mn phosphates of a pegmatite should have different Fe/(Fe+Mn) ratios if they (i) occur in different units or zones within a pegmatite, (ii) display different shapes, and (iii) are coexistent with other Fe and/or Mn minerals. Although the majority of pegmatites discussed above are in accordance with the given ideas, with Clementine II (Keller & von Knorring, 1989) an outstanding example, there are also misfits which need further investigation and discussion (e.g. Strathmore

"Petalite"). The research on the Li-Fe-Mn phosphates from Damaran pegmatites will be continued in respect of these and other still open questions.

References

Bergholz, J. and Kubanek, F. 1981. Zur Spurenverteilung in pegmatitischen Na-Feldspäten als Prospektionshilfe am Beispiel Tsaobismund/SWA. *Mineral. Deposita*, **16**, 31-43.

Cameron, E.N. 1955. Concepts of the internal structure of granitic pegmatites and their applications to certain pegmatites of South West Africa. *Trans. geol. Soc. S. Afr.*, **58**, 46-70.

De Kock, W.P. 1932. The lepidolite deposits of South-West Africa. *Trans. geol. Soc. S. Afr.*, **35**, 97 -113.

Diehl, M. 1986. Preliminary report on the Cape Cross - Uis pegmatite field. *Communs geol. Surv. S.W. Africa/Namibia*, **2**, 39-45.

Diehl, M. 1991. Pegmatites of the Cape Cross - Uis pegmatite belt, Namibia: geology, mineralisation, rubidium-strontium characteristics and petrogenesis. *J. Afr. Earth Sci.* (*in press*).

Fransolet, A.-M., Keller, P. and Fontan, F. 1986. The phosphate mineral associations of the Tsaobismund pegmatite, Namibia. *Contr. Miner. Petrol.*, **92**, 502-517.

Frommurze, H.F., Gevers, T.W. and Rossouw, P.J. 1942. The geology and mineral deposits of the Karibib area, South West Africa. *Expl. Sheet 79, (Karibib, S.W.A.)*. Geol. Surv. S. Afr., 172 pp.

Gevers, T.W. 1963. Geology along the north-western margin of the Khomas Highlands between Otjibingwe-Karibib and Okahandja, South West Africa. *Trans. geol. Soc. S. Afr.*, **66**, 199-251.

Gevers, T.W. and Frommurze, H.F. 1929. The tin-bearing pegmatites of the Erongo area, South West Africa. *Trans. geol. Soc. S. Afr.*, **32**, 111-149.

Ginsburg, A.I. 1960. Specific geochemical features of the pegmatitic process. *21st int. geol. Congress Sess. Norden Rep.*, **17**, 111-121.

Haack, U. and Gohn, E. 1988. Rb-Sr data on some pegmatites in the Damara orogen (Namibia). *Communs geol. Surv. S.W. Africa/Namibia*, **4**, 13-17.

Haack, U., Hoefs, J., and Gohn, E. 1983. Genesis of Damara granites in the light of Rb/Sr and ^{18}O data. *In*: Martin, H. and Eder, F.W. (Eds) *Intracontinental Fold Belts*. Springer, Berlin, 847-872.

Haughton, S.H., Frommurze, H.F., Gevers, T.W., Schwellnus, C.M. and Rossouw, P.J. 1939: The geology and mineral depoits of the Omaruru area, South West Africa. *Expl. Sheet 71 (Omaruru, S.W.A.)*. Geol. Surv. S. Afr., 151 pp.

Hawkesworth, C.J., Kramers, J.D. and Miller, R. McG. 1981. Old model Nd ages in Namibian Pan-African rocks. *Nature*, **289**, 278-282.

Jahns, R.H. 1982. Internal evolution of pegmatite bodies. *In*: Cerny, P. (Ed.) *Short course in granitic pegmatites in Science and industry*. Mineralog. Ass. Canada, Short Course Handbk. No. **8**, 293-327.

Karnin, I.D. 1980. Petrographic and geochemical investigations on the Tsaobismund pegmatite dyke, South West Africa, Namibia. *Neues Jb. Miner. Mh.*, 192-205.

Keller, P. 1974. Phosphatmineralien aus Pegmatiten Südwestafrikas. Aufschluss, 25, 577-591.

Keller, P. 1980a. Giniit, $Fe^{2+} Fe_4^{3+} (H_2O)_2(OH)_2(PO_4)_4$, ein neues Mineral aus dem Pegmatit von Sandamab bei Usakos, Namibia. *Neues Jb. Miner. Mh.*, 49-56.

Keller, P. 1980b. Giniit, $Fe^{2+} Fe_4^{3+} (H_2O)_2(OH)_2(PO_4)_4$, neue kristallographische Daten. *Neues Jb. Miner. Mh.*, 561-563.

Keller, P. 1985. Neue Mineralfunde aus dem Pegmatit von Sandamab, SWA/Namibia. *Aufschluss*, **36**, 117-119.

Keller, P. 1987. Skelettkristalle von Phosphaten aus Pegmatiten Namibias und der Black Hills, U.S.A. *Fortschr. Miner.*, **65**, 85 pp.

Keller, P. 1988. Dendritic phosphate minerals and their paragenetic relation to the silicate minerals of pegmatites from Namibia and from the Black Hills, South Dakota, U.S.A. *Neues Jb. Miner. Abh.*, **159**, 249-281.

Keller, P. and von Knorring, O. 1985. Phosphatminerale von Pegmaliten der Farm Okatjimukuju, Karibib, Namibia. *Fortschr. Miner.*, **63**, 110 pp.

Keller, P. and von Knorring, O. 1989. Pegmatites at the Okatjimukuju farm, Karibib, Namibia. Part I: Phosphate mineral associations of the Clementine II pegmatite. *Eur. J. Miner.*, **1**, 567-593.

Martin, H. 1983. Overview of the geological, structural and metamorphic development on the intercontinental branch of the Damara orogen. *In*: Martin, H. and Eder, F.W. (Eds) *Intracontinental Fold Belts*. Springer, Berlin, 473-502.

Miller, R. McG. 1969. The geology of the Etiro pegmatite, Karibib District, S.W.A. *Ann. geol. Surv. S. Afr.*, **7**, 125-130.

Moore, P.B. and Ito, J. 1973. Wyllieite, $Na_2Fe^{2+}Al(PO_4)_3$, a new species. *Mineral. Rec.*, **4**, 131-136.

Reuning, E. 1923. Pegmatite und Pegmatitminerale in Südwestafrika. *Z. Kristallogr.*, **58**, 448-459.

Roering, C. 1966. Aspects of the genesis and crystallization sequence of the Karibib pegmatites, South West Africa. *Econ. Geol.*, **61**, 1064-1089.

Roering, C. and Gevers, T.W. 1964. Lithium- and beryllium-bearing pegmatites in the Karibib District, South West Africa. *In*: Haughton, S.H. (Ed.) *The geology of some ore deposits in Southern Africa*. Vol. **2**. Geol. Soc. S. Afr., 463-496.

Rose, D. 1980. Brabantite, $CaTh[PO_4]_2$, a new mineral of the monazite group. *Neues Jb. Miner. Mh.*, 247-257.

Seeliger, E. and Mücke, A. 1970. Emstit, ein neues Mn^{2+}-Fe^{3+}-Al-Phosphate und seine Beziehungen zu Eosphorit. *Neues Jb. Miner. Mh.*, 289-298.

Smith, D.A.M. 1965. The geology of the area around the Khan and Swakop rivers. *Mem. geol. Surv. S. Afr., SWA Series*, **3**, 113 p.

Uebel, P.-J. 1977. Internal structure of pegmatites, its origin and nomenclature derived from petrographic studies of deeply dipping dykes in South West Africa and extended to gently dipping dykes observed in southern Norway. *Neues Jb. Mineral. Abh.*, **131**, 83-1 13.

Von Knorring, O. 1976. Mineralogical notes from southern Africa. *20th Ann. Rep. Res. Inst. Afr. Geol., Univ. Leeds*, 53-55.

Von Knorring, O. 1985a. Some mineralogical, geochemical and economic aspects of lithium pegmatites from the Karibib Cape Cross pegmatite field in South West Africa/Namibia. *Communs geol. Surv. S.W. Africa/ Namibia*, **1**, 79-84.

Von Knorring, O. 1985b. Niobium and tantalum minerals. *Communs geol. Surv. S.W. Africa/Namibia*, **1**, 85-88.

Wagner, P.A. 1916. The geology and mineral industry of South-West Africa. *Mem. geol. Surv. S. Afr.*, **7**, 119 p.

Wagner, P.A. 1921. On some mineral occurrences in the Namib desert. *Trans. geol. Soc. S.Afr.*, **24**, 71-97.

Winkler, H.G.F. 1983. A survey of granitic rocks of the Damara orogen and considerations on their origin. *In*: Martin, H. and Eder, F.W. (Eds) *Intracontinental Fold Belts*, Springer, Berlin, 817-837.